Environmental Comparison of Window Materials

By: Peter Lyons & Associates, Building Energy Consultants, Australia and Tony Paterson, Technical Director, AFSA

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1. Introduction

This paper was commissioned by the South African Fenestration & Insulation Energy Rating Association (SAFIERA) and coincides with the introduction of the US National Fenestration Rating Council (NFRC)[1] system by South Africa. Our report explores the relative environmental advantages and disadvantages of aluminium, timber, uPVC and steel windows. All calculations are based on a 1200mm (h) x 1500mm (w) 2-light window with one vertical mullion.

When one considers environmental impact on buildings, three energy periods are involved during the life cycle. These are the energy of construction, the energy of use and the energy of demolition, the embodied energy, the operational energy and the residual energy respectively. (The typical energy usage in Europe over a 50 year life span is 132 Terra joules. Of this, 18 Terra joules (14%) relates to materials and construction, 80 (61%) to use, 21 (16%) to maintenance, and 12 to fitting out (9%).) For calculation consistency, a factor of three (about 75% 61/14 to allow for the more benign RSA conditions) has been used between embodied energy and thermal loss to measure environmental impact.

Embodied energy is defined as the total primary energy that has to be removed from a stock within the earth to produce a specific product or service. Operational energy is the quantity of energy (mainly heating, lighting and air conditioning) consumed during the life of the building and lost through the building envelope, a function of thermal loss through conductivity and leakage. Residual energy is the embodied energy that can be reclaimed at end of life. Greenhouse gases are contributed to by the production of energy, the extent of contribution depending on the energy source used. In South Africa about 0,361kg of CO_2-e is produced per MJ of energy produced mainly from coal.

Based on a common source of energy, comparisons between materials are relatively simple. However the embodied energy in electricity production differs widely depending on the conversion efficiency related to the source of energy; Hydro and nuclear power require 3600, coal 18784, natural gas 28360 and fuel oil 27180MJ/MWh respectively (source IAI). The conversion efficiency of each source to electricity can be assessed from the scientific definition 1J=1Ws. As an example, the conversion efficiency of coal to electricity is about 20%.

Throughout this report we have used as our unit of energy the megajoule [1 MJ = 10^6 joules (J)], gigajoule (1 GJ = 10^9 joules = 1000 MJ) and petajoule (1 PJ = 10^{15} J = 10^9 MJ). For electricity only we have used the kilowatt-hour (1 kWh = 3.6 MJ, ie, 1Ws=1J) as an alternative unit of energy. The basis for analysing embodied energy of windows is the *'hybrid input-output method'* (Crawford 2005).(1)

2. Window materials

All factory-manufactured windows used glass, or occasionally PMMA (acrylic sheet). In this report we assume that various glazing options are available equally among competing window frame technologies, and therefore the environmental impacts of the glazed part of windows are not considered further.

2.1 Greenhouse-gas impact of frame materials

The use of energy contributes to the development of the greenhouse gases that impact on global warming. The material analyses that follow are made up of three components. The first is the production of electricity, the second the manufacture of the material, the third the residual energy.

Aluminium

Aluminium is the most widely-used frame material in South Africa's windows. It is smelted locally. While it is highly conductive, this potential heat flow disadvantage can be all but eliminated by better frame design and/or additional measures such as thermal breaks.

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The South African primary aluminium smelters draw 14MWh (50MJ) of electricity per ton of primary aluminium. Thus when manufactured solely from primary aluminium (ie, derived from alumina), without any recycled content, and using coal as 95% of the source of electricity (remainder hydro and nuclear), it requires approximately 70MWh (250MJ) of embodied energy to manufacture 1 kg of aluminium. (This compares well with the Lawson mean of 250MJ/kg (2). The embodied energy varies from one smelter to another depending mainly on the energy source and to some extent on smelter efficiency. While the range 200 – 300 MJ/kg is suggested by Lawson, using differing energy sources for an equally efficient smelter show this range to be too small, the factor of 1,5 is reasonable as an assessment of the smelter efficiency range.

While this 'embodied energy' on a per-kilogram basis using primary aluminium is apparently high, a typical window both uses a proportion of recycled metal and retains energy at end of life; the majority of the embodied energy in the material itself is reclaimed on remelting – it is not lost; it remains embodied energy.

To remelt aluminium theoretically takes 5% of the energy required to initially separate the metal from its oxide. This can be repearted time and again, theoretically infinitely, as the metal, being an element, does not degrade with reuse.

Embedded energy use - extrusions

Primary aluminium extrusions include primary metal and recycled metal. Recycled metal can be run round scrap (scrap that does not leave the premises) and bought in scrap. As aluminium is an element, remelting does not degrade the material – however as the recycling process does add small quantities of other elements such as iron pick up from the holding furnace, there is a need to add some primary metal as a "sweetener".

Original kg primary metal 250 MJ/kg

Practical extrusion

39% primary material, 61% remelt 105,1MJ/kg

From Table 1 based on the Lawson model, the mass of aluminium in a typical residential window is about 7kg which, based on primary aluminium requires about 1489MJ of electricity to produce, (equivalent to about 537kg of CO_2-e of greenhouse gas emissions) in South Africa. However as average aluminium extrusions include 61% recycled stock, the electricity requirement is 704MJ/kg. A recycled content of 90% is possible which will reduce the above figures to as low as 47 kWh (169 MJ), or 61 kg CO_2-e.)

Use phase – thermal loss

Thermal flow can be divided into two sections; loss through ill fitting windows and loss through material properties and loss through leakage. Shapiro and James (3) consider timber sash windows 900mm wide x1500mm high. They found leakage of timber windows to be between the equivalent of a hole 554mm^2 (tight fitting) and 1794mm^2 loose fitting). Including an vinyl insert reduced the leakage to 187mm^2. The work shows that before upgrading refit the average loss through leakage was 21%. After retrofit, with the exception of a poorly fitting sash (ignored), the contribution of leakage to energy costs was 7%, the remainder being non leakage costs.

Aluminium with a thermal break is assumed to show the same properties as PVC windows. (HS has figures that can be added – and extended to include the 7% leakage – note that the hot box can be used to verify the combination.)

Demolition/ reuse

Residual energy embodied in the frame which can be released on end of life, remelted and reused 90% recovery x 250 1MJ/kg = 150MJ/kg. The net energy used is apparently negative (105,1 – 150) because the remelted material is measured against the energy requirements of primary metal which would otherwise be used. However the greenhouse gases associated with the original production remain.

Timber

The most common timbers used in residential windows are kiln-dried softwoods and hardwoods. All timbers are highly thermally insulating. The most popular wood used to be western red cedar from the northwest United States and western Canada. In Australia in recent years this has been supplemented or replaced by cheaper hardwood imports from Southeast Asia (especially Malaysia) such as meranti and merbau (kwila). In some countries, construction timbers come from local plantation forests.

In South Africa, much window-frame timber is imported from Gabon. Increasingly, rainforest timbers used for windows have been the subject of close scrutiny by environmental groups because they are typically harvested on an unsustainable basis. This accelerates the destruction of tropical forests and with them the habitat for irreplaceable flora and fauna; it also contributes to soil erosion, landslides and the loss of living forest biomass as a carbon sink. There have been strong concerns about illegally harvested Malaysian timber being imported into Australia.

Several third-party certification schemes exist to provide unbiased information about the origin and consequences of using imported timbers in construction but these schemes do not operate in all countries.

Using the Crawford hybrid input-output model, the embodied energy of kiln-dried hardwood is about 25 MJ/kg. This translates to about 414 MJ embodied energy in a typical wooden window frame. This is spread over extraction, milling and transportation – processes which depend on fossil fuels. The coal-fired electrical carbon equivalent is 150 kg CO_2-e.

uPVC

Unplasticised polyvinyl chloride (uPVC) is a widely-used frame material in Europe and North America. It is highly insulating (on a par with timber), oil-based and extruded like aluminium. Its Crawford embodied energy is estimated at 163 MJ/kg which translates to about 849 MJ embodied energy in a complete, typical uPVC window. Some uPVC windows require additional internal aluminium or hardwood reinforcing which increases the embodied energy. Taking a round figure of 1000 MJ, this is more than the embodied energy of an aluminium window having a recycled content greater than 40%. The coal-fired electrical carbon equivalent is 360 kg CO_2-e.

Steel

Mild steel is a widely-used window frame material in South Africa. It is highly conductive. Its Crawford embodied energy is estimated at 85.3 MJ/kg which translates to about 2646 MJ embodied energy in a complete steel window of frame mass 31kg. This is about 57% larger than the embodied energy in an aluminium window frame of the same dimensions. The coal-fired electrical carbon equivalent is 956 kg CO_2-e.

2.2 Impact of frame material surface finishes

Aluminium

Apart from the energy and CO_2 impacts of aluminium production, there is a small impact from the anodising or powder-coating of window frame sections. The expected lifetime of such surface finishes is good – typically in excess of 20 years.

Timber

Most timber windows require staining or painting to withstand the weather. Normally these treatments are re-applied every 2 – 5 years. It is true that western red cedar contains oils which resist rot and weathering much longer than other timbers, but many building owners do not like the coarse, weathered silver appearance that cedar takes on if it is not protected. The result is that most timber windows end up being recoated a number of times during their service life.

uPVC

Most uPVC windows are supplied white and do not require painting or other forms of surface protection. In the past, some uPVC frames were not stabilised against degradation from ultraviolet radiation, and this was a serious problem in sunny countries like South Africa. Modern uPVC windows should be structurally stable in all climates.

Steel

Steel window frames must be painted to prevent corrosion, especially in coastal areas. It is assumed that such finishes must be re-applied every 5 – 10 years.

3. Conclusions

Using the most up-to-date assessment methods, it is clear that all window frame materials cause some environmental damage. Like other industries, the South African aluminium industry must strive to reduce its energy usage and carbon emissions. However it is clear that aluminium windows can compete directly with timber windows on an embodied-energy basis if the recycled aluminium content is greater than 75%.

Aluminium frames can compete with uPVC windows if the recycled content is greater than 40%. The damage caused by sourcing of some rainforest timbers is of very serious concern and requires a coordinated approach by government, academics and consumer groups to provide society with information it requires.

UPVC windows have the lowest ongoing exterior maintenance costs, followed closely by aluminium, while timber windows require the most maintenance to maintain appearance and function. The embodied energy of steel windows is, on average, greater than that of aluminium windows. The maintenance requirements of steel windows are fairly high: greater than those of aluminium windows and potentially approaching those of timber windows.

References

1. Crawford, RH. *Validation of the Use of Input-Output Data for Embodied Energy Analysis of the Australian Construction Industry*, Journal of Construction Research, 6, 1, pp 71-90 (2005).
2. Lawson, Bill. *Embodied Energy of Building Materials*. BDP Environment Design Guide, Royal Australian Institute of Architects, Pro 2 (August 2006).
3. Shapiro A M and James B *Creating windows of energy –saving opportunity* Home Energy magazine Online September/October 1997 (homeenergy.org/archive/hem.dis.anl.gov/ehem/97/970908)

Material	Crawford embodied energy (MJ/kg)	Mass (1200h x 1500w window)	Crawford embodied energy (MJ)	Crawford embodied energy (kWh)	Crawford embodied CO2-e (kg)
Aluminium	252.6	6.7	1690	469	610
Aluminium, 61% recycled	105,1	6.7	704	195	238
Kind-dried hardwood	25.1	16.5	414	115	150
uPVC	192.0	5.2	998	277	360
Structural steel	85.3	31.0	2646	735	956

Table 1. Embodied energy and CO_2-equivalent for window frame materials, assuming electricity used to manufacture each material