



Conservation Group

## Technical Paper 9

# Slim-profile double glazing

## Thermal performance and embodied energy



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September 2010

The views expressed in the research report(s), presented in this Historic Scotland Technical Paper, are those of the researchers, and do not necessarily represent those of Historic Scotland.

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This paper should be quoted as  
'Historic Scotland Technical Paper 9'.

We like to thank our project partners:



## Definitions

**Embodied energy** is the energy that was used in the work to make a product. Embodied energy is an accounting methodology which aims to find the sum total of the energy necessary for an entire product lifecycle. This lifecycle includes raw material extraction, transport, manufacture, assembly, installation, disassembly, deconstruction and/or decomposition. However, within this report, a *cradle to site analysis* has been used incorporating data relating only to raw material extraction and processing, and manufacturing and transporting.

**Inert gas** is a non-reactive gas. The cost of the gas and the cost of purifying the gas are usually a consideration when deciding to use it. Examples for inert gases are nitrogen, argon, krypton or xenon. The latter three gases are used as infill gases for the cavities of double-glazed units.

**U-value** (or thermal transmittance co-efficient) is a measure of how much heat will pass through one square metre of a structure when the temperature on either side of the structure differs by 1 degree Celsius. The lower the U-value, the better is the thermal performance of a structure. The U-value is expressed in  $W/m^2K$ .

## **Slim-profile double glazing**

Thermal performance and embodied energy

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### **Executive summary**

Historic Scotland Technical Paper 9 consists of three research reports presenting the results and analysis of studies on the thermal performance and embodied energy of slim-profile double glazing. Other factors, such as appearance, cost or practicalities of slim-profile double glazing or secondary glazing are not considered in this Technical Paper. Two of the research reports were part of a wider project, developed and led by Changeworks for the City of Edinburgh Council from March 2009 to March 2010.

Slim-profile double glazing is of smaller thickness than conventional double glazing. Due to this slimness, it is, in many cases, possible to fit it into windows designed for single glazing.

For the research, the thermal performance of ten slim-profile double-glazing systems was measured, and the performance of the whole windows calculated from the measurements. For comparison, a single-glazed window was calculated with and without secondary glazing.

The best thermal performance was calculated for the window fitted with vacuum double glazing. The thermal performance of the single-glazed window fitted with secondary glazing was not as good as that with vacuum glazing, but better than the other slim-profile double-glazing systems (with one minor exception). Better thermal performance was calculated for slim-profile double glazing when fitted into Victorian style '1 over 1' windows compared to Georgian style '6 over 6' windows.

Inert gases account for a significant proportion of the embodied energy in most double-glazing systems with xenon carrying a particular high embodied energy.

## Introduction

In 2008 Historic Scotland published Historic Scotland Technical Paper 1<sup>1</sup> presenting research findings on technical measures for improving the thermal performance of single-glazed windows. The research, at the time, tested blinds, curtains, shutters, and secondary glazing. It also included one measurement for retrofitted slim-profile double-glazed units.

Historic Scotland Technical Paper 9 now focuses on the option of slim-profile double glazing. The paper consists of three research reports presenting the results and analysis of studies on the thermal performance and embodied energy of slim-profile double glazing. The studies involved the in-situ U-value measurements of ten slim-profile double-glazing systems, calculations of whole-window U-values from these measurements, and assessment of the embodied energy involved in the production and transportation of such glazing. For comparison, the thermal performance of single-glazed windows was also calculated, with and without secondary glazing. Other factors, such as the appearance, cost or practicalities of slim-profile double glazing, or secondary glazing, are not considered in this paper.

Reports 1 and 2 were part of a wider project developed and led by Changeworks, an Edinburgh-based sustainable development organisation, for the City of Edinburgh Council. The Changeworks project was carried out from March 2009 to March 2010, and was supported by Lister Housing Cooperative, Edinburgh World Heritage Trust and Historic Scotland.

Within the Changeworks project, Historic Scotland provided support for the technical assessment of the thermal performance and embodied energy of the slim-profile double glazing installed.

Reports 1 and 2 have also been published in the Changeworks Project Report<sup>2</sup> presenting the wider Changeworks project, which not only considered the thermal performance and embodied energy of slim-profile double glazing, but also included other issues related to this type of glazing, such as visual impact, longevity, maintenance, cost, carbon savings and social impact. Secondary glazing was not considered in the Changeworks project.

Report 3 in this paper was prepared for Historic Scotland, and was not part of the Changeworks project. Report 3 provides a more detailed analysis of whole-window U-value calculations compared to those provided with report 1, and also included, for comparison, calculations for single-glazed windows with and without secondary glazing.

The three reports are outlined in more detail below following a technical introduction to slim-profile double glazing and secondary glazing.

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<sup>1</sup> Baker, P. (2008). *Thermal performance of traditional windows*. (Historic Scotland Technical Paper 1) Edinburgh: Historic Scotland.

Available at [www.historic-scotland.gov.uk/technicalpapers](http://www.historic-scotland.gov.uk/technicalpapers)

<sup>2</sup> Changeworks (2010). *Double glazing in listed buildings: project report*. Edinburgh: Changeworks. Available at [www.changeworks.org.uk/publications.php](http://www.changeworks.org.uk/publications.php)

## Slim-profile double glazing

Conventional double glazing, as used in new-built construction, consists of two layers of glass up to 25 mm apart with dry air or inert gas in the cavity. This considerably reduces the heat loss through the glazing due to the thermal conductivity of these gases and the additional layer of glass. Triple glazing consists, accordingly, of three layers of glass with two cavities in-between.

The glazing systems considered in this paper are examples of slim-profile<sup>3</sup> double glazing. Such glazing has a considerably smaller cavity compared to conventional double glazing, and therefore results in a smaller overall thickness. For comparison, thicknesses for the different glazing types are given in Table 1 below.

**Table 1** – Typical overall thicknesses of glazing units

Single glazing	4 to 6 mm
Slim-profile double glazing*	8.2 to 16 mm
Conventional double glazing	20 to 25 mm
Triple glazing	35 to 45 mm

\* Thicknesses of the glazing measured for report 1 in this paper.

The reduced thickness of slim-profile double-glazing units makes it possible to fit them, in many cases, into windows designed for single glazing. Such windows can be existing windows, or new windows made to match existing profiles.



Figure 1 Slim-profile double glazing (left photo) has a slimmer cavity, and therefore overall thickness, than conventional double glazing (right photo).

<sup>3</sup> In report 3 the term 'slimline' is used instead of 'slim-profile'. Sometimes, these glazing systems are also referred to as 'slim-cavity' double glazing.

## Secondary glazing

In report 3, the installation of secondary glazing has been considered as an alternative to retrofitting windows with slim-profile double glazing.

Secondary glazing involves the installation of new, fully independent secondary window frames (generally on the room side) of an existing window. Secondary glazing systems can vary significantly in appearance, design and thermal efficiency.

The calculations for report 3 are based on the secondary glazing system that had been used in the testing for Historic Scotland Technical Paper 1. The product used, at the time, was a vertically sliding window with '1 over 1' glass panes and only one of the sashes able to slide. The system was manufactured by Storm Windows Ltd. The glazing used was single glazing with low emissivity coating. The system was mounted within the 'staff beads' of the sash and case windows.



Figure 2 Secondary glazing installed to single-glazed sash & case window on the room side: the left photo shows the meeting rails, the right photo the bottom of the window.

## Research reports

Conclusions and recommendations from the research reports included in this paper are outlined at the beginning of reports 1 and 2, and at the end of report 3. A summary of the conclusions is given below following the brief description of the different reports.

Report 1 in this paper was produced by Glasgow Caledonian University on behalf of Changeworks, and provides the results and analysis of a thermal performance study of slim-profile double-glazing systems. For this study the U-values of ten systems, retrofitted into Georgian style windows in ten different properties in two buildings, were measured in-situ. The systems had varying types and thicknesses of glass and cavity. Eight systems had gas-filled cavities, either filled with argon or krypton, or with a mix of xenon and krypton. The cavity of one system was air-filled. One glazing system had a vacuum cavity. The measured centre-of-pane U-values were complemented by calculated whole-window U-values.

Report 2 was prepared by Heriot-Watt University on behalf of Changeworks, and provide the results and analysis of an embodied energy study of slim-profile double-glazing units. The products of seven window and glazing manufacturers have been investigated with 15 options presented. (Some of these options had been measured in the study for report 1.) In addition, three uPVC replacement windows have also been presented as base-case options for comparison.

Report 3 was prepared by Glasgow Caledonian University, and refines the calculations of whole-window U-values carried out for report 1. It also provides calculations to allow the comparison between slim-profile double glazing installed into Georgian and Victorian style windows, and between slim-profile double-glazed windows and single-glazed windows with and without secondary glazing.



Figure 3 Dr. Paul Baker measuring in-situ centre-of-pane U-values (Photo © Changeworks)

## Conclusions

The key findings from the three research reports in this paper are summarised below. More detailed conclusions and recommendations are presented at the beginning of reports 1 and 2, and at the end of report 3.

Please note that, in the summary below where 'Georgian windows' and 'Victorian windows' are stated, this should be read as 'Georgian style windows with "6 over 6" glass panes' and 'Victorian style windows with "1 over 1" glass panes'.

- The best thermal performance was calculated for the window fitted with vacuum double glazing. (Refer to report 3.)
- The calculated thermal performances of single-glazed windows with secondary glazing were not as good as those of windows with vacuum double glazing, but better than the other slim-profile double-glazing system (with one minor exception). (Refer to report 3.)
- Better thermal performances were calculated for slim-profile double glazing when fitted into 'Victorian windows' compared to 'Georgian windows'. (Refer to report 3.)
- The centre-of-pane U-values of the slim-profile double glazing measured in-situ ranged from 1.0 to 2.8 W/m<sup>2</sup>K compared to 5.4 W/m<sup>2</sup>K for single glazing. Most systems achieved a U-value close to 2.0 W/m<sup>2</sup>K. (Refer to report 1.)
- For windows retrofitted with slim-profile double-glazing systems, the calculated whole-window U-values ranged from 1.9 to 3.4 W/m<sup>2</sup>K for 'Georgian windows', and 1.4 to 3.0 W/m<sup>2</sup>K for 'Victorian windows'. This is equivalent to a calculated reduction in heat loss of 35 to 63 % for 'Georgian windows', and 41% to 73 % for 'Victorian windows', compared to their single-glazed equivalents. (Refer to report 3.)
- For equivalent single glazed windows retrofitted with secondary glazing, the calculated whole-window U-values were 2.0 and 2.1 W/m<sup>2</sup>K for 'Georgian windows' and 'Victorian windows' respectively. This is equivalent to a calculated reduction in heat loss of 61 % for 'Georgian windows, and 59 % for 'Victorian windows', compared to their single-glazed equivalents. (Refer to report 3.)
- For equivalent single-glazed windows, whole-window U-values of 5.2 and 5.1 W/m<sup>2</sup>K were calculated for 'Georgian windows' and 'Victorian windows' respectively. (Refer to report 3.)
- Inert gases account for a significant proportion of the embodied energy in most double glazing systems due to the energy-intense processes needed to extract them from the air. Xenon in particular carries a very high embodied energy. (Refer to report 2.)
- The frames of new sashes also add to the embodied energy. This makes retrofitting into existing sashes a more sustainable option (than sash replacements). (Refer to report 2.)
- Further research is required to establish the manufacturing energy of double-glazed units with vacuum cavities. (Refer to report 2.)
- Manufactures should adopt a more systematic approach to the design of glazing units, when filled with gas, in order to optimise thermal performance. (Refer to report 3.)

## Further information

For further information on the technologies mentioned in the research reports, please visit the websites listed below.

<b>Glazing system</b>	<b>Website</b>
Conservation Glazing	<a href="http://www.conservationglazing.co.uk">www.conservationglazing.co.uk</a>
Histoglass	<a href="http://www.histoglass.co.uk">www.histoglass.co.uk</a>
Pilkington energiKare Legacy	<a href="http://www.pilkington.com/europe/uk+and+ireland/english/energikareconsumer/energikare-range/legacy.htm">www.pilkington.com/europe/uk+and+ireland/english/energikareconsumer/energikare-range/legacy.htm</a> <a href="http://www.nsg-spacia.co.jp">www.nsg-spacia.co.jp</a>
Sashworks	<a href="http://www.sashworks.co.uk">www.sashworks.co.uk</a>
Slenderglaze	<a href="http://www.sashconsultancy.co.uk">www.sashconsultancy.co.uk</a>
Slimlite	<a href="http://www.slimliteglass.co.uk">www.slimliteglass.co.uk</a>
Storm Secondary Glazing	<a href="http://www.stormwindows.co.uk">www.stormwindows.co.uk</a>
Supalite	<a href="http://www.peternobleglazing.com">www.peternobleglazing.com</a>



# Report 1

## Thermal performance of slim-profile double glazing

A research report by  
Nicholas Heath, Changeworks,  
and  
Dr. Paul Baker, Glasgow Caledonian University

March 2010

## Report 1 *Thermal performance* – Key findings

This report provides the results and analysis of a thermal performance study which involved retro-fitting a range of bespoke, slim-profile double-glazing units.

The key findings from the study are as follows:

- The U-value of the different systems ranged from 1.0 to 2.8. Most systems achieved a U-value close to 2.0.
- With a small number of exceptions, the *in-situ* U-values tend to be slightly higher than the manufacturers' laboratory-tested U-values. This may be explained by the exposure to the elements that materials face once installed in buildings, rather than in closely controlled laboratory conditions.
- Having only air in the cavity will result in an improved U-value over single glazing alone, however the improvement is smaller than if the cavity contains inert gases or a vacuum.
- Having 100% argon in the cavity does give a lower U-value than air, however the improvement is marginal when the cavity is small. To achieve a significantly lower U-value using argon only, a much wider cavity is needed (as with standard double glazing).
- Xenon- and krypton-filled cavities achieve a lower U-value than air- or argon-filled cavities. This makes these gases better suited to slim-profile double glazing, if thermal performance is the main priority.
- The vacuum glazing achieved the lowest U-value, by a significant margin – despite the fact the cavity is much smaller (0.2 mm) than those of the other units. This demonstrates the effectiveness of a vacuum as a thermal barrier.

Notes.

These key findings have been published in: Changeworks (2010). *Double glazing in listed buildings: project report*. Edinburgh: Changeworks.

Available at [www.changeworks.org.uk/publications.php](http://www.changeworks.org.uk/publications.php)

U-value (or thermal transmittance co-efficient) is expressed in  $W/m^2K$ . A lower U-value indicates a better thermal performance.

U-values presented above are centre-of-pane U-values, and not whole-window U-values.

# Double Glazing In Listed Buildings

## Research report 1: Thermal performance

Report commissioned by Changeworks on behalf of Historic Scotland, March 2010

This report provides the results and analysis of a thermal performance study, carried out as part of a Changeworks project, **Double Glazing In Listed Buildings**. This project ran from March 2009 to March 2010, and involved retro-fitting a range of bespoke, slim-profile double-glazing units into category 'A' and 'B' listed buildings in Edinburgh's Old and New Towns, both of which are conservation areas and form a UNESCO World Heritage Site.

A full project report has been prepared for The City of Edinburgh Council by Changeworks, and is available on request. This report provides full background to the project and the different system specifications, together with analysis of costs, installation and maintenance details, longevity, occupant impact and further recommendations.

**This report should be read in conjunction with the full *Double Glazing In Listed Buildings project report* (see above) by Changeworks, and with *Research report 2: Embodied energy*, prepared for Changeworks by Heriot Watt University.**



# ***In situ* measurements of the U-values of double glazed replacement units in Georgian sash and casement windows**

Prepared for Changeworks by Dr Paul Baker

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March 2010

## Introduction

This report summarises an investigation carried out by the Centre for Research on Indoor Climate & Health, School of the Built & Natural Environment, Glasgow Caledonian University (GCU) on behalf of Changeworks to evaluate the thermal performance of various “slimline” double-glazed replacement units in Georgian sash and casement windows. These units were installed as part of Changeworks’ *Double Glazing In Listed Buildings* project at the ‘A’ listed offices of Edinburgh World Heritage (5 Charlotte Square) and in nine ‘B’ listed tenement flats owned by Lister Housing Co-operative (Lauriston Place and Archibald Place) in Edinburgh. The measurements were carried out over the winter season 2009-2010. Table 1 gives the locations and specifications of the glazings.

The test method using heat flow meters has been used previously to evaluate methods for reducing heat loss through traditional windows for Historic Scotland [1]. As part of the Historic Scotland project *in situ* measurements were carried out in a tenement flat and the offices of Lister at Lauriston Place in Edinburgh, following the installation of insulation measures under Changeworks’ previous *Energy Heritage* project [2]. The results on refurbished shutters and a high specification secondary glazing system showed good agreement with laboratory tests on similar systems.

## Test Method

The test objective is to measure the centre-of-glazing U-value of the double-glazed replacement units. The test method uses Hukseflux Type HFP01 heat flux sensors, which are affixed to the room-side surface of the glass with double sided adhesive tape. The sensors have a quoted manufacturer’s thermal resistance of less than  $6.25 \times 10^{-3} \text{ m}^2\text{K/W}$ . Type-T thermocouples are used to measure the surface temperature of the glazing internally and externally and also of the heat flux sensor. The thermocouples are affixed with transparent tape. Two sensors are used on each window typically, as shown in Figure 1. Campbell Scientific dataloggers are used, which record at 5-second intervals and store data as 10-minute averages.

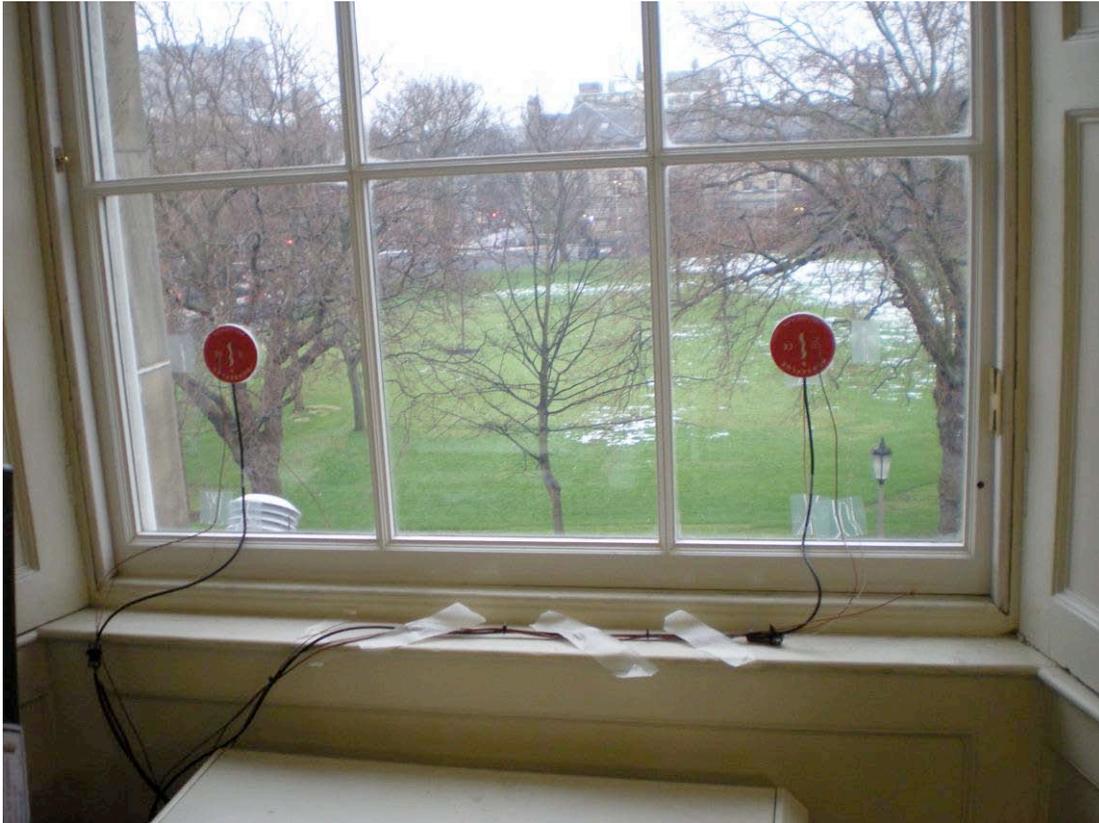
Experience has shown that generally about two weeks’ data are required to give a satisfactory result with dynamically changing indoor and outdoor conditions. A U-value (Equation 1) can be calculated from the average heat flux sensor reading and the surface temperature difference between the outer glazing surface and the surface of the heat flux sensor, as follows:

$$U = \frac{1}{\left(\frac{T_{si} - T_{se}}{Q}\right) + 0.17 - 6.25 \times 10^{-3}} \text{ W/m}^2\text{K} \quad \text{Equation 1}$$

where  $T_{si}$  and  $T_{se}$  are, respectively, the internal and external surface temperatures, and  $Q$  is the heat flux. The term 0.17 is the sum of the standard internal and external surface resistances. The term  $6.25 \times 10^{-3}$  is a correction for the thermal resistance of the heat flux meter.

Alternatively, a dynamic analysis software tool, LORD [3] can be used to determine the U-value.

The heat flux sensors were generally applied to North facing windows to excluded the effect of direct solar radiation, except at Charlotte Square (South; the only elevation with replacement glazing), Flat 1/4 Archibald Place (West; only accessible elevation) and 37 Lauriston Place (West; only accessible elevation).



**Figure 1:** Typical test arrangement on glazing in Georgian sash

**Table 1:** Location and specification of the replacement glazing. The glazing configuration gives the inner pane, gap and outer pane thicknesses

Address	System / manufacturer	Glazing configuration - inner pane / cavity / outer pane (mm)	Inner pane glazing type	Gap fill	Comments	Manufacturer's Centre of Pane U-value - upper limit [W/m <sup>2</sup> K]
1/1 Archibald Place	Sashworks	4-8-4	Low-E	argon	New sashes	1.8
1/2 Archibald Place	Histoglass	3-4-4	Low-E	krypton		1.9
1/3 Archibald Place	Histoglass	3-4-4	Low-E	krypton	Crown-effect outer pane	1.9
1/4 Archibald Place	Pilkington energiKare Legacy	4-0.2-3	Low-E	vacuum		1.3
1/5 Archibald Place	Slimlite	3-3-3	Low-E	air		2.6
1/6 Archibald Place	Slimlite	3-3-3	Low-E	xenon & krypton	Crown-effect outer pane	2.1
1/7 Archibald Place	Slenderglaze	4-3.9-4	Low-E	xenon & krypton		2.1
1/8 Archibald Place	Slimlite	3-3-3	Low-E	xenon & krypton		2.1
37 Lauriston Place	Supalite	4-4.8-3	Low-E	argon	New sashes	2.5
5 Charlotte Square	Slimlite	3-3-3	Low-E	xenon & krypton	New sashes	2.1

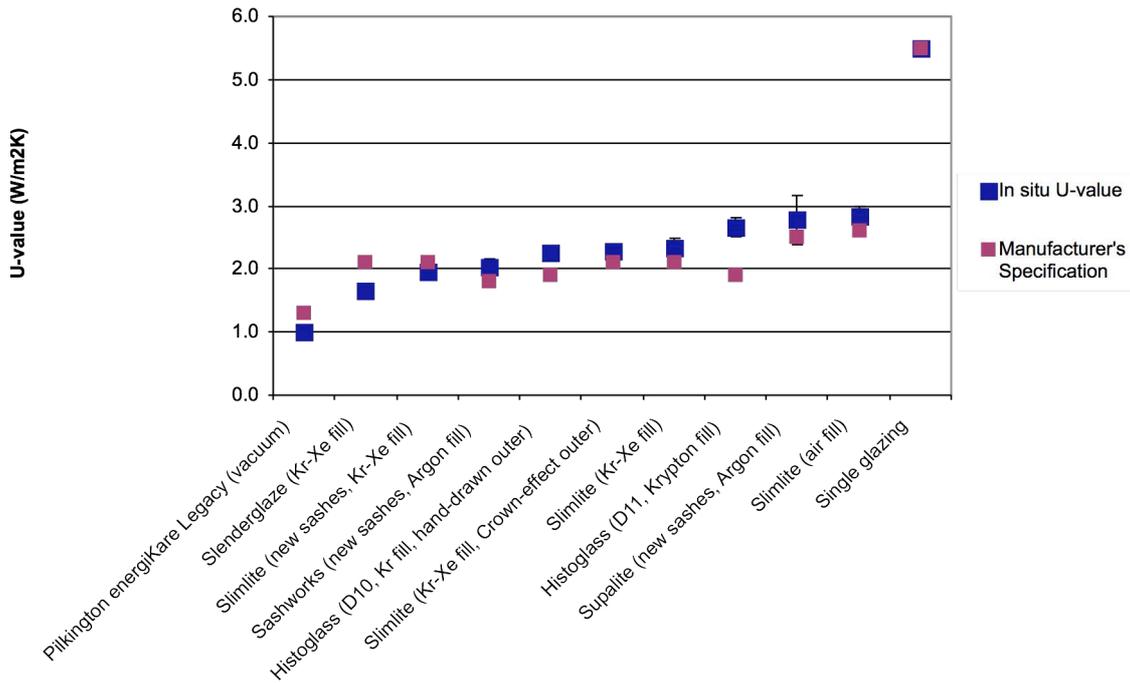
**Table 2:** Test results

<b>Glazing Type</b>	<b>Location</b>	<b>Test start</b>	<b>Test end</b>	<b>U-values, W/m<sup>2</sup>K</b>	<b>Uncertainty</b>
Sashworks (new sashes, argon fill)	1/1 Archibald Place	22/02/2010	08/03/2010	2.0	7%
Histoglass (D11, krypton fill)	1/2 Archibald Place	08/03/2010	22/03/2010	2.7	5%
Histoglass (D10, krypton fill, hand drawn outer)	1/3 Archibald Place	08/03/2010	22/03/2010	2.3	5%
Pilkington energiKare Legacy (vacuum)	1/4 Archibald Place	08/03/2010	22/03/2010	1.0	11%
Slimlite (air fill)	1/5 Archibald Place	05/02/2010	22/02/2010	2.8	5%
Slimlite (xenon & krypton fill, Crown-effect outer)	1/6 Archibald Place	22/02/2010	08/03/2010	2.3	5%
Slenderglaze (xenon & krypton fill)	1/7 Archibald Place	22/02/2010	08/03/2010	1.7	6%
Slimlite (xenon & krypton fill)	1/8 Archibald Place	05/02/2010	22/02/2010	2.3	7%
Supalite (argon fill, new sashes)	37 Lauriston Place	08/03/2010	22/03/2010	2.8	14%
Slimlite (xenon & krypton, new sashes)	5 Charlotte Sq.	22/12/2009	13/01/2010	2.0	7%

## Results

The South- and West-facing windows were affected by solar radiation, therefore analysis of the data from Charlotte Square, Flat 1/4 Archibald Place and 37 Lauriston Place was carried out using night-time data only with the LORD software [3].

The centre-of-pane U-value estimates are given Table 2. Figure 2 compares the measured values with the manufacturers' specification. The results show that the glazing units exhibit a range of values, from 1.0 W/m<sup>2</sup>K for the vacuum glazing to 2.8 W/m<sup>2</sup>K for one of the Slimlite glazing units and the Supalite glazing. Note that the U-value of single glazing is about 5.5 W/m<sup>2</sup>K.



**Figure 2:** Measured centre of pane (COP) U-values compared with manufacturers' specifications

There is higher uncertainty on the U-values measured on the West-facing glazings during March 2010, particularly the Supalite glazing used in 37 Lauriston Place, since there were less data available, which excluded the influence of solar radiation, due to increasing day length. The uncertainty on the other measured values is 5-7%.

Generally the manufacturer's specification tends to overestimate the performance of the glazing unit, except for the Pilkington energikare Legacy vacuum glazing and the Slenderglaze unit.

The vacuum glazing is effective as the evacuated gap prevents convective heat transfer between the two panes. However, heat is transferred through the small support pillars separating the panes and the edge seal. The performance of the gas filled units, whilst not as effective as vacuum glazing, is generally better than the unit filled with air. The performance of the individual glazing type depends on the following:

- The emissivity of the low-e coating – the lower the emissivity the lower the U-value (note that no information was available on the type of low-e glazing used in the double glazed units).
- The gas type – Argon, Krypton and Xenon have superior properties to air, however the *gap width* should be optimised for the gas type. For air the optimum gap width is 16mm, Argon 15mm, Krypton 11mm and Xenon 8mm.
- The benefits of using gases other than air are most significant using low-e glass with lower emissivities and the optimum gap width.

A useful reference is BS EN ISO 10077-1:2006 Appendix C [4], which gives the thermal transmittance of double glazing filled with different gases.

The gas-filled replacement panes tested are not optimised for thermal performance. This is sacrificed in order to produce slimmer units suitable for conservation-grade buildings.

A simple area weighting method has been applied to estimate the influence of the centre-of-pane U-value of the slimline replacement panes on the whole window U-value, based on the whole window U-value of a similar window design measured for the Performance of Traditional Windows project [1]. The U-value of the single-glazed window was 4.4 W/m<sup>2</sup>K with a glazed area of about 55% of the total window area. The results are given in Table 3.

**Table 3:** Whole window U-value estimates

Glazing Type	Location	Whole window U-value, W/m <sup>2</sup> K
Single glazing	-	4.4
Sashworks (new sashes, argon fill)	1/1 Archibald Place	2.5
Histoglass (D11, krypton fill)	1/2 Archibald Place	2.8
Histoglass (D10, krypton fill, hand drawn outer)	1/3 Archibald Place	2.6
Pilkington energiKare Legacy (vacuum)	1/4 Archibald Place	1.9
Slimlite (air fill)	1/5 Archibald Place	2.9
Slimlite (xenon & krypton fill, Crown-effect outer)	1/6 Archibald Place	2.6
Slenderglaze (xenon & krypton fill)	1/7 Archibald Place	2.3
Slimlite (xenon & krypton)	1/8 Archibald Place	2.7
Supalite (new sashes, argon fill)	37 Lauriston Place	2.9
Slimlite (new sashes, xenon & krypton fill)	5 Charlotte Sq.	2.5

The Pilkington energiKare Legacy vacuum glazing is the most effective option, reducing the whole window U-value by 56% compared with the single glazed window.

## Conclusions

The *in situ* U-values of various “slimline” double glazed replacement units in Georgian sash and casement windows has been measured.

The Pilkington energiKare Legacy vacuum glazing is the most effective option, offering both good thermal performance with a narrow profile. The other double glazed options, whilst giving a significant improvement, are not optimised for thermal performance. This is sacrificed in order to produce slimmer units suitable for conservation-grade properties.

Improving the design of the gas-filled units may be a challenge: using Xenon with lower emissivity glazing could result in U-values in the range 1.1-1.5 W/m<sup>2</sup>K for cavity widths of 6-8mm.

## References

[1] Baker P.H. Thermal Performance of Traditional Windows, Technical Paper 1, Technical Conservation Group, Historic Scotland, November 2008 ([http://www.historic-scotland.gov.uk/gcu-technical-\\_thermal-efficiency-traditional-windows.pdf](http://www.historic-scotland.gov.uk/gcu-technical-_thermal-efficiency-traditional-windows.pdf))

[2] The project is fully described in the comprehensive guide *Energy Heritage: A guide to improving energy efficiency in traditional and historic buildings*, Changeworks, 2008 ([http://www.changeworks.org.uk/uploads/83096-EnergyHeritage\\_online1.pdf](http://www.changeworks.org.uk/uploads/83096-EnergyHeritage_online1.pdf))

[3] Gutschker O. LORD 3.2, Modelling and identification software for thermal systems, Manual, BTU Cottbus / Angewandte Physik, 2003

[4] BS EN ISO 10077-1:2006 Thermal performance of windows, doors and shutters – Calculation of thermal transmittance – Part 1: General. BSI, London, ISBN 0 580 49527 2

## Report 2

# Embodied energy of slim-profile double glazing

A research report by  
Nicholas Heath, Changeworks,  
and  
Dr. Gillian Menzies, Heriot-Watt University

July 2010

The appendix to this report is available  
as Excel spreadsheet for online download at:  
[www.historic-scotland.gov.uk/technicalpapers](http://www.historic-scotland.gov.uk/technicalpapers)

## Report 2 *Embodied energy* – Key findings

This report provides the results and analysis of an embodied energy study which involved retro-fitting a range of bespoke, slim-profile double-glazing units. Some of the retro-fitting options included new window sashes. The embodied energy considered in this report for glazing (and new sashes where applicable) is a cradle-to-site analysis.

The key findings from the study are as follows:

- Although the Pilkington energiKare Legacy system is manufactured in Japan and has to be freighted to Britain, it has by far the lowest embodied energy when freighted by sea. The reason for this is that it contains a vacuum rather than inert gases (and no frame materials were required as the units were fitted into existing timber frames). However, further research is required to establish the manufacturing energy of vacuum unit designs.
- Inert gases account for a significant proportion of the embodied energy in most double glazing systems, due to the energy-intense processes needed to extract them from the air. Xenon in particular carries a very high embodied energy (see below).
- The type of gas used can have a considerable impact on the embodied energy. Using a vacuum, air, argon or krypton, the energy embodied within the window could be repaid many times throughout its life. However, using 100% xenon, the reverse could be the case (i.e. the window will never save as much energy as went into its manufacture).
- Using a mix of gases (e.g. krypton and xenon) appears to be increasingly commonplace. This increases the thermal performance of a unit, which to some degree then offsets its embodied energy. However, this is a *cradle to site* study only: a full life cycle energy analysis would confirm this.
- The frames of the new sashes also add to the embodied energy. This makes retrofitting into existing sashes a more sustainable option (as well as the more evident benefits of re-using existing materials).
- Freightng materials by air is not a suitable option, as the embodied energy spirals once air-freighting is included.
- uPVC frames have a far higher embodied energy than timber frames. When combined with xenon, a uPVC window would carry by far the highest embodied energy.

Notes.

These key findings have been published in: Changeworks (2010). *Double glazing in listed buildings: project report*. Edinburgh: Changeworks.

Available at [www.changeworks.org.uk/publications.php](http://www.changeworks.org.uk/publications.php)

# Double Glazing In Listed Buildings

## Research report 2: Embodied energy

Report commissioned by Changeworks on behalf of Historic Scotland, July 2010

This report provides the results and analysis of an embodied energy study, carried out as part of a Changeworks project, **Double Glazing In Listed Buildings**. This project ran from March 2009 to March 2010, and involved retro-fitting a range of bespoke, slim-profile double-glazing units into category 'A' and 'B' listed buildings in Edinburgh's Old and New Towns, both of which are conservation areas and form a UNESCO World Heritage Site.

A full project report has been prepared for The City of Edinburgh Council by Changeworks, and is available on request. This report provides full background to the project and the different system specifications, together with analysis of costs, installation and maintenance details, longevity, occupant impact and further recommendations.

**This report should be read in conjunction with the full *Double Glazing In Listed Buildings project report* (see above) by Changeworks, and with *Research report 1: Thermal performance*, prepared for Changeworks by Glasgow Caledonian University.**





**Embodied Energy Analysis of retrofit glazing options for listed buildings**

**Dr Gillian Menzies**

**BEng PhD CEng CEnv MIE MBIFM MHEA**

**Heriot-Watt University**

**Edinburgh**

**July 2010**

## Executive Summary

The embodied energy has been calculated for a number of retrofit window and glazing unit options for use in traditional buildings, specifically category 'B' listed Georgian tenement buildings in the UNESCO World Heritage Site, Edinburgh, as part of Changeworks' *Double Glazing In Listed Buildings* project. This Cradle-to-Site analysis incorporates data relating to raw material extraction and processing, manufacturing and transportation.

**This report finds that Krypton gas filled units demonstrate lower embodied energy values than units with a mix of heavier gases. The omission of inert gases in Pilkington Energikare units significantly reduces their embodied energy, but further research is required to establish the manufacturing energy of vacuum unit designs. It also finds that transportation energy can be significant in *Cradle to Site* analyses and demonstrates the increased environmental impact of air freight over more sustainable means of transport.**

**It is recommended that these embodied energy figures be used in combination with operational energy consumption analysis, based on the individual U-values achieved by various unit options. This type of analysis is likely to expose greater differences in options when evaluated over a 40-year operational lifecycle.**

## 1 Introduction

This report accompanies the spreadsheet, *LCI Data 2010*. The products of seven various window and glazing manufacturers have been investigated, with 18 options presented. Three base-case options have been presented, although it is recognised that these will not actually be installed: one each of uPVC replacement windows of comparable size and efficiency with Argon, Krypton and Xenon infill gas options. These are for comparative purposes only. Two further options are presented which also illustrate the embodied energy of replacement timber sashes.

## 2 Data sources

Due to time and resource restrictions this report uses embodied energy findings from third parties:

1. Hammond, G.P. and Jones, C.I., 2008. *Embodied energy and carbon in construction materials*, *Energy*, 161 (2): 87-98. Sourced at <http://www.bath.ac.uk/mech-eng/serf/embodied/>
2. Weir, *Life Cycle Assessment of Muti-Glazed Windows*, PhD Thesis, Napier University, Edinburgh, 1998
3. Asif, Davidson and Muneer, *Life Cycle of Window Materials – A Comparative Assessment*, Napier University, Edinburgh. Sourced at <http://www.cibse.org/pdfs/Masif.pdf>
4. Fernie and Muneer, 1996 *Monetary, energy and environmental cost of infill gases for double glazings*, *Building Services Engineering Research & Technology*, 17 (1) 43-46
5. Department for Environment, Food and Rural Affairs (Defra), 2009, *Greenhouse Gas Conversion Factors for Company Reporting*. Sourced at <http://www.defra.gov.uk/environment/business/reporting/conversion-factors.htm>
6. Sustainable Energy Authority of Ireland (SEAI), conversion factors sourced at [www.sustainableenergyireland.com/Publications/Statistics\\_Publications/Emission Factors](http://www.sustainableenergyireland.com/Publications/Statistics_Publications/Emission_Factors)

### 3 Assumptions

A number of assumptions have been necessary throughout the study. These are explained below:

- Work by Weir (1998) shows life cycle inventory data based on four main activities from cradle to gate: material extraction, manufacture, packing and transportation. Where possible this methodology has been followed. No specific allocation has been given in this study for ironmongery (n/a unless entire window replaced) or butyl sealants (information available is very limited; Weir (1998) makes no allocation for this material). An estimation for the energy consumed during assembly of the glazing units has been given: this includes the energy associated with assembling glazing units and cutting and forming spacers, and an allocation for factory heating, lighting and administration.
- No specific data relating to the manufacture energy associated with the creation of a vacuum for the Pilkington energiKare Legacy product was found. Literature searches on the topic revealed that the technology and associated analyses are in their infancy.
- Embodied energy data for aluminium assumes a UK recycling rate of 33% (Hammond and Jones, 2008)
- Embodied energy data for glass assumes a UK recycling rate of 38% (Hammond and Jones, 2008)
- Transport data makes no allowance for warehouse storage/handling requirements, and relates purely to the energy embodied in various transport means – the functional unit is MJ/km/kg transported. Data from Defra is included within *LCI data 2010.xls* spreadsheet *Freight Transport*. The UK average for all HGVs has been used for road transport since no specific data is available on lorry type and size, with an average of 7.23 tonnes of goods per vehicle (56% weight laden). For long-haul international flights a 9% uplift factor has been used, in accordance with the IPCC's *Aviation and the Global Atmosphere* which states that 9-10% should be added to take into account non-direct routes (i.e. not along the straight line, great circle distances between destinations) and delays/circling. Airline industry representatives have indicated that the percentage uplift will be higher for short-haul flights and lower for long-haul flights; however specific data is not currently available to provide separate factors.

## 4 Embodied Energy (EE) Results

**(The main body of results is contained in spreadsheet *LCI data 2010*. The following text and figures present a brief overview of this detailed analysis.)**

The Life Cycle Inventory data presented in spreadsheet *LCI data 2010* includes the extraction of materials required for the various windows or glazing units, namely: glass, infill gases, spacers, low emissivity coating(s), and (where appropriate) frame/sash materials, based on work by Weir (1998). EE values for glass and aluminium were taken from Hammond and Jones (2008), while EE values for Argon, Krypton and Xenon gases were taken from Fernie and Muneer (1996), and EE values for low emissivity coatings and assembly functions from Weir (1998). Information relating to frame and sash materials were derived from Asif *et al.*

Figure 1 (below) shows the summary of EE data for all options, while Figure 2 (below) shows the same information excluding uPVC options, and Pilkington energiKare Legacy products arriving by air. **The source of EE difference between various options is limited in the main to two factors: transportation and infill gas.**

**Transport by air is energy-intensive due to the load capabilities of jet transport. Container ship over the same distance is less energy-intensive when based on a kg-km basis.**

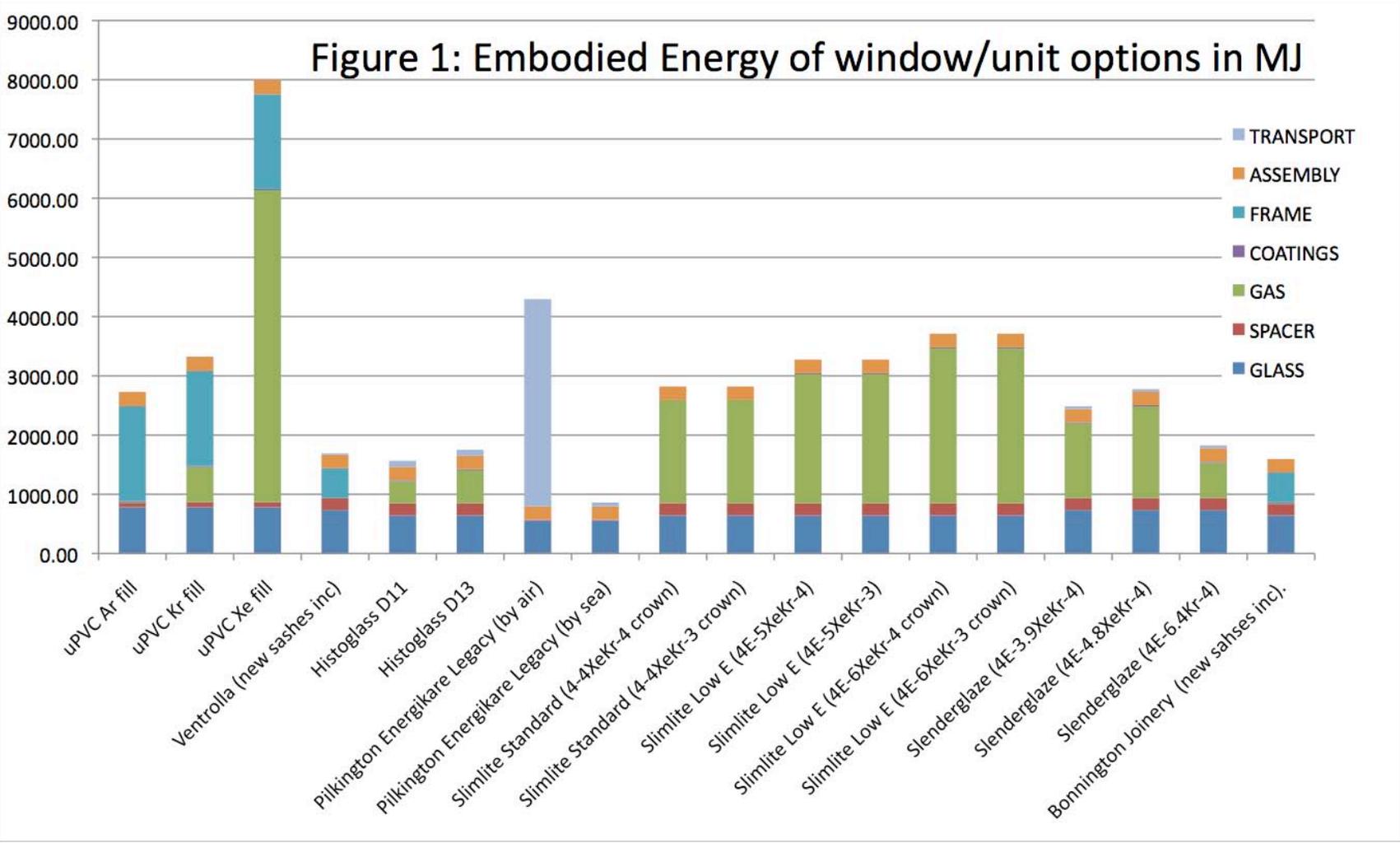
**It is seen that Xenon gas leads to extremely high EE values. Weir (1998) found that it would take many times the design life intended to justify the use of Xenon gas filled constructions. Using a mix of inert gases now appears to be more commonplace, and may offer good energy accounting. What is presented in this report is a *Cradle to Site* analysis. A full Life Cycle Energy Analysis of window options is required in order to select the optimum window design. Despite their higher embodied energy it is possible that a window/unit design which contains a mix of inert gases may offer lower lifecycle energy consumption via reduced U-values. i.e. less heat is lost through the window during its operational phase, thus off-setting the raised embodied energy value.**

## 5 Sensitivity Analysis

The ICE database (Hammond and Jones, 1998) publishes low and high estimates of EE for raw materials. For extruded aluminium this is +/- 20%, while for glass is +/- 30%. No sensitivity data is available for the EE of gases, low-E coatings, assembly, transport or frame information.

Figure 3 (below) shows the resulting maximum and minimum EE data for all options. "Estimated EE Data" refers to the calculated embodied energy values presented in Figure 1.

Figure 1: Embodied Energy of window/unit options in MJ



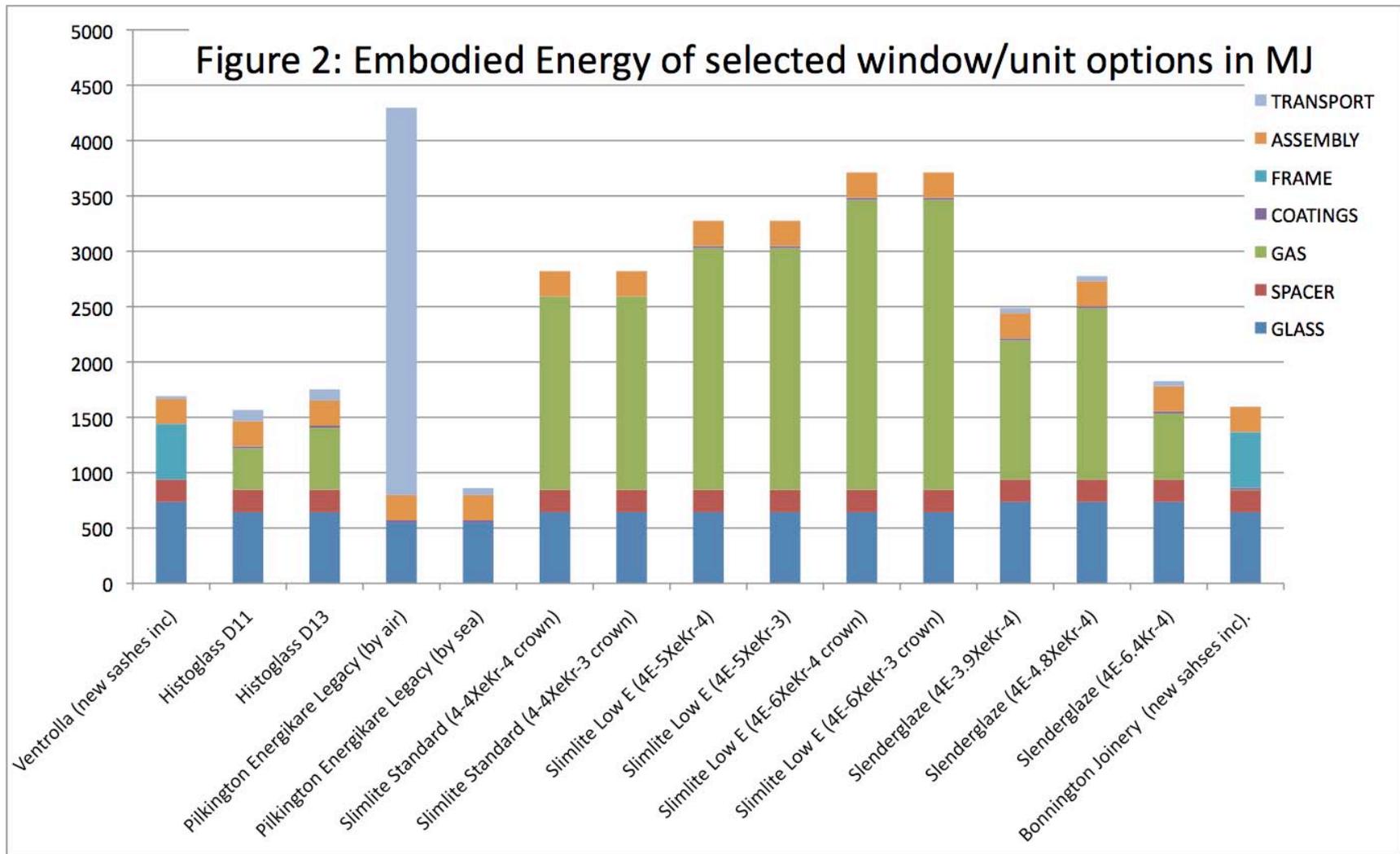
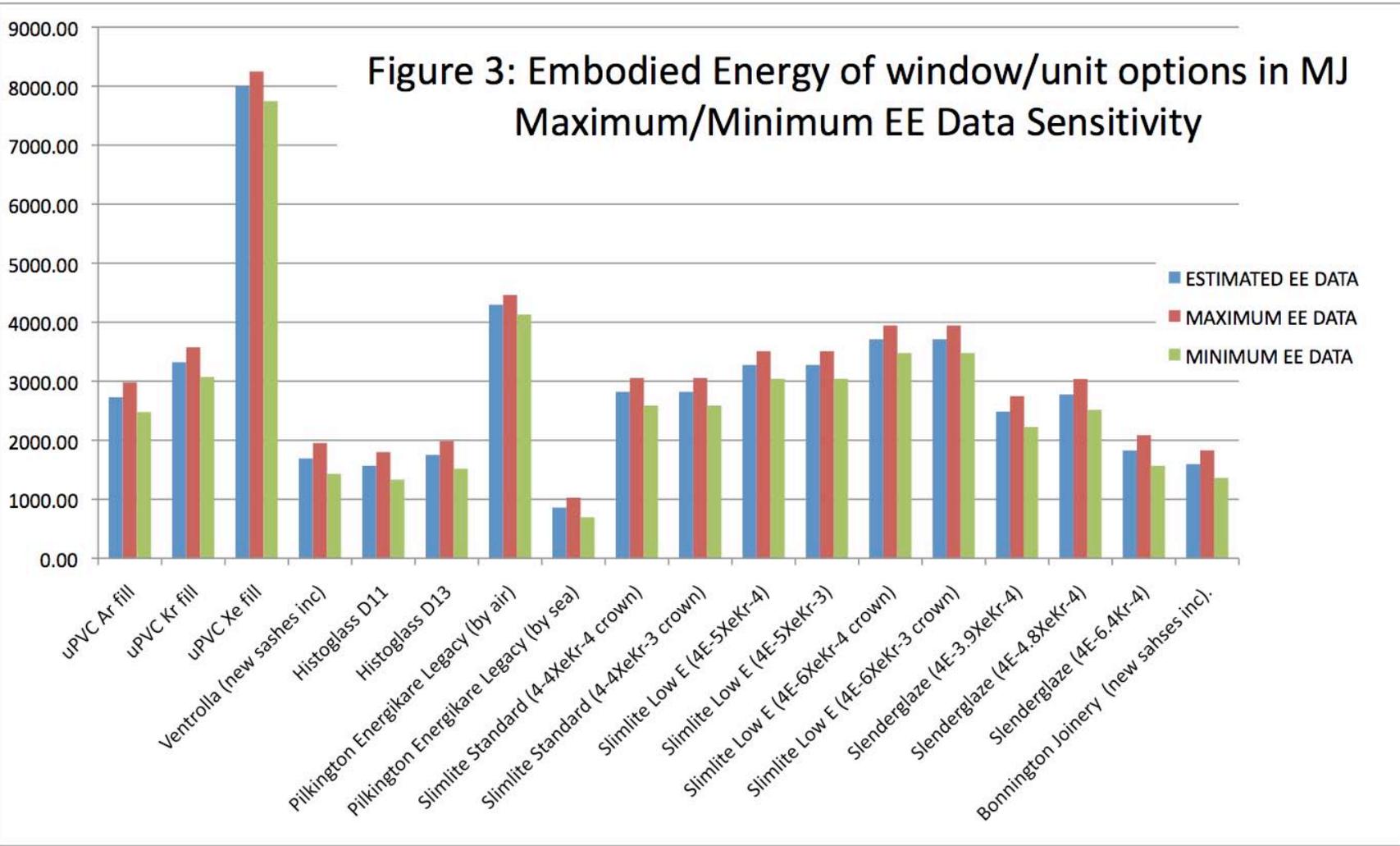


Figure 3: Embodied Energy of window/unit options in MJ  
Maximum/Minimum EE Data Sensitivity



## 6 Conclusions

The *Cradle to Site* analysis performed in this report demonstrates that Krypton-filled units demonstrate lower embodied energy values. The omission of inert gases in Pilkington EnergiKare units significantly reduces their embodied energy, but further research is required to establish the manufacturing energy of vacuum unit design.

It is clear to see from Figure 1 that Krypton- and Xenon-filled window cavities lead to higher EE values. Argon-filled windows offer marginally increased thermal resistance compared to air-filled cavities, and have significantly lower EE values than Krypton- and Xenon-filled windows. Weir (1998) showed that both Argon- and Krypton-filled windows demonstrated positive life cycle energy analyses – i.e. the energy embodied within the window could be repaid many times throughout the life of the window – whereas Xenon-filled windows showed this analysis to be negative. Weir's analysis was based on cavities of 16, 12 and 8mm for Argon, Krypton and Xenon respectively.

With slim-profile glazing units the cavities are much smaller, and therefore the gas quantities are significantly reduced. This has an obvious knock-on effect on the EE of the glazing unit, but also on the increased centre-pane U-value of the the unit. The use of various Xenon/Krypton gas concentrations in window units needs further investigation to include the operational use phase of the building. Only once a full energy analysis has been performed can this question be fully answered – see recommendation below.

The embodied energy of air transport (Pilkington energiKare Legacy option) is significant, showing that despite a product with lower EE of materials and manufacture, the means of transport cannot be ignored. Container ship transport embodies considerably less energy and carbon per kg-km than air transport.

With more accurate data on the manufacturing process of Pilkington energiKare Legacy the LCI data for this product could be made more complete. In this case it is likely that the further pursuit of reliable data would show positively in a sensitivity analysis.

## 7 Recommendation

The EE data presented in this report should be used in combination with U-value analysis and resulting operational energy of the windows/units/properties concerned. A holistic evaluation of this nature would present the optimum choice in terms of full life cycle energy analysis.



**Embodied energy analysis of retrofit  
glazing options for listed buildings**

**APPENDIX 1  
LCI Data 2010  
spreadsheet**

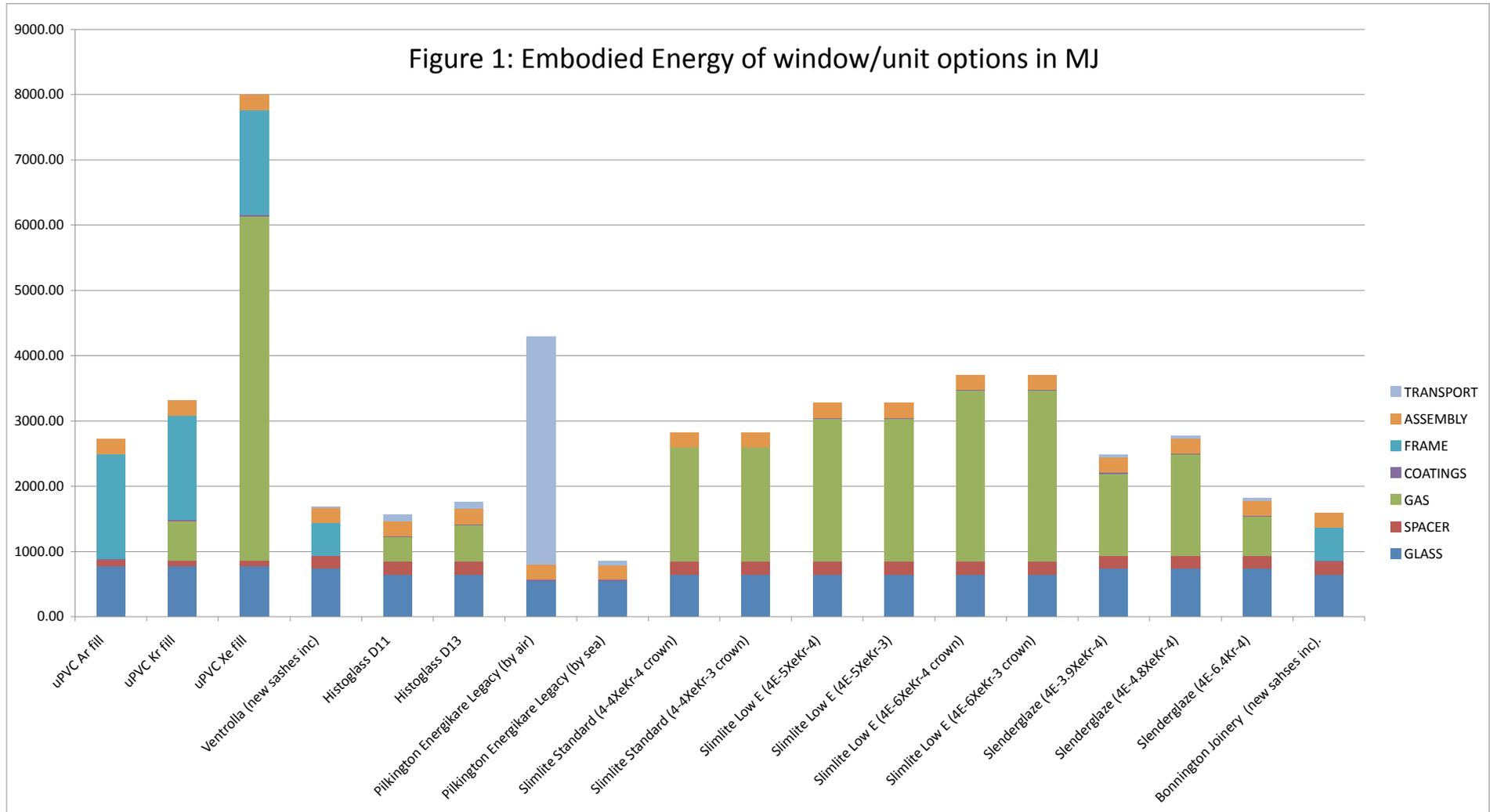
**Dr Gillian Menzies  
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**Heriot Watt University  
Edinburgh**

**July  
2010**

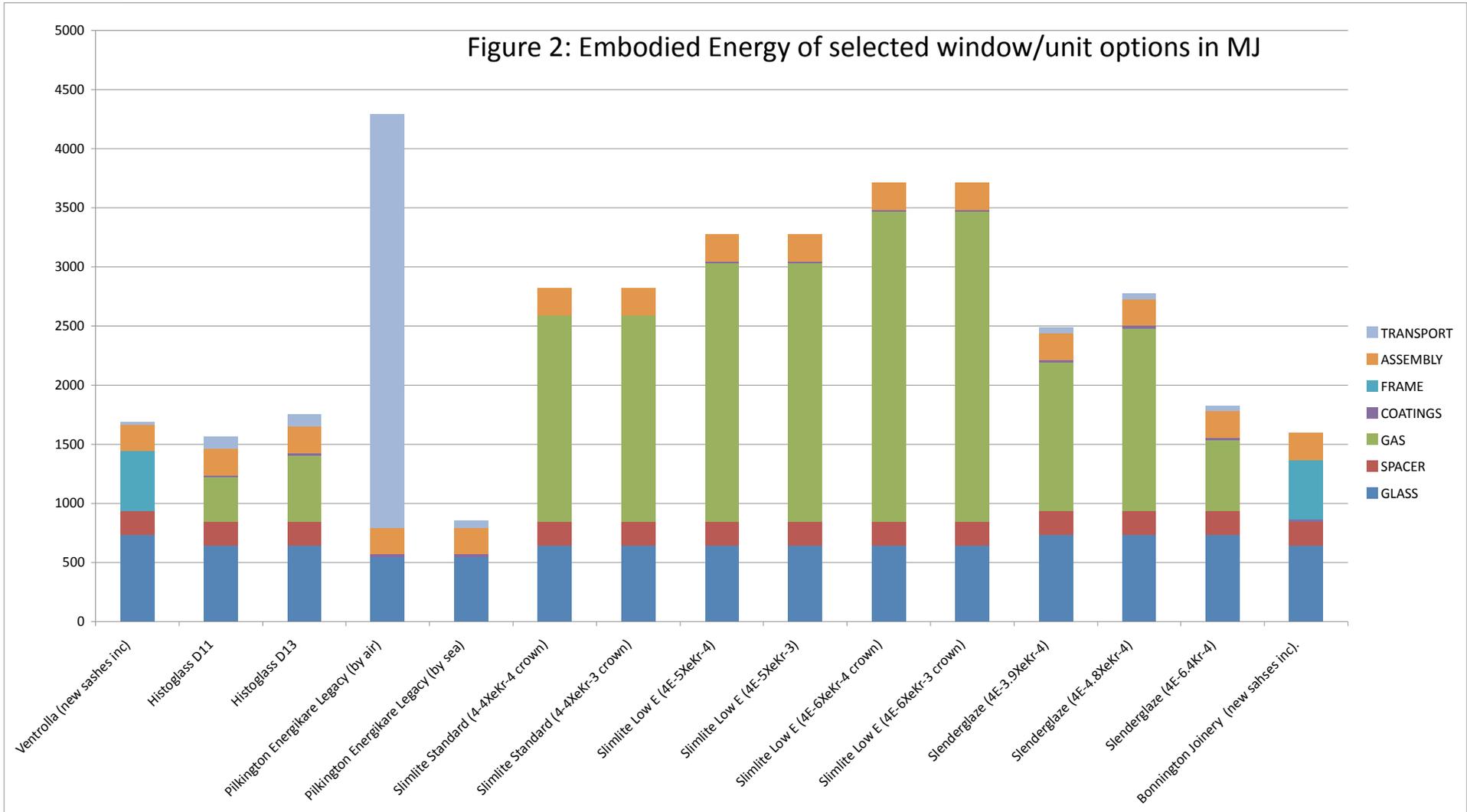


**FIGURE 1**



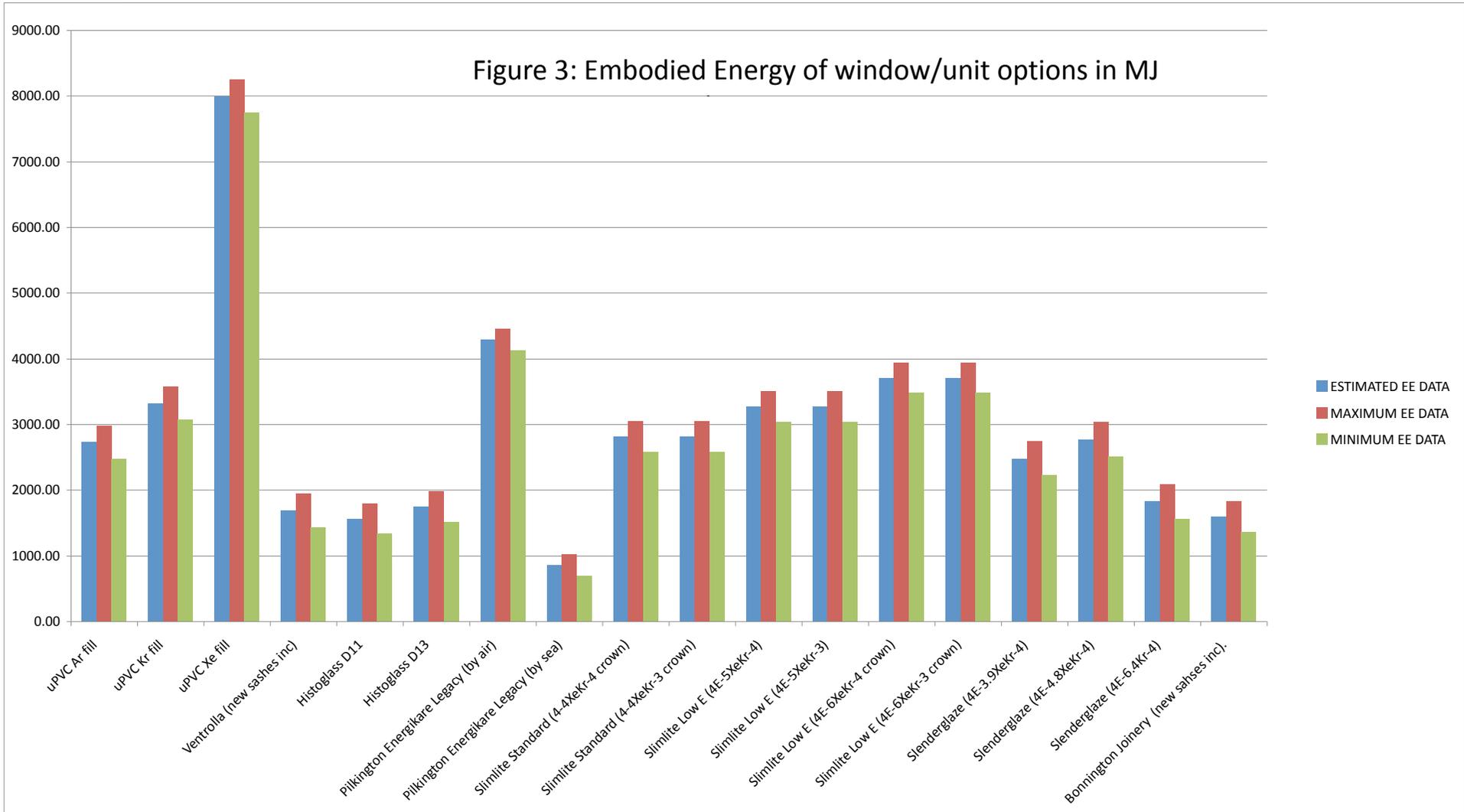


**FIGURE 2**



SENSITIVITY ANALYSIS															
	EXISTING EMBODIED ENERGY (MJ)														
WINDOW OPTION	GLASS	GLASS + 30%	GLASS - 30%	SPACER	SPACER + 20%	SPACER - 20%	GAS	COATINGS	FRAME	ASSEMBLY	TRANSPORT	EXISTING TOTAL	MAXIMUM TOTAL	MINIMUM TOTAL	
uPVC Ar fill	782.07	1016.70	547.45	83.90	100.68	67.12	0.01	19.71	1599.27	243.31	0.00	2728.27	2979.68	2476.87	
uPVC Kr fill	782.07	1016.70	547.45	83.90	100.68	67.12	595.06	19.71	1599.27	243.31	0.00	3323.32	3574.72	3071.91	
uPVC Xe fill	782.07	1016.70	547.45	83.90	100.68	67.12	5269.47	19.71	1599.27	243.31	0.00	7997.73	8249.13	7746.32	
Ventrolla (new sashes inc)	734.47	954.81	514.13	204.02	244.82	163.22	0.00	0.00	501.48	228.50	23.22	1691.69	1952.84	1430.55	
Histoglass D11	642.66	835.46	449.86	204.02	244.82	163.22	372.56	18.51	0.00	228.50	99.67	1565.92	1799.52	1332.32	
Histoglass D13	642.66	835.46	449.86	204.02	244.82	163.22	558.84	18.51	0.00	228.50	99.67	1752.20	1985.80	1518.60	
Pilkington Energikare Legacy (by air)	550.85	716.11	385.60	0.00	0.00	0.00	0.00	18.51	0.00	228.50	3498.15	4296.01	4461.27	4130.76	
Pilkington Energikare Legacy (by sea)	550.85	716.11	385.60	0.00	0.00	0.00	0.00	18.51	0.00	228.50	62.45	860.31	1025.56	695.05	
Slimite Standard (4-4XeKr-4 crown)	642.66	835.46	449.86	204.02	244.82	163.22	1745.40	0.00	0.00	228.50	0.00	2820.59	3054.19	2586.99	
Slimite Standard (4-4XeKr-3 crown)	642.66	835.46	449.86	204.02	244.82	163.22	1745.40	0.00	0.00	228.50	0.00	2820.59	3054.19	2586.99	
Slimite Low E (4E-5XeKr-4)	642.66	835.46	449.86	204.02	244.82	163.22	2181.76	18.51	0.00	228.50	0.00	3275.45	3509.05	3041.84	
Slimite Low E (4E-5XeKr-3)	642.66	835.46	449.86	204.02	244.82	163.22	2181.76	18.51	0.00	228.50	0.00	3275.45	3509.05	3041.84	
Slimite Low E (4E-6XeKr-4 crown)	642.66	835.46	449.86	204.02	244.82	163.22	2618.11	18.51	0.00	228.50	0.00	3711.80	3945.40	3478.20	
Slimite Low E (4E-6XeKr-3 crown)	642.66	835.46	449.86	204.02	244.82	163.22	2618.11	18.51	0.00	228.50	0.00	3711.80	3945.40	3478.20	
Slenderglaze (4E-3.9XeKr-4)	734.47	954.81	514.13	204.02	244.82	163.22	1255.59	18.51	0.00	228.50	44.83	2485.93	2747.07	2224.78	
Slenderglaze (4E-4.8XeKr-4)	734.47	954.81	514.13	204.02	244.82	163.22	1545.35	18.51	0.00	228.50	44.83	2775.68	3036.82	2514.53	
Slenderglaze (4E-6.4Kr-4)	734.47	954.81	514.13	204.02	244.82	163.22	596.09	18.51	0.00	228.50	44.83	1826.42	2087.57	1565.28	
Bonnington Joinery (new sashes inc).	642.66	835.46	449.86	204.02	244.82	163.22	0.01	18.51	501.48	228.50	0.00	1595.18	1828.78	1361.58	

**FIGURE 3**



## Data Info

Density of float glass	2530 kg/m <sup>3</sup>	Source	<a href="http://en.wikipedia.org/wiki/Soda-lime_glass">http://en.wikipedia.org/wiki/Soda-lime_glass</a>	
EE Float Glass	15 MJ/kg		38% recycling rate (British Glass)	
	source		ICE database version 1.6, Bath, accessed 19/3/10	sensitivity +/- 30%
			includes typical UK rate of 38% recycled glass	
low-E coating	7.65 MJ/m <sup>2</sup>	Source	Weir, 1998	
<b>Gas EE</b>				
Xe	511.4 MJ/litre	Source	Fernie & Muneer, 1996	
Kr	38.5 MJ/litre	Source	Fernie & Muneer, 1996	
Ar	0.672 kJ/litre	Source	Fernie & Muneer, 1996	
Aluminium				
typical UK extruded Al	154 MJ/kg	source	ICE database version 1.6, Bath, accessed 19/3/10	sensitivity +/- 20%
			includes typical UK rate of 33% recycled Al	

## FRAME INFO

A standard window (1.2m × 1.2m) has been evaluated for its embodied energy with aluminium, PVC, Al-clad timber and timber manufacture. It has been found that the aluminium windows consume the highest amount of energy equal to 6GJ. PVC, Alclad timber and timber windows have their respective embodied energy equal to 2980 MJ, 1460MJ and 995MJ as shown in Fig.7.

Fig. 7 Embodied energy of frames\*\*

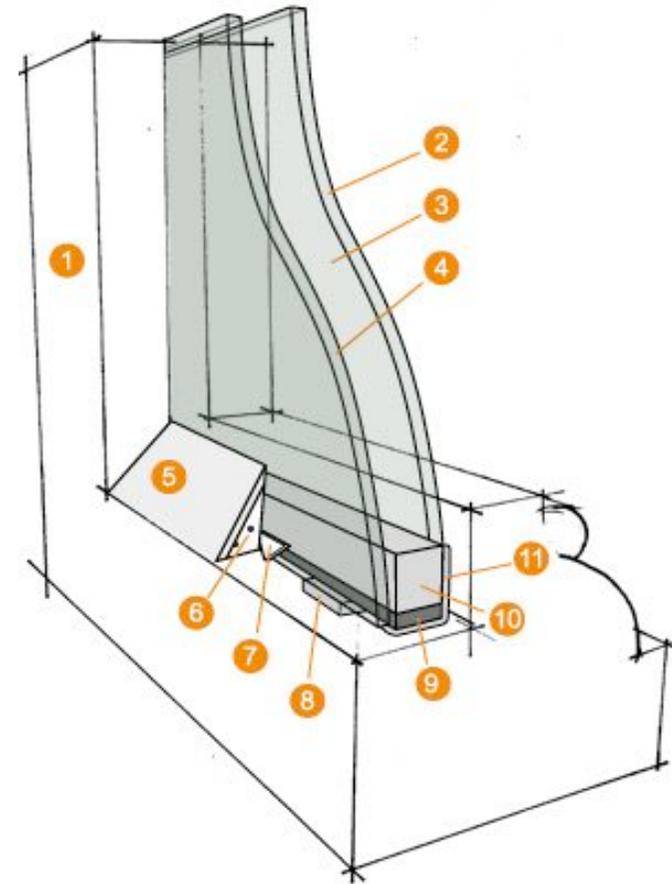
source LIFE CYCLE OF WINDOW MATERIALS - A COMPARATIVE ASSESSMENT  
M. Asif BSc MSc, A. Davidson BSc and T.Muneer PhD DSc CEng MImechE  
FICBSE Millennium Fellow  
School of Engineering , Napier University, 10 Colinton Road, Edinburgh EH10 5DT,  
U.K.  
found at <http://www.cibse.org/pdfs/Masif.pdf> on 19/3/10

EE per linear length of frame material =	620.8333 MJ/m length	uPVC
EE per linear length of frame material =	207.2917 MJ/m length	timber

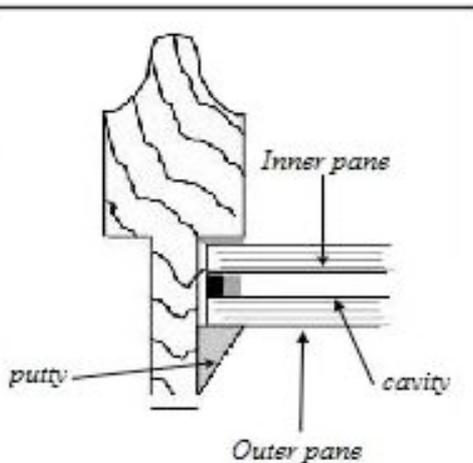


# HISTOGLASS

1. Window frame
2. 3mm Low-E float glass inner pane
3. Gas filled cavity
4. Outer Pane
5. Paint overlapping onto the glass by 1-2mm
6. Modified putty
7. Sprig
8. Hardwood spacer
9. Perimeter Seal
10. Aluminium profile
11. Sealant



# SLENDERGLAZE



## **Glazing options**

### Inner pane

4mm Low Emissivity glass that reflects heat back into the room (can be supplied toughened)

### Outer pane

4mm float glass  
(can be supplied toughened)  
6.4 laminated  
6.8 sound reducing laminated glass

### Antique glass

One of the most aesthetically pleasing aspects of old windows is the reflection given off by imperfect crown or cylinder glass. To replicate this we offer the option of reproduction cylinder glass in the outer pane. Patterned or Acid etched glass can also be specified.

### Putty

Slenderglaze is glazed with a special Polymer rich glazing putty that will keep out water, remain flexible and can be over-painted. This ensures the sealed unit will not breakdown due to water ingress or brittleness - problems associated with normal putty.

### Cavity

Slenderglaze can be supplied with the following centre pane U values:

3.9mm U value 1.9  
4.8mm U value 1.8  
6.4mm U value 1.6  
7.9mm U value 1.5  
9.5mm U value 1.4  
1.1mm U value 1.3

All units are gas filled

## Report 3

# Calculation of whole-window U-values from in-situ measurement

A research report by  
Dr. Paul Baker, Glasgow Caledonian University

August 2010

## Historic Scotland Technical Paper 9

The key findings are presented on page 8 of this report.

## Calculation of whole-window U-values from in-situ measurements



Prepared for Historic Scotland by Dr. Paul Baker

Centre for Research on Indoor Climate & Health  
School of the Built & Natural Environment  
Glasgow Caledonian University

[Paul.Baker@gcu.ac.uk](mailto:Paul.Baker@gcu.ac.uk)

July 2010

This report is to be read in conjunction with the GCU research report '*In-situ* measurements of the U-values of double glazed replacement units in Georgian sash and casement windows' prepared by Dr. Paul Baker in March 2010 for Changeworks as part of the *Double Glazing in Listed Buildings* research project [1].

The GCU report has also been published in Historic Scotland Technical Paper 9 [2].

## Introduction

The *in-situ* centre-of-pane U-values of various 'slimline' double-glazed replacement units, fitted into Georgian sash and casement windows, were measured in 2009/2010 by the Centre for Research on Indoor Climate & Health, School of the Built & Natural Environment, Glasgow Caledonian University (GCU). These measurements were part of the *Double Glazing In Listed Buildings* research project by Changeworks published in July 2010 [1]. This paper has also been published as part of Historic Scotland Technical Paper 9 [2].

In addition to these centre-of-pane U-value measurements, whole-window U-values were estimated using a basic area-weighted calculation method. (For details, please refer to page 8 of the Changeworks report.) These calculations were based on assumptions from a previous research project in 2008, *Performance of Traditional Windows* [3], in which a similar window design had been measured.

This led to three concerns: Firstly, to estimate the whole-window U-values for the windows measured in 2009/2010 more precisely, accurate dimensions of the actually measured windows should be used rather than an assumption from a previous research project.

Secondly, the windows tested were Georgian style windows (with '6 over 6' glass panes, see Figure 3). It was felt that it would be beneficial to also calculate windows of the same size but of two Victorian window designs ('2 over 2' and '1 over 1').

And thirdly, the application of an area-weighted calculation method could be improved by using the software programme FRAME 3.1 which is a 2-D finite element model and has specifically been designed for window calculations [4].

In addition to this, it was thought beneficial to also provide a comparison between slim-profile double glazing and secondary glazing, and indeed both options combined.

The above listed amendments to the calculation method resulted in improved whole-window U-values which are reported in this paper, together with a comparison of the impact of the three window style designs, and a comparison with the use of secondary glazing.

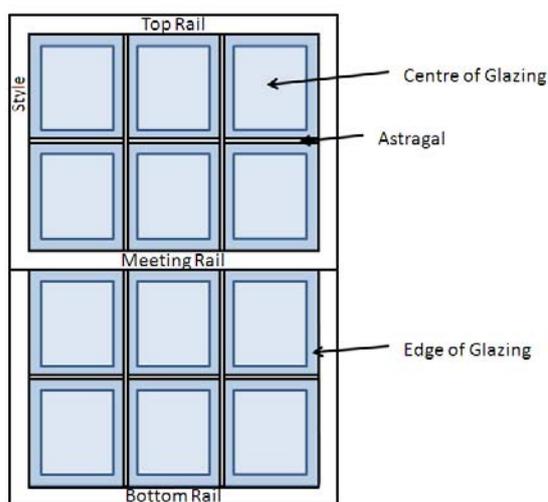
## Methodology of calculation

The overall dimensions of the window were supplied by Historic Scotland. The dimensions of the window were assumed to be 1120mm x 2300mm. The width of the window rails and styles was assumed to be 50mm, and the width of the astragals to be 20mm.

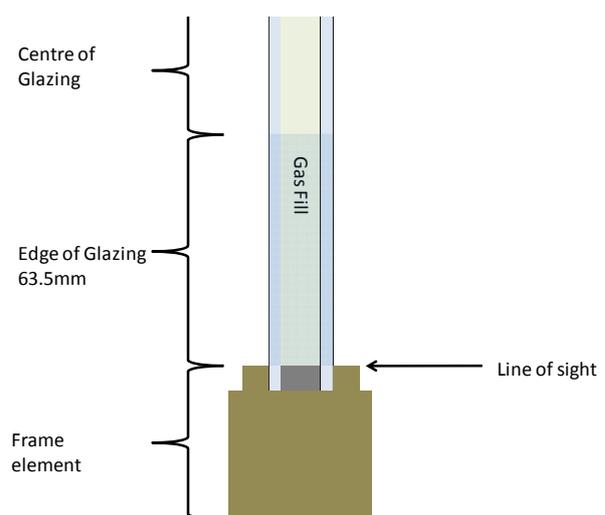
The window was divided into a number of sections as shown in Figure 1, and the corresponding cross-section was modelled. The properties of the glazing system (gas fill, surface emissivities, etc.) can be specified in the FRAME programme, and the database of the software contains a range of typical glazing and frame materials.

The FRAME programme estimates the U-value of the following (Figure 2):

- the frame (below the line of sight of the glazing),
- the edge-of-glazing region which extends 63.5mm up from the frame,
- the centre of pane.



**Figure 1: Schematic diagram of window divisions for FRAME calculations**

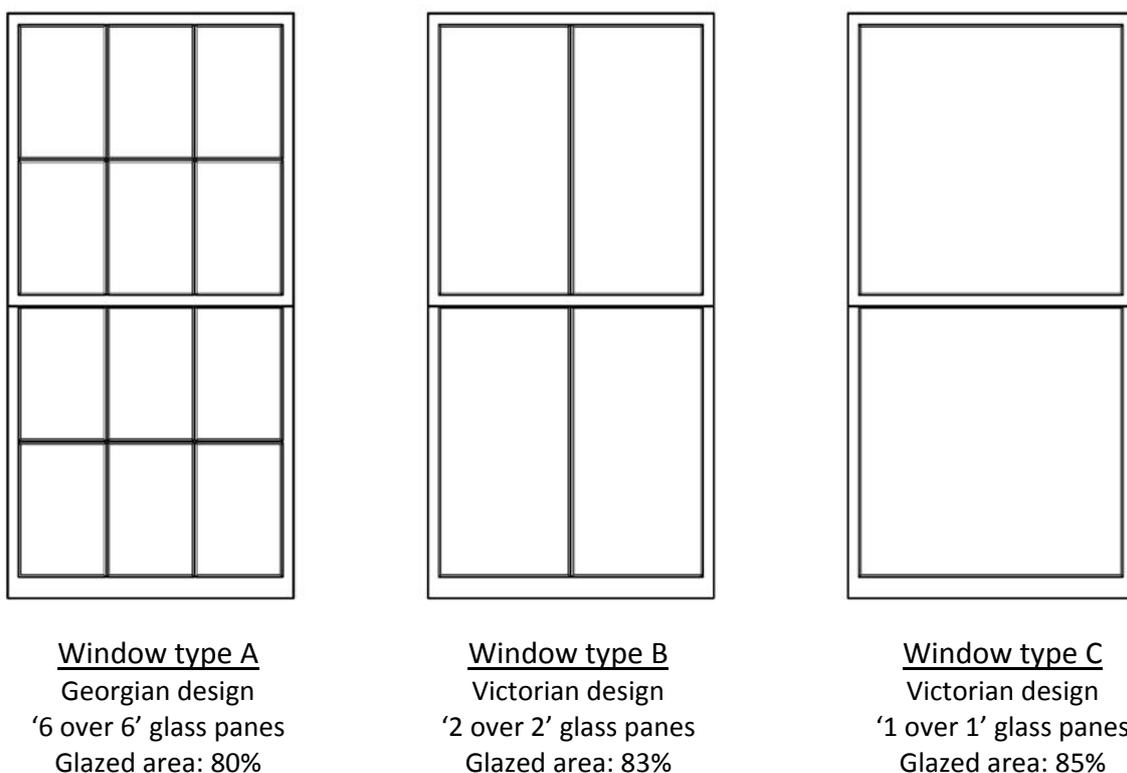


**Figure 2: Schematic cross-section and calculation zones used by FRAME: centre of glazing, edge of glazing & frame**

The resulting U-values for the frame and the edge-of-glazing were area-weighted with the actual as-measured centre-of-pane U-values to estimate a whole-window U-value. These calculations were carried out for windows with various 'slimline' double glazed units.

## Window types

The U-values were estimated for three different window style types (one Georgian style and two Victorian styles) as illustrated in Figure 3.



**Figure 3: Window types**

Please note that the whole-window U-values reported in the Changeworks report [1] were based on a glazed area of only 55%. This was the glazed area of the test window used in the 2008 research report [2]. Whereas for the calculation presented in this paper a glazed area of 80% to 85% (depending on the window type) was used in accordance with the dimensions provided by Historic Scotland.

Whilst the '2008 test window' and the Type A window are both Georgian '6 over 6' designs, the latter has more slender timber profiles.

The results are given in Table 1 with the manufacturers' glazing specifications and the measured centre-of-pane U-values. For detailed information on the tested glazing systems, please refer to the Changeworks report [1] or Historic Scotland Technical Paper 9 [2]. Results are also given for the addition of a secondary glazing system, such as that tested for the 2008 research report [2], to both a single glazed window and one with replacement double glazed panes.

**Table 1: Centre-of-pane and whole-window U-values**

ID	Glazing type	Cavity filling	Glazing configuration see notes below	U-value centre-of-pane, W/m <sup>2</sup> K		U-value whole-window, W/m <sup>2</sup> K calculated from measured U-value centre-of-pane		
				as per spec	as measured	Window type A '6 over 6'	Window type B '2 over 2'	Window type C '1 over 1'
0	Single glazing	n/a	4	n/a	5.4	5.2	5.1	5.1
1	Sashworks	argon	4-8-4	1.8	2.0	2.6	2.4	2.2
2	Histoglass D11	krypton	3-4-4	1.9	2.7	2.9	2.7	2.7
3	Histoglass D10	krypton	3-4-4	1.9	2.3	2.7	2.5	2.4
4	Pilkington energiKare Legacy	vacuum	4-0.2-4	1.3	1.0	1.9	1.6	1.4
5	Slimlite	air	3-3-3	2.6	2.8	3.4	3.1	3.0
6	Slimlite	xenon & krypton	3-3-3	2.1	2.3	2.8	2.6	2.4
7	Slenderglaze	xenon & krypton	4-3.9-4	2.1	1.7	2.5	2.2	2.0
8	Slimlite	xenon & krypton	3-3-3	2.1	2.3	2.8	2.6	2.5
9	Supalite	argon	4-4.8-3	2.5	2.8	3.0	2.9	2.8
10	Slimlite	xenon & krypton	3-3-3	2.1	2.0	2.7	2.4	2.2
11	Single glazing with secondary glazing	n/a	n/a	n/a	1.7	2.0	2.0	2.1
12	Slimlite (ID 6) with secondary glazing	n/a	n/a	n/a	1.4	1.6	1.5	1.5

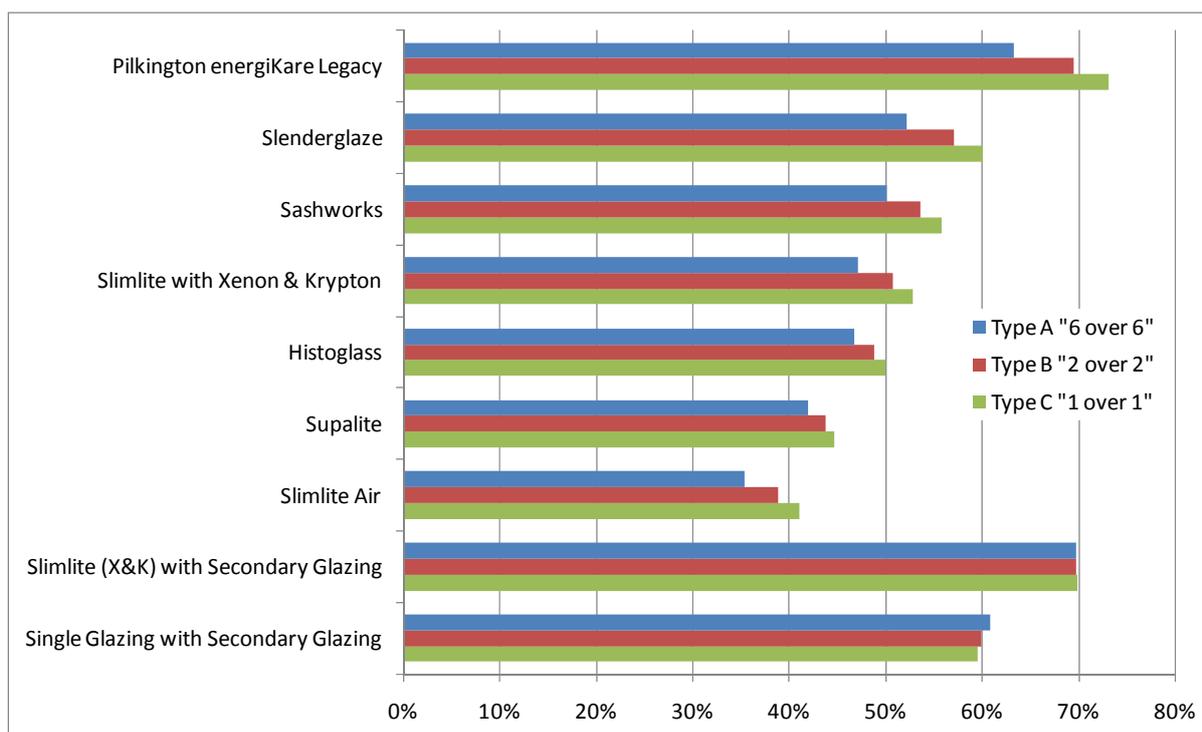
**Notes**

- U-values are expressed in W/m<sup>2</sup>K.
- All glazing has a low emission inner glazing pane.
- Glazing configuration in mm: inner pane - cavity - outer pane.
- For the measured centre-of-pane U-value of single glazing, please refer to Historic Scotland Technical Paper 1 [2].
- ID 3 has hand-drawn glass as outer pane.
- ID 6 has crown-effect glass as outer pane.
- ID 11 the centre of pane U-value was measured for the 2008 research report [2]
- ID 12 the centre of pane U-value was calculated using the FRAME program [4]

## Discussion

The results for the Georgian style window, Type A, show higher whole-window U-values than the results for the Victorian style windows, Types B and C. This is due to larger areas for the frame and the edge of glazing produced by the greater proportion of astragals and smaller glazed units in the '6 over 6' configuration. All this results in increased thermal bridging. That means that Victorian style windows perform better thermally when fitted with 'slimline' double glazed units than Georgian style windows (due to the increased use of astragals in the window design). This is shown in Figure 4 which compares the reduction in heat loss through the windows, with all the double glazing options having the greatest effect for the '1 over 1' window.

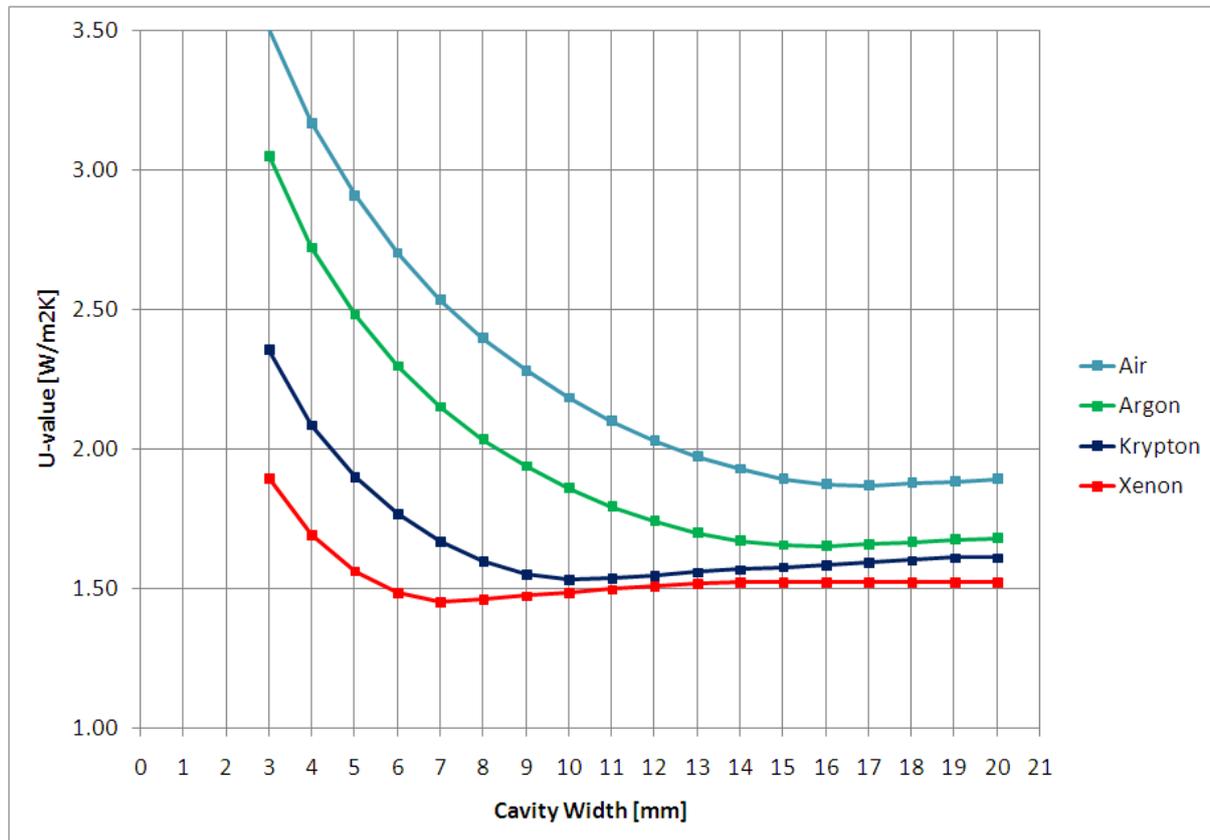
Considering the Type A window, the vacuum glazing is the most effective option giving a whole-window U-value of 1.9 W/m<sup>2</sup>K, and a 63% reduction in heat loss through the window compared to single glazing (Figure 4). The various gas filled units achieve reductions in heat loss between 42% to 52%. The only measured air filled unit ('Slimlite Air') results in a reduction of 35%. Slenderglaze is the most effective of the gas filled units with a reduction of 52%.



**Figure 4: Estimated reduction in heat loss through the whole window compared with single glazed window for the three window types**

For similar cavity widths (3 to 5mm), units filled with krypton, or a xenon-krypton mix, are better than the argon filled Supalite unit. The argon filled unit by Sashworks achieves a 50% reduction in heat loss with the widest cavity (8mm) of the units tested. Replacing the argon fill in this unit with krypton, or a xenon-krypton mix, would give much improved results as the 8mm cavity width is about the optimum value.

This is further illustrated in Figure 5 showing U-values of double glazing (with a build-up of 4mm-Xmm-4mm with the inner pane having a low-emissivity coating) for varying cavity fills and widths calculated in accordance with ISO 15099:2003 [5]. This shows an optimum cavity width for krypton at about 10mm, and for xenon at about 7mm. The procedure to calculate the properties of gas mixture is more complicated but the optimum cavity width for a krypton-xenon mix might be estimated to be about 8mm.



**Figure 5: U-values calculations in accordance with ISO 15099:2003 [5] for double glazing (with a built-up of 4mm-Xmm-4mm with the outer pane having a low-emissive coating)**

The vacuum glazing is the most effective option offering good thermal performance with a slim profile. The other double glazed options, whilst giving a significant improvement, are not optimised for thermal performance. This is sacrificed in order to produce slimmer units suitable for conservation-grade properties.

The window type has less effect on the performance of adding secondary glazing, since it covers most of the window with the result that the calculated values for each of the zones used by the FRAME program are similar. The results show that single glazing with secondary glazing is almost as effective as vacuum glazing and generally out performs the other double glazing options, except for the Slenderglass system in the Type C window. Using secondary glazing in conjunction with double glazing is comparable with the vacuum glazing.

The results indicate that secondary glazing is an effective option where the use of replacement double glazed panes is to be avoided.

## Conclusions and recommendations

The key findings from this study are as follows:

- Windows, retrofitted with slim-profile double glazing, achieved a reduction in heat loss of 35 to 63 % compared to being single-glazed. Secondary glazing fitted to a single-glazed window can achieve a reduction in heat loss of 61%.
- The whole-window U-values, calculated for the windows measured for report 1, ranged from 1.9 to 3.4 W/m<sup>2</sup>K compared to 5.2 W/m<sup>2</sup>K for single glazing.
- The whole-window U-value of 2.0 W/m<sup>2</sup>K was calculated for a single-glazed window fitted with secondary glazing. Retrofitting the same window with the best-performing gas-filled double glazing would achieve a whole-window U-value of 1.6 W/m<sup>2</sup>K.
- Slim-profile double glazing achieved a better thermal performance when fitted into Victorian style windows (with '1 over 1' or '2 over 2' glass panes) compared to being fitted into Georgian style windows (with '6 over 6' glass panes). This is due to the use of more astragals in Georgian style windows resulting in increased thermal bridging.
- The glazing with a vacuum cavity achieved the best thermal performance (1.9 W/m<sup>2</sup>K) compared to the other systems. Glazing with air-filled cavities showed the worst performance (3.4 W/m<sup>2</sup>K). Glazing with cavities filled with different gases achieved varied performances (2.5 to 3.0 W/m<sup>2</sup>K) depending on the cavity thickness and the type, or mix, of gas used.
- Single-glazed Georgian style windows with '6 over 6' glass panes fitted with secondary glazing achieved better U-values (whole-window U-value of 2.0 W/m<sup>2</sup>K) than windows fitted with the best-performing gas-filled double glazing (2.5 W/m<sup>2</sup>K). For Victorian style '1 over 1' windows, the performance of both glazing types were nearly equal (2.1 and 2.0 W/m<sup>2</sup>K respectively). This indicates that secondary glazing is an effective option where the use of replacement double glazing is to be avoided. However, slim-profile double glazing with vacuum cavities still achieved the best thermal performance (1.9 and 1.4 W/m<sup>2</sup>K for Georgian and Victorian style windows respectively).
- It is recommended that manufacturers adopt a more systematic approach to the design of glazing units, when filled with gas, in order to optimise thermal performance. Standard calculation procedures [6] and software are available to this end.

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**Published by  
Historic Scotland  
Conservation Group**

**September 2010**

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