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Technical note

Multiglazed windows: potential for savings in energy, emissions and cost

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This paper details case studies undertaken in four office buildings in Edinburgh, Scotland. Analyses were undertaken of the energy requirements to maintain room temperature in each building. Alternative high performance window specifications were analysed and compared to results for existing specifications. Comparisons were made between the additional embodied energy and associated emissions, and financial cost required to install higher performance windows at the initial build stage, and the potential savings in life-cycle energy and running costs. Results showed substantial savings can be made over the lifespan of windows by optimizing specification. Payback periods for energy and financial cost for some window systems were within acceptable limits, when specified in the initial build. The financial payback periods for replacement windows were higher, emphasizing the need for sustainable and energy efficient choices at the initial design stage.

Practical application: This paper contains recent case study findings and practical issues relating to the embodied energy of materials and components used in multiglazed windows; and life cycle costing issues which prevail in all current building sectors. Many construction professionals are calling for more detailed and widely available information relating to the sustainability of building components. Pressure is rising for manufacturers and suppliers to meet this demand effectively.

1 Introduction

Worldwide, windows are responsible for a disproportionate amount of unwanted heat gain and heat loss between buildings and the environment.[1] In the USA, over 3% of total energy consumption is lost through windows, in Sweden this figure is 7%[2] and in Britain 6% for residential buildings alone.[3] There are many factors to consider in the selection of multiglazed (double- and triple-glazed) windows. These include thermal, aural and visual performance, choice of materials, design, durability and cost; inevitably trade-offs have to be made.

Previous studies have questioned professionals within the building industry to examine issues of design and selection of multiglazed windows.[4] The selection of windows is dominated by technical, visual and financial considerations, with capital cost being an overriding issue. Sustainable

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development is frequently overlooked—few specifiers consider long-term costs, embodied energy or the policies of manufacturers. While there is a willingness in the architectural community to take on board environmental and sustainability issues, little is actually being seen in on-the-ground changes. Lack of information is cited as an impediment to architects who wish to use more sustainable components, while suppliers appear reluctant to deliver information without believing a demand exists.

This study investigates energy, emissions and cost savings achievable through improved window performance as part of a wider study into professional preferences for the design and selection of sustainable multiglazed windows. By producing easily understandable figures of potential savings, it is hoped that this research will help to address the problem of lack of information evident in the multiglazed window industry and therefore assist specifiers in making selections based on sustainability measures as well as financial and technical considerations.

2 Multiglazed window alternatives

Building life-cycle energy studies imply that energy efficiency may be more effective than increased insulation.[5] Well oriented, high performance windows can be a major part of this energy efficiency. Windows can provide architects with a significant opportunity to conserve energy, as well as being a major part of the character of a building.[6] The design components that can strongly influence energy conservation and window sustainability are numerous.

Low-emissivity coatings allow a high proportion of the visible light in the solar spectrum to be transmitted, but block much of the other wavelengths responsible for solar heat gains.[7,8] Optimization of the glazing gap thickness can significantly improve energy efficiency,[9] while larger widths provide extra resistance up to a certain limit.[10,11] Suppression of convection in the window cavity using argon, krypton and sulphur hexafluoride is beneficial,[12] whilst in certain latitudes triple-glazed, argon filled, low-e coated units are considered to be one of the most cost-effective solutions.[13,14] Choice of frame materials can have a profound effect on the overall window U-value,[10,15] and the life-cycle assessment.[16]

In terms of window lifespan, researchers believe insulating glass units should last *in situ* for between 20 and 60 years. Asif[17] undertook a survey of companies and developers to look at the estimated lifespan of various window frame materials. Table 1 compares the average results from the survey to various estimates found in the literature.[18–22] Recent research indicates that although uPVC windows may last between 25 and 40 years, the current trend is to replace windows after approximately 10 years of use, leading to a scenario where windows become a ‘disposable’ building component.[23]

Single-glazed timber framed windows have the lowest embodied energy of any window unit. The payback period for more thermally

Table 1 Lifespan and embodied energy of window units, various frame types

Frame material	Embodied energy (MJ)[a]	Survey results (years)[a]	Literature review range (years)
Aluminium	5978	43.6	35 to 60
uPVC	2657	24.1	25 to 30
Timber	738	39.6	35 to over 60
Aluminium-clad timber	899	46.7	45

[a] Embodied energy and survey results from Asif.[17]
Embodied energy figures are for window units measuring 1.2 m by 1.2 m, with argon gas infill.

efficient windows, such as double-glazed units, may be as short as one year; however, high-tech glazing systems, such as triple-glazing with inert gas in the cavities, may not recover their embodied energy even after 100 years.[24,25] The embodied energy of different frame types varies considerably (Table 1), with timber the lowest, followed by aluminium-clad timber, uPVC, steel and aluminium.[17,26]

Plastic materials used in window frames have several important life-cycle issues. Although they have good thermal efficiency, production of plastics has significant environmental impacts. Plastics are not easily recyclable, with both incineration and landfill options leading to further environmental impacts.[24] While aluminium has a high embodied energy, it should be remembered that unlike uPVC it is easily recyclable and up to 95% of the embodied energy can be recouped.[27]

3 Building case studies: methods

In order to examine the influence of window design and selection on energy use within buildings, the performance of *in situ* windows was compared to a number of alternatives, each of which had a higher performance specification than the existing windows. Embodied energy levels for all types of glazing units were calculated using data from Weir.[25] Embodied energy calculations include the energy required to obtain raw materials, energy used in manufacturing and packaging processes, and transportation energy consumption incurred to get the window units to site. U-values were calculated using data from Muneer *et al*.[28]

The energy required in each room to maintain a temperature of 19°C during working hours, for one year was calculated, using research techniques developed by Weir.[25] Carbon dioxide emission levels and the financial cost of the energy were also calculated. Similar calculations were completed for alternative window specifications to enable comparison of the embodied energy and capital cost of higher specification windows with the energy and running cost savings over the lifespan of the window units. Xenon filled windows were not considered in the analysis due to the prohibitively high embodied energy of collecting xenon gas.[25]

Four office buildings were chosen, specifically in the south-west Edinburgh area, due to availability of detailed weather data. All four buildings offered a mix of open plan and single or double occupancy offices, and were mainly occupied by workers who spent the majority of their time working at their desks. Communal rooms, such as cafeterias and meeting rooms were not included in the analysis, and rooms with either no windows or internal windows were also discounted. All the buildings had double-glazed window units installed, with a variety of different specifications; in some cases a building had more than one window specification, due to window replacement schemes or extensions to the building. In addition, the buildings were chosen to represent four different window frame materials. Each building was surveyed, with measurements taken of room width, depth and height and window width and height. The specification of the windows was also ascertained.

Table 2 details the alternative higher performance specifications studied and the additional embodied energy each contains, compared to a standard specification window (double-glazed, air-filled, no low-e coating).

4 Building case studies: results and discussion

Table 3 details the window specification, total window area and room volumes for each building.

Of the four case study buildings, the windows in Buildings A and C were the most energy efficient, incorporating a low-

Table 2 Alternative window specifications

Window type (glazing, infill gas, coating)	Specification[a]	Glazing unit[b] U-value (W/m^{2}K)	Additional embodied energy per window unit (MJ)
Double, air, no coating	4 – 20Air – 4	2.76	standard specification
Double, air, low-e	4e – 20Air – 4	1.58	8.42
Double, argon, low-e	4e – 16Ar – 4	1.31	8.43
Double, krypton, low-e	4e – 12Kr – e4	0.94	525.04
Triple, argon, low-e	4e – 16Ar – 4 – 16Ar – e4	0.65	161.56
Triple, krypton, low-e	4e – 12Kr – 4 – 12Kr – e4	0.52	1167.14

[a] Glass specification details the width of glass pane (in mm), width of gap (mm) and infill gas, and width of second glass pane (mm). 4e represents a 4 mm glass pane with one low-emissivity coating.
[b] U-value is for complete glazing unit, including glass panes, inert gas and low-e coating.

emissivity coating to improve thermal efficiency. Both also used 6 mm glass, again improving the U-value compared to 4 mm glass used in Buildings B and D. In Building B, the newer extension to the building did have an improved specification compared to the older part of the building; in Building D, windows were being replaced on a rolling scheme and an improved specification was being used. Although the window U-values were improved for both buildings, the original specification frame material was used. Steel and uPVC window frames both incur a higher embodied energy than timber or aluminium-clad timber (Table 1).

Tables 4 to 7 detail energy, emissions and cost savings for alternative building design and glazing specifications. The savings and paybacks are compared to the glazing specification currently in the building, and relate to potential savings if an alternate specification had been installed during the initial build; the figures assume the frame material does not change.

Table 4 examines the effect on energy consumption of varying the percentage of a window façade used for glazing. Despite having higher specification windows than Building B, Building C uses more energy per cubic metre to maintain the working temperature (58.9 MJ/m^3 compared to 57.2 MJ/m^3). This is explained by the high percentage of glazing in Building C, 57% compared to 27% in Building B.

Comparison of the four buildings for various glazing proportions demonstrates the efficiency of each building; the effect of building envelope design on thermal efficiency can be clearly seen, with efficiency decreasing as window area increases. These figures also show the effect of building internal design on thermal efficiency; the windows in Building C are less insulating than in Building A, yet at 20%, 40% and 60% of the façade used for

Table 3 Window specifications in case study buildings

Building	Glazing Specification(s)	Glazing unit U-value (W/m^{2}K)	Frame Type	Total window area (m^2)	Total room volume (m^3)	Average room volume (m^3)
Building A	6e – 16Air – 6	1.54	Aluminium-clad timber	37	798	99.7
Building B	4 – 16Air – 4 4 – 10Air – 4	2.76 2.94	Steel	108	2922	97.4
Building C	6e – 12Air – 6	1.77	Aluminium	178	2224	76.7
Building D	4 – 16Air – 4 4 – 12Air – 4	2.78 2.85	uPVC	227	3804	152.2

Table 4 Influence on energy use of varying the area of glass as a percentage of the area of the window façades.

Building	Existing glazed area as percentage of window façade	Annual energy use (MJ/m^3)	Annual energy use alternative glazed areas as a percentage of window façade (MJ/m^3)			
			20%	40%	60%	80%
Building A	26	55	54.2	57.6	61.0	63.2
Building B	27	57.2	55.2	61.4	67.6	73.8
Building C	57	58.9	53.0	56.4	59.9	63.3
Building D	37	62.7	56.9	63.9	70.9	77.9

All energy use calculations based on existing glazing specifications for each building.

glazing, it is more efficient. Buildings B and D are very similar in terms of window U-value, yet have quite different energy use figures over the four percentages. This result may be explained by examining the layout and thermal mass of rooms within the buildings: larger rooms require more energy to maintain their temperature than smaller rooms.

Potential energy savings from the use of alternate glazing specifications are detailed in Table 5. Higher specification glazing could have saved between 1.7% and 20.3% of the energy used to heat the buildings. By offsetting the potential energy saved through improved glazing in the buildings, against the additional embodied energy required to manufacture and supply the units, allowed for an energy payback period to be evaluated. Krypton filled windows all had a considerably longer payback period than air or argon-filled windows, with payback periods of up to nine years. Payback periods for argon-filled windows ranged from 15 days (double-glazed, Building B) to 1.5 years (triple-glazed, Building A). Low-emissivity coatings would have repaid themselves in embodied energy terms in around 20 days in Buildings B and D.

Examination of the reduction in carbon dioxide emissions (Table 6) clearly shows the importance of high thermal efficiency in multiglazed windows. The use of low-emissivity coatings would have reduced CO_2 emissions from electricity production by around 10% in Buildings B and D; the financial cost of this coating would have been paid back in under five years, and in terms of energy in only one month.

The financial cost of improved window specification at the initial build stage are significant in some cases (Table 7). However, the payback periods for low-emissivity coating and argon gas in either double- or triple-glazing are not high compared to the life-span of the windows and of the buildings. The cost of double-glazed krypton filled windows is probably beyond an acceptable level, particularly as triple-glazed argon filled units are both lower in cost and higher in thermal efficiency. Triple-glazed krypton filled windows were not considered in this part of the analysis due to a lack of cost information. The 'adjusted for interest' figure represents the financial payback period if the additional initial cost had been invested rather than spent, assuming an interest rate of 3% per annum.

The previous results have compared *in situ* windows with alternatives of the same frame material. Table 8 details energy and emissions savings resulting from the use of aluminium-clad timber as an alternative frame material in Buildings C and D. Building A is not included in the analysis as it already has low embodied energy aluminium-clad timber windows; Building B is discounted due to a lack of information regarding steel-framed windows. Triple-glazed krypton filled windows have not been included in this study due to the relatively high payback periods found in the previous results.

Table 5 Energy savings for alternate window specifications, compared to current specification in buildings

Building	Energy savings	Alternative glazing specification				
		Double-glazed, air, low-e	Double-glazed, argon, low-e	Double-glazed, krypton, low-e	Triple-glazed, argon, low-e	Triple-glazed, krypton, low-e
Building A	Annual energy use	–	54.1 MJ/m^3	52.5 MJ/m^3	51.4 MJ/m^3	50.8 MJ/m^3
	Annual energy saving	–	0.8 GJ (1.7%)	1.5 GJ (3.5%)	2.9 GJ (6.7%)	3.3 GJ (7.6%)
	Additional embodied energy	–	0.2 GJ	13.3 GJ	4 GJ	29.6 GJ
	Payback period	–	0.3 years	8.7 years	1.4 years	8.8 years
Building B	Annual energy use	52.7 MJ/m^3	51.8 MJ/m^3	50.5 MJ/m^3	49.7 MJ/m^3	49.0 MJ/m^3
	Annual energy saving	13 GJ (8.0%)	16 GJ (9.5%)	20 GJ (11.7%)	23 GJ (13.5%)	24 GJ (14.3%)
	Additional embodied energy	0.6 GJ	0.6 GJ	39 GJ	12 GJ	87 GJ
	Payback period	0.05 years	0.04 years	2 years	0.5 years	3.6 years
Building C	Annual energy use	–	55.2 MJ/m^3	52.4 MJ/m^3	50.6 MJ/m^3	49.7 MJ/m^3
	Annual energy saving	–	8.2 GJ (6.2%)	14 GJ (11.0%)	18 GJ (14.0%)	20 GJ (15.6%)
	Additional embodied energy	–	1 GJ	65 GJ	20 GJ	144 GJ
	Payback period	–	0.1 years	4.5 years	1.1 years	7 years
Building D	Annual energy use	56.8 MJ/m^3	55.1 MJ/m^3	53.0 MJ/m^3	50.7 MJ/m^3	50.0 MJ/m^3
	Annual energy saving	22 GJ (9.4%)	29 GJ (12.0%)	37 GJ (15.4%)	46 GJ (19.1%)	48 GJ (20.3%)
	Additional embodied energy	1.3 GJ	1.3 GJ	83 GJ	25 GJ	184 GJ
	Payback period	0.06 years	0.05 years	2.3 years	0.6 years	3.8 years

Table 6 Savings in electricity-related CO_2 emissions due to alternative window specifications

Building	CO_2 Emissions saving (pa)[a]	Alternative glazing specification				
		Double-glazed, air, low-e	Double-glazed, argon, low-e	Double-glazed, krypton, low-e	Triple-glazed, argon, low-e	Triple-glazed, krypton, low-e
Building A	Mass	–	97 kg	195 kg	374 kg	428 kg
	Per unit vol.	–	0.12 kg/m^3	0.24 kg/m^3	0.47 kg/m^3	0.54 kg/m^3
Building B	Mass	1704 kg	2035 kg	2505 kg	2876 kg	3054 kg
	Per unit vol.	0.58 kg/m^3	0.70 kg/m^3	0.86 kg/m^3	0.98 kg/m^3	1.05 kg/m^3
Building C	Mass	–	1044 kg	1840 kg	2345 kg	2618 kg
	Per unit vol.	–	0.47 kg/m^3	0.83 kg/m^3	1.05 kg/m^3	1.18 kg/m^3
Building D	Mass	2866 kg	3671 kg	4698 kg	5826 kg	6173 kg
	Per unit vol.	0.75 kg/m^3	0.97 kg/m^3	1.24 kg/m^3	1.53 kg/m^3	1.62 kg/m^3

[a] Based on factor of 0.46 $kgCO_2/kWh$ for electricity.[29]

Table 7 Financial costs of alternate window specifications compared to existing windows

Building	Financial costs including adjustments for interest (£ sterling)[a]	Alternate glazing specification			
		Double-glazed, air, low-e	Double-glazed, argon, low-e	Double-glazed, krypton, low-e	Triple-glazed, argon, low-e
Building A	Annual cost savings	–	£16	£32	£61
	Additional initial cost	–	£157	£1140	£505
	Payback period (adj. for interest)	–	9.8 (16) years	35.6 (never) years	8.3 (12) years
Building B	Annual cost savings	£278	£332	£408	£469
	Additional initial cost	£1184	£1647	£4345	£2671
	Payback period (adj. for interest)	4.3 (5) years	5.0 (6) years	10.6 (19) years	5.7 (8) years
Building C	Annual cost savings	–	£170	£300	£382
	Additional initial cost	–	£764	£5213	£2454
	Payback period (adj. for interest)	–	4.5 (6) years	17.4 (never) years	6.4 (9) years
Building D	Annual cost savings	£467	£599	£766	£950
	Additional initial cost	£2497	£3475	£9155	£5634
	Payback period (adj. for interest)	5.3 (7) years	5.8 (8) years	12.0 (26) years	5.9 (8) years

[a] Based on approximate cost of electricity of 7.5p/kWh. Cost of low-e coating assumed to be £11/m^2 glass.[17]

There were no plans for a large-scale replacement of windows with higher specification units for any of the buildings in the study. However, if this had been considered, Table 9 demonstrates the energy and financial implications of replacement with aluminium-clad timber windows of double glazed construction with either air or argon gas. Upgrading the windows in Buildings A and C is clearly not financially viable, with payback periods far longer than any likely building lifespan. While the energy payback period for Buildings B and D is well within acceptable limits, the financial cost payback period is still too long; the lifespan of the window units is estimated to be around 45 years. It would not be possible to regain all costs before the end of the window usable life. This demonstrates the value of selecting the right frame and glazing options at the building design stage. Rectification of errors at a later stage may be environmentally beneficial, but could be financially costly.

5 Conclusions

Qualitative studies by Menzies and Wherrett[4] discovered that while many architects and surveyors do consider sustainability and environmental issues when selecting windows, the overriding factor is certainly cost. Performance and reliability issues come to the fore, although consideration of maintenance and materials does bring some level of sustainable development into the arena. The analysis of energy use in the case study buildings provides

Table 8 Energy and emissions savings for use of aluminium-clad timber frames with current glazing specification

Building	Current frame type	Glazing specification	Total reduction in embodied energy (GJ)	Total reduction in CO_2 emissions (kg)
Building C	Aluminium	Double-glazed, air filled, low-e coating	628	80223
Building D	uPVC	Double-glazed, air filled	277	35351

Table 9 Energy and financial implications of replacing existing windows

Building	Savings and payback period	Glazing specification (aluminium-clad timber frames)			
		Double, Air, low-e		Double, Ar, low-e	
		Energy	Financial[a]	Energy	Financial[a]
Building A	Savings (pa)	–	–	0.8 GJ	£16
	Initial cost	–	–	23 GJ	£5.6 K
	Payback period	–	–	30.3 years	356 years
Building B	Savings (pa)	13 GJ	£278	16 GJ	£332
	Initial cost	67 GJ	£16.2 K	67 GJ	£16.6 K
	Payback period	5.1 years	58.2 years	4.2 years	50 years
Building C	Savings (pa)	–	–	8 GJ	£170
	Initial cost	–	–	111 GJ	£27.4 K
	Payback period		–	13.6 years	160 years
Building D	Savings (pa)	22 GJ	£467	29 GJ	£559
	Initial cost	142 GJ	£34 K	142 GJ	£35 K
	Payback period	6.3 years	72.8 years	4.9 years	58.4 years

[a] Not including labour costs.

vital missing information in the drive towards more sustainable development.

The results displayed give an indication of the savings obtainable, with the energy, and financial cost payback time scales. A similar analysis could be run on any building, at the drawing board stage, to optimize life-cycle energy consumption. However, many architects do not have the time nor desire to conduct these analyses, and therefore generic recommendations must be drawn from which they and their clients can take appropriate information.

5.1 Design

The higher the proportion of glazing in an external façade, the higher the energy used to maintain a suitable working temperature. If a design requires a large glazed area (greater than 40%), the specification of the windows should be raised as far as practicable (minimum: double-glazed with argon infill, and low-e coating, U-value 1.31 W/m^{2}K).

5.2 Materials

Timber and aluminium-clad timber frames have significantly lower embodied energy than uPVC or metal-based frames (738 MJ and 899 MJ compared to 2657 MJ or higher). The savings in embodied energy and associated emissions considerably outweigh potential savings from the use of improved glazing systems alone. In addition, timber based frames offer higher insulation properties than aluminium or uPVC.[10]

5.3 Life-cycle energy costs

In order to reduce life-cycle energy costs as far as possible, glazed units using argon gas appear to be the optimal solution for the Scottish climate (payback of less than six months for double-glazed units, and less than 18 months for triple-glazed units). This finding is reinforced by work by Clarke *et al*.[13] and Karlsson *et al*.[14]. While krypton filled units offer higher thermal efficiency, the energy payback period could be significantly longer (up to 8 years). The use of multi-glazed, argon filled windows will also reduce carbon dioxide emissions by up to 20% compared to double-glazed air filled windows.

5.4 Capital costs

Capital cost payback periods are longer than those for energy savings. However, within the lifetime of a building, the use of a higher specification window will normally be repaid by the savings in heating/cooling costs. Again, the optimum solution is double or triple-glazed argon filled windows. By including loss of interest earned on the additional capital costs in the analysis, it can be seen that in some cases krypton filled windows will not recoup the additional cost spent. Replacement costs are far higher, in terms of energy and financial costs. This emphasizes the importance of specification of appropriate high performance windows in the initial build.

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