Whole Life Analysis of timber, modified timber and aluminium-clad timber windows

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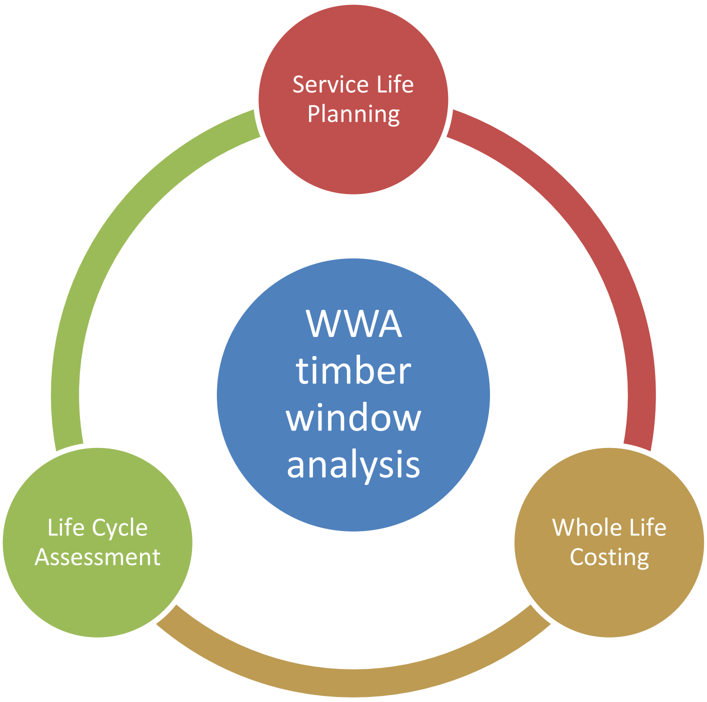
Whole Life Analysis of timber, modified timber and aluminium-clad timber windows: Service Life Planning (SLP), Whole Life Costing (WLC) and Life Cycle Assessment (LCA)



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June 2013

Executive Summary

This report compares the service life, ownership cost and environmental impact of windows using timber, modified timber, aluminium-clad timber and PVC-U frames.

It uses defined methodologies to compare the Service Life Planning (SLP), Whole Life Cost (WLC) and Life Cycle Assessment (LCA) of a standard window (1230x1480 mm with one side-opening light) in each of the four frame materials, taking into account the relative durability of the materials and their maintenance requirements.

Service Life Planning (SLP) is a decision process which addresses the development of the service life of a building, constructed work, or in this case, a component. Its purpose is to give a structured response to establishing normal service life from a reference or estimated service life framework. The objective of SLP is to provide reasonable assurance that the estimated service life of a building or construction on a particular site, with appropriate maintenance, is at least as long as the design of that building. The results show timber frames to have an expected service life of between 56 and 65 years. Acetylated timber frames show an expected service life of 68-80 years, and timber frames, clad with profiled aluminium, 71-83 years.

Whole Life Cost (WLC) was assessed using a standard discounting method, Net Present Value (NPV), which allows the time value of money to be allowed for in the value of future payments or incomes. The NPV of purchase, installation, repair and maintenance costs were evaluated over building design lives of 60, 80 and 100 years and under mild, moderate and severe exposure conditions. Over a 60-year design life, the results show that timber windows offer the lowest cost alternative for mild scenarios, while aluminium-clad and modified timber offer lower whole life costs for moderate and severe scenarios. Despite having the lowest capital cost, PVC-U windows were shown to have the highest whole life costs over 60 years in all scenarios.

Life Cycle Assessment (LCA) is an internationally recognised tool for assessing the environmental impact of products, processes and activities. It is a methodology for evaluating the environmental load of processes and products during their whole lifecycle and is one of various environmental management tools currently available for assessing impact and sustainability. LCA is used to assess the environmental impact of processing raw materials, manufacture of finished products and components, during construction, to transport materials and products to site, to maintain components, and to process materials at their end-of-life to recycle and/or dispose of materials. This report is conducted within ISO 14040 and PAS2050 guidelines and sets a new standard for the whole life cycle appraisal of timber windows. It considers a base case scenario plus 6 alternative scenarios which test the sensitivity of inventory data and boundary inclusions on Global Warming Potential (GWP) of the frame materials considered. This report finds that all timber based window frame materials are preferable to PVC-U alternatives in every scenario considered.

Using the methods adopted in this report, recycling is found to be the optimum end of life treatment for timber based window frames. The report conclusions lean to supporting the aims of WRAP in pursuing greater waste segregation, and possible tighter restrictions on timber waste entering landfill sites. This report also demonstrates the significant sensitivity of GWP outputs to the sustainable and ethical sourcing of timber under FSC or equivalent standards.

Life Cycle Assessment of timber, modified timber and aluminium-clad timber windows. Report for the Wood Window Alliance, June 2013.

This work allows a complete like-for-like longevity, cost and environmental impact comparison of timber, modified timber, aluminium-clad timber and PVC-U frame materials. It concludes that there is no single or optimal timber based window frame material; there is not a one-size-fits-all solution. For various exposure conditions and applications one timber based product may be preferable over another in service life terms, while others may prevail in cost or global warming potential terms. It is clear that PVC-U windows are not comparable with wood alternatives in GWP terms. Indeed PVC-U windows are not comparable with wood alternatives over a number of LCA impact factors.

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1.0 Introduction

This report analyses the Service Life Planning (SLP), Whole Life Costing (WLC) and Life Cycle Assessment (LCA) of factory-finished timber, modified timber and aluminium-clad timber window frames (herein referred to as timber based windows) designed to Wood Window Alliance (WWA) criteria, under various exposure and maintenance conditions. It was commissioned by the WWA and completes work started at Imperial College London in 2010. The report defines a methodology to enable frame properties to be compared on a like-for-like basis. The service life work on timber windows is published in partnership with Imperial College London, and its extension, to include modified timber and aluminium-clad timber windows, is the work of Dr. Gillian Menzies at Heriot Watt University.

Timber windows referred to in this report are constructed from high quality, preservative treated softwood to BS EN 942,BS EN 599 and BS 817; constructed from a defect free enhanced substrate (heartwood); and with endgrain and construction joint sealing. Although the analysis here is limited to frame materials only, all window units are factory glazed and assumed to be installed in a recess.

In this report, modified timber is defined as timber which has undergone acetylation. This technique creates a high performing wood which can be used in demanding outdoor applications, including windows, doors, decking, cladding, and bridges. Wood contains hydroxyl groups that interact with water according to changes in climatic conditions - the main reason wood swells and shrinks. Acetylation converts these hydroxyl groups to acetyl groups by reaction with acetic anhydride. Naturally grown timbers already contain a proportion of acetyl groups, but the acetylation process increases this proportion significantly and the resulting timber is more dimensionally stable, indigestible (rot resistant) and durable.

Aluminium-clad timber windows, as referred to here, are timber windows with a full aluminium profile clad to the exterior of the window. The aluminium is commonly protected with a powder coating, typically guaranteed for around 25 years. The interior of the window appears as a timber window. The aluminium can be repainted after 20-30 years to maintain good aesthetic appeal, or left untreated with no loss of functional performance. The aluminium profile can also be removed, recycled, and a replacement clipped into place.

PVC-U windows are constructed from 70mm extruded PVC-U extrusions with mild steel reinforcement.

The SLP analysis is based on *ISO 15686* methodology to differentiate the service life of timber-based windows manufactured using best practice window design, manufacture and coating.

WLC data is derived using a standard discounting technique, Net Present Value (NPV), which allows two or more alternatives with differing financial outlay/income in different accounting periods to be compared on an equal basis.

The LCA analysis has been carried out using SimaPro 7.3.2 software and the Ecoinvent 2.2 database which accompanies the software. ISO 14040: Environmental Management – Life Cycle Assessment – Principals and Framework has been used as the guiding framework for the analysis contained within this report. All assumptions made throughout the analysis are stated. Any deviations from the Ecoinvent 2.2 database have been justified.

2.0 Service Life Planning

Establishing a service level base case is an essential precursor to the WLC and LCA analyses that follow; the estimated service life will predict how many maintenance events are necessary in various exposure conditions over the life of a window. Each maintenance event requires materials and resources to perform and has both a financial and environmental cost attached it.

2.1 ISO 15686

ISO 15686 is the international standard dealing with service life planning; it is a decision process which addresses the development of the service life of a building, constructed work, or in this case, a component. Its purpose is to give a structured response to establishing normal service life from a reference or estimated service life framework. The objective of SLP is to provide reasonable assurance that the estimated service life of a building or construction on a particular site, with appropriate maintenance, is at least as long as the design of that building.

ISO 15686-1 describes the general principles of service life planning, of which there are a number of approaches that can be used to estimate service life. Figure 2.1 shows the possible approaches to service life estimation.

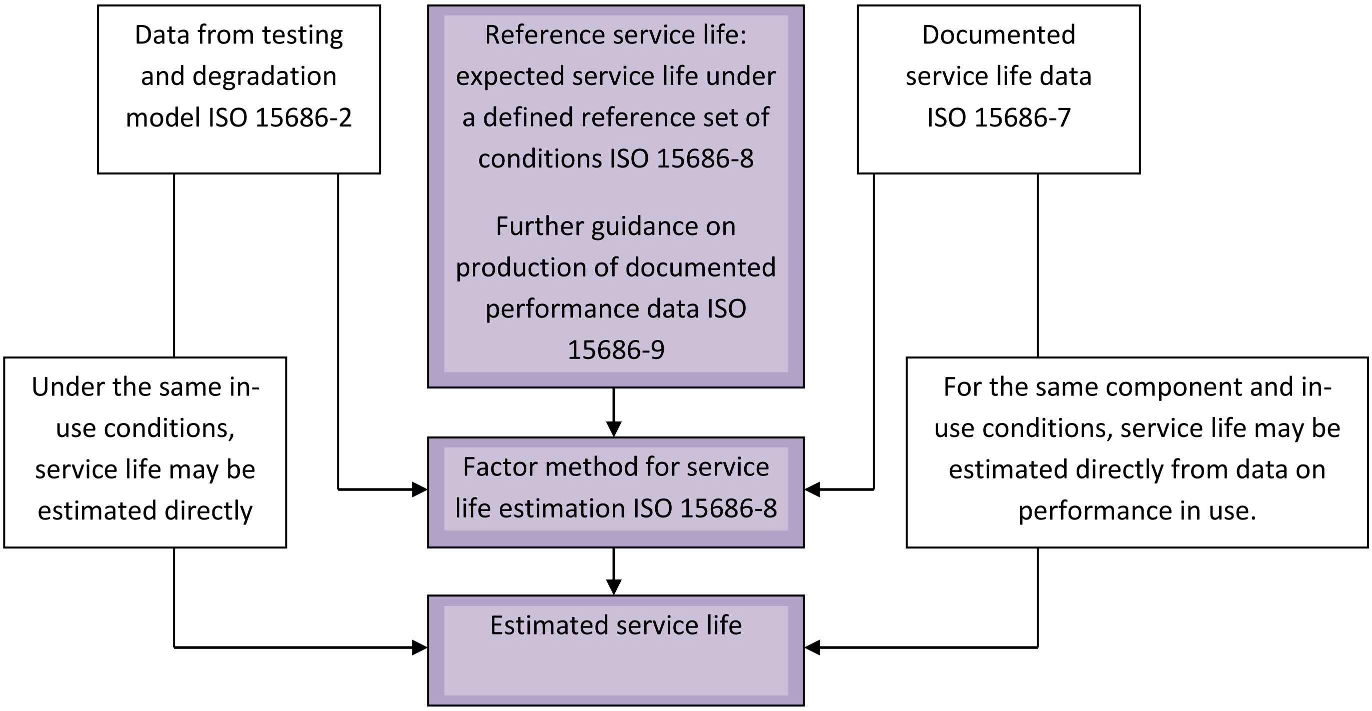


Figure 2.1: Approaches to service life estimation. ISO 15686-8, page 8.

The factor method for service life estimation, ISO 15686-8 is used in this report, and is based on earlier work completed at Imperial College London. Seven factor categories are used to estimate service life impact, as shown in Table 2. 1. The factor method is used to obtain an Estimated Service Life (ESL) of a component or a design object by modifying a Reference Service Level (RSL) by considering the differences between the object-specific and the reference in-use conditions under which the RSL is valid [ISO 15686:8 page 11]. The RSL used here is derived from the Building Research Establishment Green Guide for Specification, which gives a service life of 35 years for Timber Window Accreditation (TWA) Scheme windows. Wood Window Alliance membership criteria require members to meet this standard as a minimum.

Table 2.1 Factors and factor categories of the factor method ISO 15686-8, page 16.

Factor	Factor category
A	Inherent performance level
B	Design level
C	Work execution level
D	Indoor environment
E	Outdoor environment
F	Usage conditions
G	Maintenance level

A factor > 1.00 denotes longer service life estimation, while a factor < 1.00 denotes shorter service life estimation. The factors applied can be seen in Appendix 2.1. No single factor applied is greater than 1.25. This is deemed conservative, but in line with ISO 15686 guidance, whereby service life estimation should be within 2 standard deviations of a documented or tested normal service life distribution [ISO 15686:8 page 15]. ISO 15686:8 also states that it is preferable for all factors to be within the interval of 0.8 to 1.2, although Note 7 states that larger deviations from unity are possible if just a few factors deviate from unity and can be assumed to be independent of each other [ISO 15686:8 page 13]. The single factor of 1.25 is applied to aluminium-clad windows only and relates to the aluminium material used under Factor A. This is independent of other factors used in the analysis.

2.2 Service Level Base Case

Establishing a service level base case has proven difficult for timber windows, despite their widespread use since the 17th Century. Evidence from traditional and historic buildings would suggest that timber windows have a life expectancy greater than 100 years [Davey, 2007]. English Heritage argues that traditional windows can be very durable: many original Georgian and Victorian timber windows are still in place [Wood et al, 2009].

Asif et al [2005] in an analysis of window sustainability, carried out a survey of over 25 organisations to determine the service life of PVC-U, timber, aluminium and aluminium-clad timber windows. The thesis conclusions on average service lives are shown in Table 2.2. The same study also reported findings from Citherlet [2000], HAPM [1996] and Worcester City Council [WCC, 1990]. Additionally, data from the Building Research Establishment have been added to show the range of studies performed to date.

Table 2.2 Various window service lives reported in literature

Life Cycle Assessment of timber, modified timber and aluminium-clad timber windows. Report for the Wood Window Alliance, June 2013.

Window type	Asif (2002)	Citherlet (2000)	HAPM (1996)	WCC (1990)	BRE generic window	BRE TWA window
Aluminium	43.6	45	35+	50-60		
PVC-U	24.1	30	25	30	25- 35*	
Timber	39.6	45	35+	40+	30	35
Alu-clad timber	46.7	45				

* 25 years in the original Green Guide, subsequently amended to 35 years following a BRE Client Study commissioned by the plastics industry

2.3 Service Life Factors

A strong trend to replace single glazing with double glazing and the promise of “maintenance free” window frames has perhaps led to many timber frame windows being replaced long before their design life has expired. A number of initiatives to improve the design quality of timber frame windows have led to quality, long-lasting systems being introduced to the market. Manufacturing criteria play a strong role in extending service life:

- Choice of sustainable, defect free, engineered timber
- Window design elements such as rounded edges, water shedding angles on cills and beads, and joint and end grain sealing
- Flexible, micro-porous protective paint
- Factory controlled glazing and coating systems

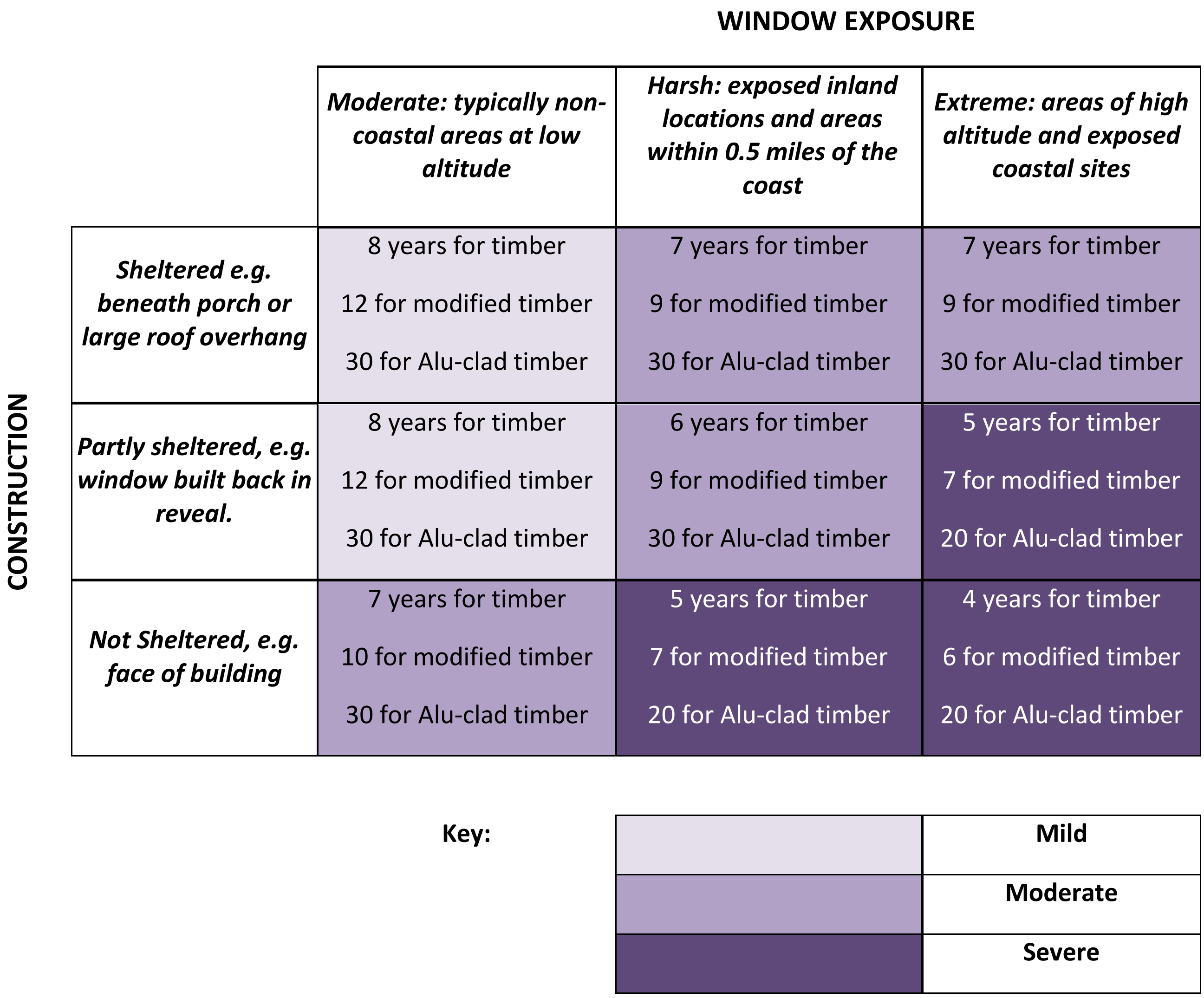
Design improvements and associated standards are listed in Table 2.3

Table 2.3 Service Life Factors for timber frame windows

Category	Influencing Factor	Associated Standard
Base substrate	High quality timber	BS EN 942
Enhanced Substrate	Clear face and defect free Laminated Heartwood	BS EN 942
Beads	Rounded edges Capillary gaps Fully coated Drained rebates	BS EN 644
Joints and Cills	Filled construction joints Exposed end grain sealed Joints fully coated with D3/D4 adhesive	WWA Design Standards
Glazing	Drained and vented upstand Coated rebates and upstands Robust glazing beads: nail and fill; aluminium; composite	BS 8000
Coatings	Preservative treated Quality tested Full factory finish: 120µ dft minimum All surfaces coated	BS EN 599 BS 8417 BS EN 927
Installation/Maintenance	Controlled transport and site storage Qualified installers Manufacturer maintenance instructions	
Environment	Waste recovery Water based coatings: VOC < 50g/l No heavy metal additives	ISO 14001
Shelter	Implementation of specific partial or full shelter measures can be envisaged at conservative factors of 1.05 and 1.10. Evidence for specific circumstances may also indicate that higher factors than these are required.	

This report considers the influence of maintenance levels on the design life and durability of three types of window frame: timber, modified timber and aluminium-clad timber. Various maintenance cycles are analysed. The influence of location is also considered for three scenarios; mild, representing sheltered or part-sheltered positions at non-coastal, low altitude locations; moderate, representing sheltered positions in harsh or extreme locations, or part-sheltered positions in harsh locations; and severe, reflecting part-sheltered or exposed positions in more exposed rural locations which may experience wind-driven rain or salt conditions.

Figure 2.2 relates these scenarios, and their associated maintenance frequencies, to the durability matrix described in BS EN 927-1: Paints and Varnishes - Coating Materials and Coating Systems for Exterior Wood - Part 1: Classification and Selection



WINDOW EXPOSURE

CONSTRUCTION

	Moderate: typically non-coastal areas at low altitude	***Harsh: exposed inland locations and areas within 0.5 miles of the coast***	***Extreme: areas of high altitude and exposed coastal sites***
Sheltered e.g. beneath porch or large roof overhang	8 years for timber 12 for modified timber 30 for Alu-clad timber	7 years for timber 9 for modified timber 30 for Alu-clad timber	7 years for timber 9 for modified timber 30 for Alu-clad timber
Partly sheltered, e.g. window built back in reveal.	8 years for timber 12 for modified timber 30 for Alu-clad timber	6 years for timber 9 for modified timber 30 for Alu-clad timber	5 years for timber 7 for modified timber 20 for Alu-clad timber
Not Sheltered, e.g. face of building	7 years for timber 10 for modified timber 30 for Alu-clad timber	5 years for timber 7 for modified timber 20 for Alu-clad timber	4 years for timber 6 for modified timber 20 for Alu-clad timber

Key:

░	**Mild**
▒	**Moderate**
▓	**Severe**

Figure 2.2 Maintenance Frequency for factory finished joinery (BS EN 927-1)

This report has also attempted to account for window obsolescence due to loss of visual appeal as well as due to functional failure. It is possible for a well-designed window, made of appropriate materials, to perform/function for more than sixty years without any painting or other decorative treatment, but it may be prone to staining, oxidation, and discolouration leading to a *perceived* need for replacement. For example, the powder coating on an aluminium-clad timber window may break down over time, having little effect on the function of the window, but affecting the visual appeal of the building in which it is installed. In these terms, service life is a function of perception as well as technical performance. The purpose of regular maintenance is therefore to maintain the life of the window by postponing obsolescence in terms of both aesthetic and technical performance.

Using ISO 15686-8 methodology, and based upon a relatively conservative service life estimate from the Building Research Establishment of 35 years, factors greater than 1.00 can be applied to account for the above design improvements. Factors can be made cumulatively, but care must be taken to exclude double counting. The workings for this analysis are given in Appendix 2. 1, and are summarised in Table 2.4. A working spread sheet is also available separately.

Table 2.4: Summary of Service Life Planning ISO 15686-8 analysis (cumulative for all factors under WWA control A, B, C, E, G)

Window type	Typical Maintenance Period	Mild	Moderate	Severe
Timber	Standard 5-7 years	**65**	**59**	**56**
Modified Timber	Standard 10-12 years	**80**	**72**	**68**
Aluminium-clad Timber	Standard 20-30 years	**83**	**75**	**71**

Comparison with literature findings

The results in Table 2.4 agree with an analysis concluded by the BRE which states that

> "*if a modified timber window built to the principles of best practice, factory finished using quality coatings, installed by competent contractors and linked to a recognised best practice maintenance and care package it will provide a window of outstanding durability and dimensional stability that would meet a 60 year service life requirement*." [Correspondence between BRE and Accsys Technologies, December 2010]

This description is roughly equivalent to windows subject to Factor A and B effects combined. Using a design life basis of 35 years and applying Factor A and B effects gives a service life of 60 years for modified timber windows using ISO 15686-8 analysis.

The results in Table 2.4 also agree with the general results concluded by Asif et al and Citherlet, which are roughly equivalent to windows subject to Factor A effects only. Using a design life basis of 35 years and applying Factor A effects in isolation gives a service life of 50 years for Aluminium-clad timber windows using ISO 15686-8 analysis.

2.4 Service Life Conclusions

Figure 2.3 (below) summarises the findings of this section of the analysis, and compares them to PVC-U windows with an average service life of 30 years, which represents a consensus of the BRE Green Guide(s) rating for PVC-U windows and the findings of both Citherlet [2000] and the WCC [1990]. The analysis shows that, where weather stress is an issue, or maintenance is constrained, modified timber or Aluminium-clad timber may be optimal. The cost of erecting scaffolding on a 10-12 year (or shorter) basis for a high-rise building can be significant, while the selection of windows with a 20-30 year maintenance schedule could be more attractive.

To make conclusions more robust, however, the cost and environmental implications of window material choice need to be considered. Section 3.0 addresses the issue of whole life cost, while LCA issues are considered in a separate report.

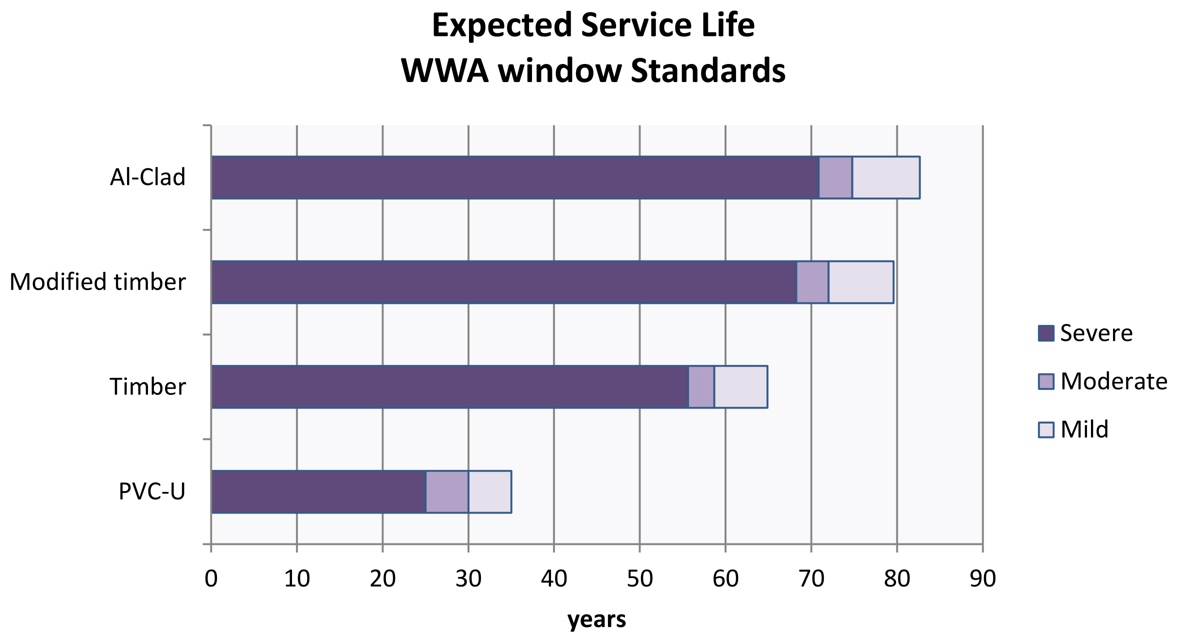


Figure 2.3 Expected Service Life for WWA window standards (Factors A, B, C, E and G)

3.0 Whole Life Costing

A whole life cost comparison was prepared using data from the SLP model and a standard discounting technique. The results are summarised in Table 3.2.

3.1 Net Present Value

The simple Net Present Value (NPV) discount model provides a useful tool for comparing the whole life costs of different investment options, although the outcomes can be significantly influenced by changing underlying assumptions. For the analysis presented here, an annual inflation rate of 3%, and an outturn interest rate of 7% have been assumed in line with local authority evaluation rates for social building finance. End-of-life disposal costs have been omitted due to lack of reliable data, and a rapidly changing landscape with regard to construction waste and recycling.

For PVC-U window frames, in–service maintenance costs have been ignored and a service life of 25-35 years assumed, in line with the findings shown in Table 2.2. The maintenance cycles for timber windows are in line with manufacturers' recommendations, with higher costs applied to longer cycles.

Timescale can also be significant in discounting models; this analysis has been completed for assumed building lives of 60, 80 and 100 years to explore sensitivity to this effect. The underlying model assumptions are shown in Table 3.1

Table 3.1 Maintenance costs and periods (all costs in £)

Window type	Capital cost	Installation cost	Maintenance Frequency (years)*			Cost of each maintenance event	Glazing cost per annum
			mild	moderate	severe		
Timber	290	84	8	6	4	20	9
Modified timber	340	84	12	9	6	24	9
Aluminium-clad timber	362	84	30	30	20	30	9
PVC-U	280	84	-	-	-	-	9

* See Figure 2.2

Table 3.2 shows the current day cost (NPV) of a window over a building lifecycle of 60, 80 and 100 years for various exposure scenarios and accommodating the maintenance frequencies described in Table 3.1. For a building predicted to last 60 years, and using a WWA timber window under moderate conditions, the NPV is £644. This means that to purchase the window and maintain it over 60 years costs £644 in today's money.

Table 3.2 NPV and indexed price comparison of windows over 60, 80 and 100 years.

		NPV of Total Cost including inflation (£)			Indexed values (PVC = 100)		
	Window type	**60 years**	**80 years**	**100 years**	**60 years**	**80 years**	**100 years**
Mild scenario	timber	590	632	639	87	92	91
	modified timber	626	657	663	92	95	94
	Ali-clad timber	622	634	657	92	92	93
	PVC-U	678	689	706	100	100	100
Moderate scenario	timber	644	659	667	95	96	94
	modified timber	639	677	684	94	98	97
	Ali-clad timber	622	658	663	92	95	94
	PVC-U	678	689	706	100	100	100
Severe scenario	timber	685	703	710	96	94	94
	modified timber	669	714	722	93	96	96
	Ali-clad timber	633	674	680	88	90	90
	PVC-U	717	747	753	100	100	100

Green denotes lowest cost option **Red denotes highest cost option**

In a mild scenario, representing sheltered or part-sheltered locations with a non-coastal climate, timber windows are consistently least expensive, while in moderate and severe scenarios aluminium-clad timber windows are seen to be the lowest cost option. This is largely reflective of their reduced maintenance period (20-30 years compared to 5-7 years). Modified timber remains consistently less expensive than PVC-U alternatives due to the significantly longer service life afforded by the acetylation of the timber. Despite the appeal of "zero" maintenance on PVC-U windows, they are consistently most expensive in all three climate/construction scenarios due to their shorter, 25-35 year, lifespan.

Service life estimations play a critical role in WLC calculations. At 65 years, the timber window will have been replaced once for all climate/construction scenarios and the PVC-U window twice, but the modified timber and aluminium-clad timber windows could have up to 18 years life left. Were the building to last in excess of 100 years and towards 150 years (or before the second replacement of timber windows), the benefit in lower WLC would increase, though the sensitivity of NPV analysis over such extended time periods is limited and 60 years is considered sufficient building longevity in most current cases [BRE Green Guide, 2009].

3.2 Cumulative NPV

The cumulative costs are perhaps best viewed on NPV graphs shown in Figures 3.1, 3.2 and 3.3.

Figure 3.1: Cumulative Lifetime Cost: Mild Exposure

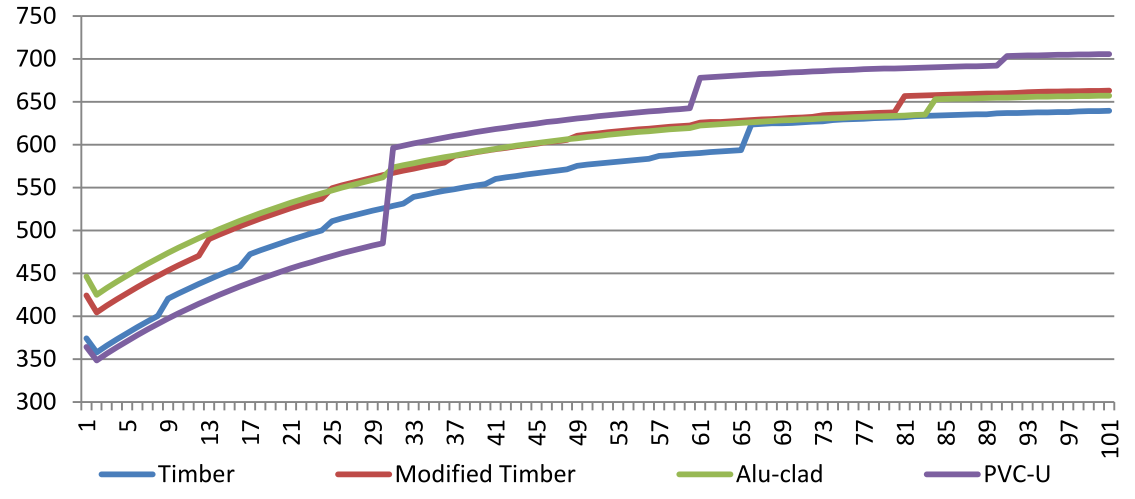
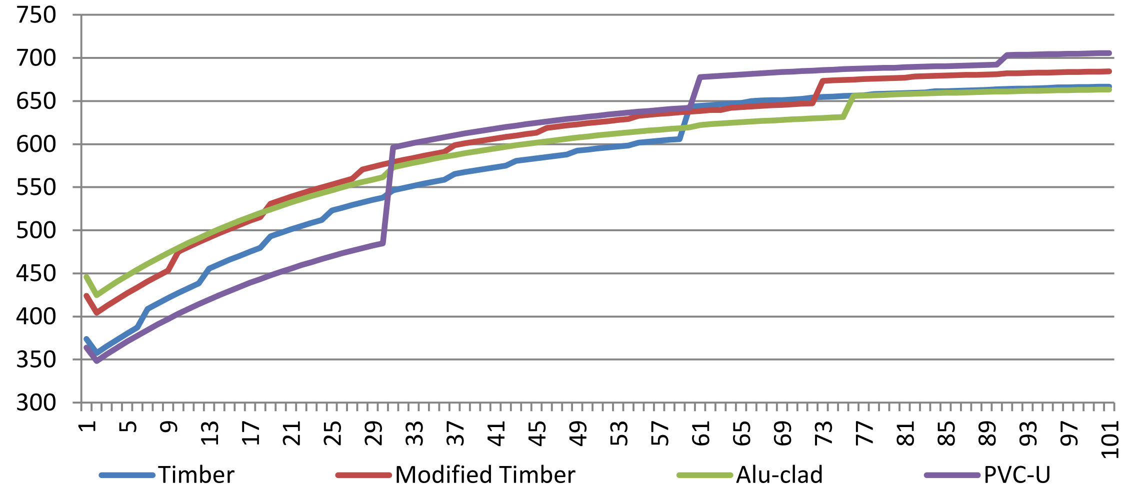
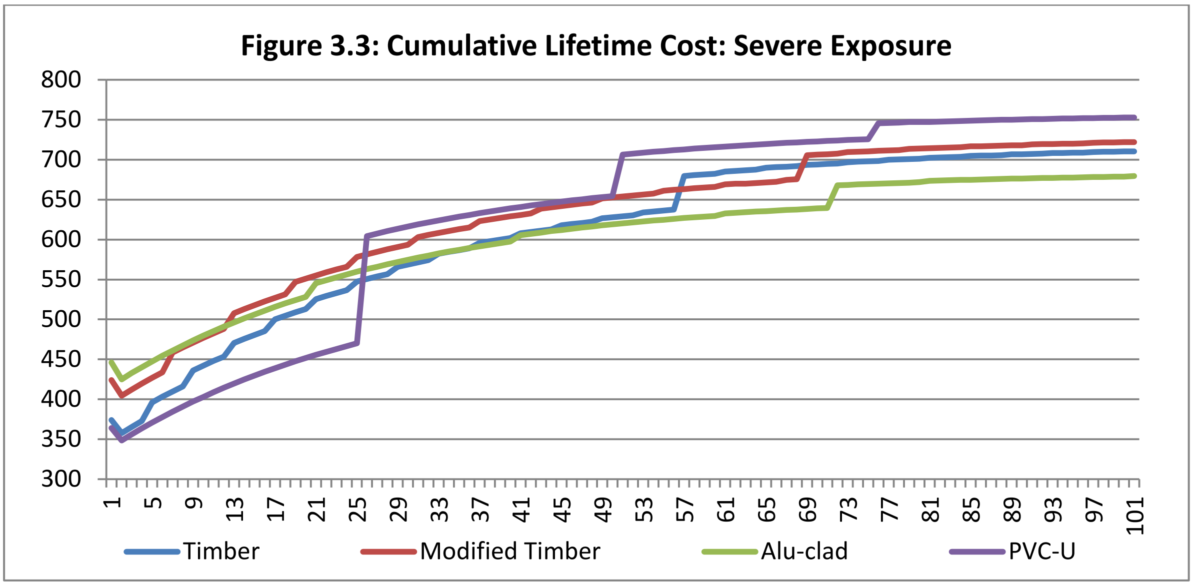


Figure 3.2: Cumulative Lifetime Cost: Moderate Exposure





3.3 Whole Life Cost Conclusions

Using NPV analysis, the whole life cost comparison for each option was also evaluated. With PVC-U windows indexed at 100, all timber based window options were indexed at less than 100: demonstrating that capital, installation, maintenance and replacement costs are lower for all building life options of 60, 80 and 100 years, and for all timber window alternatives. For mild exposures, timber windows offered the lowest lifetime cost option, while for moderate and severe exposures the more durable modified timber and aluminium-clad windows gave more favourable lifetime cost outcomes.

In practice, if initial capital cost is the only criterion, PVC-U windows are the least expensive short term option. If, however, total lifetime cost is the primary concern, this analysis suggests timber offers the lowest cost option for properties in a typical urban/suburban setting, aluminium-clad timber options would be favoured on high-rise or multi-storey buildings, benefitting from their extended service life and low access requirement, while in coastal or moderately exposed locations modified timber or aluminium-clad timber windows may be optimal.

4.0 Life Cycle Assessment

The construction industry is the highest consumer of materials globally, consuming around 6 tonnes of material per person per year. Energy is needed to create buildings through extraction and processing of raw materials, manufacture of finished products and components, during construction, to transport materials and products to site, to maintain components and to process materials at their end-of-life to recycle and/or dispose of materials [Consoli et al., 1993]. If a boundary is drawn around this lifecycle and an assessment of inputs and outputs which cross this boundary is made, some attempt is given at assessing a building's Life Cycle Assessment (LCA).

4.1 Introduction to LCA

Figure 1 illustrates the lifecycle of window materials. Sometimes whole buildings are assessed in LCA terms, but more commonly individual materials and components are subject to detailed analysis.

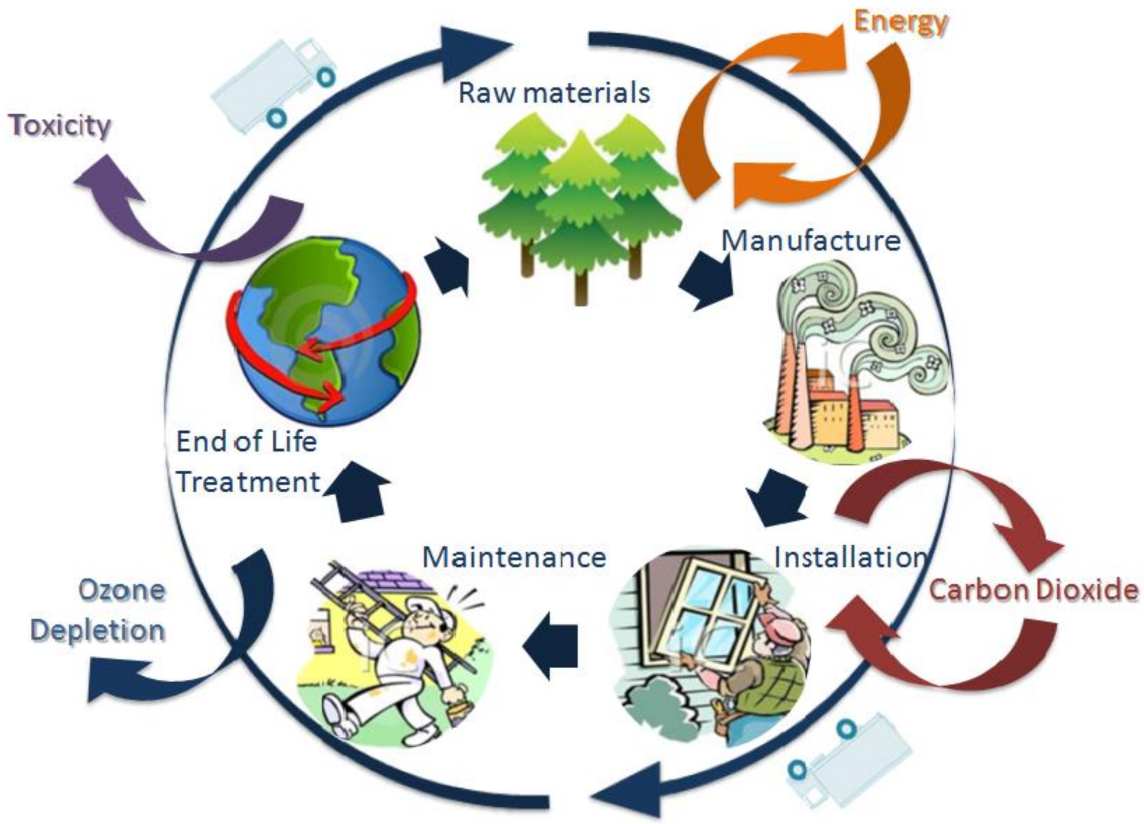


Figure 1: Life Cycle Assessment of Window Materials

There are many methods available for assessing the environmental impacts of materials and components. LCA is a methodology for evaluating the environmental load of processes and products during their whole lifecycle and is one of various environmental management tools currently available [Sonnemann et al., 2003]. With its origins in the 1960s [Selmes, 2005] LCA has become a widely used methodology over the last two decades for understanding better the impact which product lifecycles have on local and global communities.

LCA is an internationally recognised tool for assessing the environmental impact of products, processes and activities, using indicators described in Table 1.

Table 1 SimaPro Environmental Impact Measures

Abiotic Depletion	Ozone Layer Depletion	Terrestrial Ecotoxicity
Acidification	Human toxicity	Photochemical Oxidation
Eutrophication	Fresh Water Aquatic Ecotoxicity	Global Warming Potential
Marine Aquatic Ecotoxicity		

Abiotic Depletion refers to the depletion of non-renewable resources. Some non-renewable resources can actually be renewed over a period of time, e.g. the extraction of sand from a river channel can be replenished over time by the further weathering of rocks. Many definitions refer to a 500 year period. If resources are not renewable within this period they are termed non-renewable.

Acidification refers to direct outlets of acids or by outlets of gases that form acid in contact with air humidity and are deposited to soil and water.

Eutrophication is defined as an increase in the rate of supply of organic matter in an ecosystem, and the process by which a body of water acquires a high concentration of nutrients, especially phosphates and nitrates. These can promote excessive growth of algae which limit oxygen supply to other organisms.

Marine Aquatic Ecotoxicity refers to the impacts of toxic substances on marine ecosystems, such as seashores, open ocean, and estuaries.

Ozone Layer Depletion refers to the depletion of an area of the upper atmosphere which contains ozone. This layer protects the earth from high levels of ultraviolet radiation.

Human toxicity is based on tolerable concentrations in air, water, air quality guidelines, tolerable daily intake and acceptable daily intake for humans

Fresh Water Aquatic Ecotoxicity refers to the impact of toxic substances emitted to marine aquatic ecosystems.

Terrestrial Ecotoxicity refers to the impact of toxic substances emitted to terrestrial (land) ecosystems.

Photochemical Oxidation is the reaction of a chemical with light, e.g. photochemical smog which is caused by hydrocarbons and nitrous oxides reacting under the influence of UV light. It is usually measured in concentration and duration levels throughout the course of a day.

Global Warming Potential is a relative measure of how much heat a greenhouse gas traps in the Earth's atmosphere. It is measured in Carbon Dioxide equivalency (CO_2e), which is described in Table 2 below.

Some of these impacts are inter-linked. It is seen in the results to follow that as one impact rises, so do related impacts. For example photochemical oxidation occurs when hydrocarbons and nitrous oxides react under UV light. Nitrous Oxides are a type of gas that cause acidification. Abiotic depletion is a measure of non-renewable resource depletion. Fossil fuels are a non-renewable resource that when burned increase the world's global warming potential.

Life Cycle Energy Analysis (LCEA) emerged in the late 1970s and focuses on energy as the only measure of environmental impact of buildings or products. The purpose of LCEA is to present a more detailed analysis of energy attributable to products, systems or buildings; it is not developed to replace LCA but to compare and evaluate the initial (capital) and recurrent (operational) energy in materials and components. **Life Cycle Carbon Assessment (LCCA)** is likened to LCEA, and relies on prevailing energy structures to convert mega joules of energy to kilograms of CO_2. While the base case scenario in this report shows full LCA results over 10 impacts, the six scenario analyses which follow in section 6 will focus on LCCA. Other terms commonly used when discussing lifecycle definitions, energy and carbon issues are shown in Table 2.

Table 2: Commonly used lifecycle terms

Cradle to Grave	Describes all the processes which a product or component goes through from raw material extraction to obsolescence and final disposal. It assumes no EoL residual value.
Cradle to Gate	Describes the impacts associated with products, materials or processes up to the point at which they are packaged and ready for delivery to site.
Cradle to Site	Describes the impacts associated with suppliers (raw materials), transportation to manufacturing centre, manufacturing, packaging, and transportation to site. In the case of construction impacts, this would also include any processing required on site to make use of the product or component.
Cradle to Cradle	Similar to Cradle to Grave, but assumes that an obsolete component has a residual value at the end of its *first* life. It assumes that construction waste can be recycled and used to provide raw materials for re-manufacture of the same product, or new and different products.
Embodied Energy (EE)	A Cradle to Gate or Cradle to Site analysis based on energy inputs only. i.e. those energy inputs relating to raw material extraction, transportation, processing, manufacturing, and packaging.
Embodied Carbon (EC)	Converts this embodied energy from MJ to tonnes of CO_2. Frequently embodied CO_2 is given as CO_2e
Equivalent Carbon Dioxide (CO_2e)	A way of describing how much global warming a given type and amount of greenhouse gas may cause, using the functionally equivalent amount or concentration of carbon dioxide (CO_2). Put simply, if CO_2 has a Global Warming Potential (GWP) of 1, then Methane has a GWP of 25, and Nitrous Oxide a GWP of 298.

Generally speaking a material, product or component has three main stages to its cradle to grave carbon lifecycle; Embodied Carbon (EC), Operational Carbon (OC) and End of Life carbon (EoL). In the case of windows, maintenance is captured under the operational energy stage. A full dynamic LCCA of windows may also include the glazing and thermal insulation qualities (the U-value) and give some indication of the energy expended to heat a home or building. This analysis will consider only the lifecycle of the window frame materials.

A comprehensive LCCA study has four main stages:

1. Scope and boundary setting;
2. Inventory analysis;
3. Impact assessment; and
4. Improvement analysis.

A fifth and important element of LCCA includes an analysis of data sensitivity to the overall results. This may include an analysis of the quality of inventory data used, a test of the sensitivity of assumptions made, and/or a number of scenario analyses.

Before considering the specific issues relating to these LCCA stages, some points to note include:

Boundary definitions The accuracy of carbon calculations is directly related to, and profoundly influenced by, boundary definitions. Naturally, more comprehensive boundary assumptions result in more precise calculations. The direct carbon requirement for manufacturing processes is generally less than 50% of the total embodied carbon of a product, but can be up to 80%, while the indirect carbon requirement for extracting raw materials is generally less than 40%, and the carbon emitted to make the capital equipment less than 10%. In general, the carbon requirement to make the machines that make the capital equipment is very low. Inclusion/exclusion of indirect processes like raw material extraction, embodied carbon of manufacturing machinery, transportation, reoccurring embodied carbon of materials, or the feasibility of recycling and reuse, can have a significant effect on overall results.

Completeness of study The more processes which are included in a study the more complete and accurate the results become. Indirect carbon contributions depend upon many factors, including raw material sources. The Inventory of Carbon and Energy (ICE) database commonly reports data sensitivities of 30% due to varying boundary inclusions and completeness of studies [ICE, 2011].

Energy supply assumptions These assumptions can produce significant variations in embodied carbon evaluations; whether primary or secondary (delivered or end use). If primary energy is reported instead of delivered or end-use energy, the value may be 30 to 40% higher for common building materials. Lack of information regarding these factors is one of the main obstacles in comparing life cycle inventory results.

Energy source assumptions Energy sources inherently have varying carbon coefficients. Generation of electricity from hydroelectric power or other renewable sources have significantly different impacts than conventional, hydrocarbon based, fossil fuel sources. For example in Canada and Norway, aluminium is produced solely using hydroelectric power. Brick production in Nottinghamshire uses methane from landfill [Smith, 2005] rather than traditional (generally coal fired) energy supplies. Variations in energy source and distribution will impact both embodied energy values (due to cycle efficiencies), and carbon emissions resulting from energy use. Buchanan and Honey [1994] found that carbon emissions relating to material production could differ by a factor of three depending on assumptions made over energy supply.

Product specification Differences in processing and application also generate large variances. Virgin steel consumes significantly more energy than recycled steel, and different processes within the steel manufacturing industry affect embodied carbon values.

Manufacturing differences Processing efficiency levels improve over time as a result of technological advances, and can vary depending on the geographical location. Studies following Buchanan and Honey's findings [1994] in construction materials (summarised by Alcorn and Wood, 1998) indicate a continuing downward trend in processing energy for many materials. Conversely, however, there is a trend to make more technical specifications for construction projects, increasing in some cases, the length of supply chains and processing steps to final product completion.

4.2 Methodologies

There are a number of recognised approaches to LCA, LCEA and LCCA, including process analysis, Input-Output analysis, and hybrid analyses.

Process Analysis Method

This is the oldest and still most commonly used method, involving the evaluation of direct and indirect energy inputs to each product stage. It usually begins with the final product and works backwards to the point of raw material extraction. The main disadvantages centre on the difficulties in obtaining data, not understanding the full process thoroughly, and extreme time and labour intensity. These result in compromises to system boundary selections (which are generally drawn around the inputs where data is available). Furthermore it is likely to ignore some of the processes such as services (banking and insurance, finance), inputs of small items, and ancillary activities (administration, storage). The magnitude of the incompleteness varies with the type of product or process, and depth of the study, but can be 50% or more [Lenzen and Treloar, 2002]. For these reasons results are found to be consistently lower than the findings of other methodologies. Process LCA is best used to assess or compare specific options within one particular sector. This report is an example of such a method. The major advantage is the ability to define individual product life stages and material inputs, enabling in-depth sensitivity or scenario analyses to be performed.

Input Output Analysis

Originally developed as a technique to represent financial interactions between the industries of a nation, this method can be used in inventory analysis to overcome the limitations of process analysis. The method is based on tables which represent monetary flows between sectors, and which can be transformed to physical flows to capture environmental fluxes between economic sectors. The number of sectors and their definition vary within each country. The great advantage of this method is data completeness of system boundaries; the entire economic activities of a nation are represented. However despite the comprehensive framework and complete data analysis, I/O analysis is subject to many uncertainties, due mainly to the high level of aggregation of products. Many dissimilar commodities, or sectors containing much dissimilarity, are put into the same category and assumed identical; assumptions are based on proportionality between monetary and physical flows. In some countries I/O tables are not updated frequently, resulting in temporal differences with irrelevant or unrepresentative data. Unsurprisingly, LCAs based on process analysis and I/O analysis yield considerably different results. I/O-LCA is suitable for strategic policy making decisions (comparing sectors) as well as providing complementary data on sectors not easily covered by process LCA. This method would be impractical for the current study.

Hybrid Energy Analyses

The disadvantages of previous methods can be reduced if a hybrid method, combining both P-LCA and I/O-LCA methodologies, is employed. In this model some of the requirements are assessed by process analysis, while the remaining requirements are covered by input–output analysis. The main disadvantage of these techniques is the risk of double counting.

For the analysis contained in this report a process-LCA approach is adopted, using SimaPro 7.3.2 software modelling tools and the Ecoinvent 2.2 database. Deviations from the Ecoinvent 2.2 database are made in justified cases and are identified throughout the analysis. For simplicity the results are reported for Global Warming Potential (GWP) only. A number of scenario analyses are included and results are reported with potential error bars.

4.3 Boundaries, Scope and Functional Unit

The aim of this study was to define an approach for the fair and “apples for apples” comparison of various window frame materials in terms of their lifecycle environmental impact.

A lifecycle is defined as a period of 60 years for this study. This period of time is in-keeping with other analyses of building components (for example the BRE Green Guide to Specification).

The purpose of the study is to provide a comparison of materials used in contemporary window frames. The purpose is not to define absolute values for the GWP or EC of materials over their lifecycles. The results should be interpreted in terms of their relative magnitude, rather than their absolute value.

The findings of this report are to be used in conjunction with the Service Life Planning (SLP) and Whole Life Cost (WLC) report issued in June 2012, and are intended to provide information to specifiers concerned with selecting windows with a whole life appraisal approach e.g housing associations and clients/owners with a long term investment view.

The LCCA contained here adopts a process-LCA approach which includes the frame materials of the window. The boundary includes all raw material extraction, transportation and processing, manufacturing energy, finishing, site construction, maintenance over 60 years, transportation and End-of-Life (EoL) processes. It excludes the energy and impact of manufacturing the machinery required to make the windows, the glazing unit for the windows, the window ironmongery, and the dynamic differences in thermal performance of the windows (U-value factors).

The study is a Cradle to Grave analysis, although one scenario considers the Cradle to Cradle impacts of processing materials for use as recycled content in future products.

The study also assumes that timber used in windows acts as a carbon store, according to the UK PAS2050 standard [BSI, 2011]. It assumes that all timber is sustainably sourced and managed according to FSC (Forest Stewardship Council) or equivalent specification. The FSC was founded in response to public concern about deforestation and demand for a trustworthy wood-labelling scheme. FSC certification is focused on forest management and a chain of custody.

The functional unit of the study is $kgCO_2e$ per window. The window size is consistent for all options and scenarios in the study: a standard window unit measuring 1230mm wide by 1480mm high.

4.5 Inventory Analysis

A base case scenario was developed to describe as closely as possible the current assumptions, processes, transportation, locations, energy mix, disposal and other prevailing factors. Later in Section 6.0 a number of alternative scenarios are described and assessed.

The basic process, materials, waste, energy, heat and transportation needed over the lifecycle of a basic timber window is described and quantified in Figure 2. Information to populate Figure 2 was taken from a report by Davis Langdon to the Wood Window Alliance [Davis Langdon, 2010] which details quantities of material used, co-products generated, waste streams and energy sources throughout the manufacturing process.

Other data used is taken from the Ecoinvent 2.2 database for all raw materials, transportation, energy consumption, avoided products and processes required.

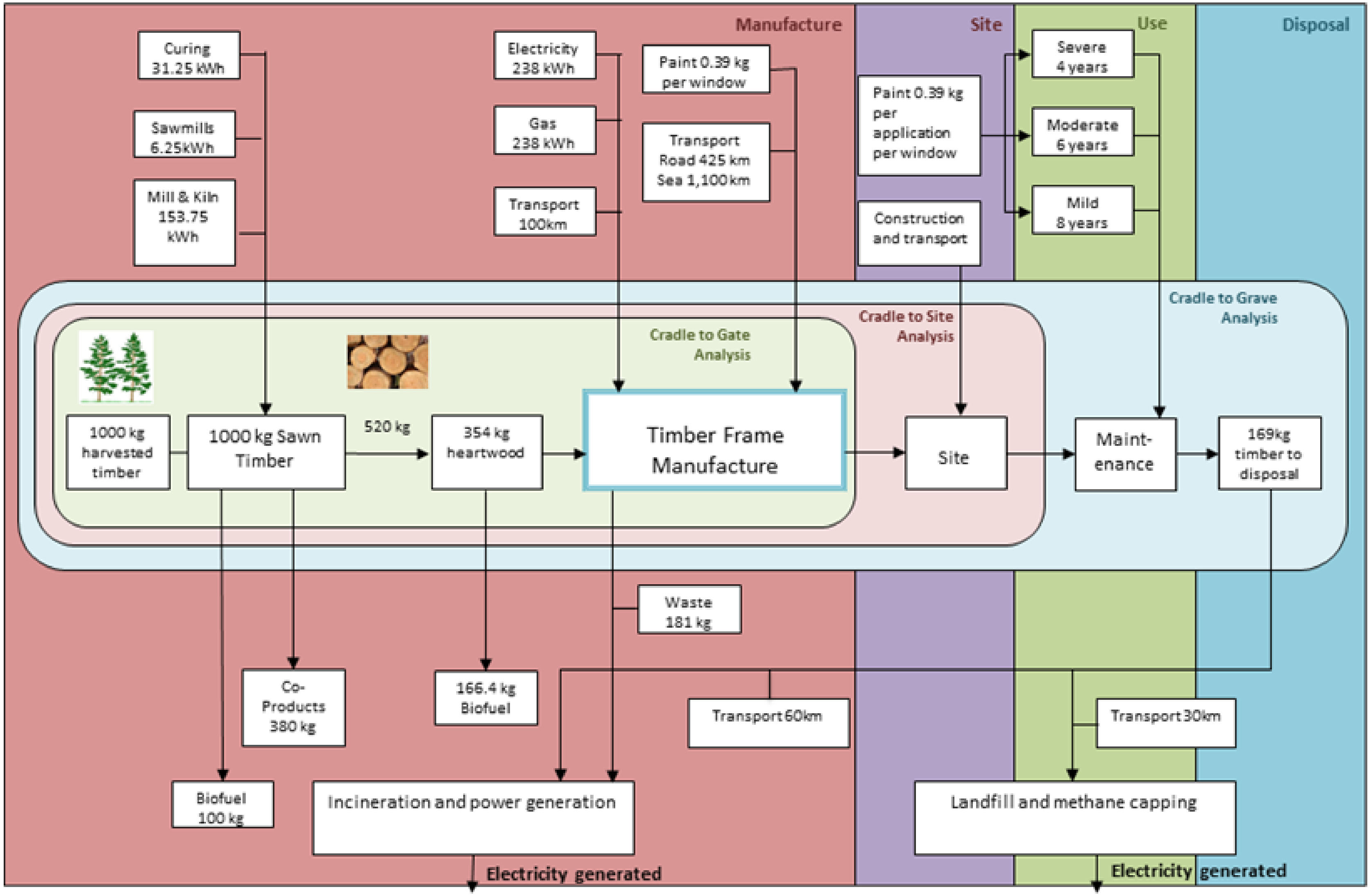


Figure 2: Cradle to Grave Inventory of inputs and outputs for a base case timber window frame (quantities stated are per 12 windows)

Inventory notes for frame materials

For aluminium-clad (Al-clad) timber windows a mass of 5.4kg of aluminium is accounted for, including 5% waste. Over a 60 year lifecycle it is assumed that the aluminium profile is replaced once in mild and moderate exposure scenarios, and twice in a severe exposure scenario. All aluminium is recycled.

For modified timber wood is sourced from the Radiata pine species in New Zealand. The transportation requirement via sea freight is accounted for in addition to the requirements for the wood acetylation process. This requires acetic anhydride as a raw material and produces high performance, durable timber as a product, and acetic acid as a by-product of the acetylation process. The LCA simulation is based on the Halcon process and a new database entry made in SimaPro to provide inventory information using data from Accsys Technologies, and provided by Imperial College London [Hillier & Murphy, 2002]. A major consideration of the Halcon process is the large credit given for the avoided production of acetic acid. An adjustment was also made to the quantity of wood required for the frame manufacture stage. Radiata pine undergoes acetylation in a range of set dimensions. Based on the size of window frame for this study, an inventory of acetylated timber sections was compiled, and the associated quantity of waste calculated.

For timber and modified timber frame options 0.39kg of paint is factory applied to the finished windows. At each maintenance event, based on a mild, moderate or severe exposure scenario a further 0.39kg of paint is applied.

For PVC-U windows a mass of 17.45kg of Polyvinylchloride and 4kg of reinforcing steel is accounted for. PVC-U windows are produced in many locations throughout the UK and EU. With no specific data on transportation from factory to site, this is excluded from the study at present. The mass of PVC-U is based on a 70mm A-rated window. The mass of steel is taken from a BRE client report on Generic Environmental Profiles of Timber Windows, cited in Davis Langdon [2010].

Co-products and biofuel

Co-products of the life cycle (used as skirting boards and architraves) are removed from the system in the same way as cradle to grave elements, assuming no residual EoL value, but also implying no impact on the current lifecycle.

Biofuel in the LCA system refers to offcuts and sawdust which are used to provide heat and/or power within the lifecycle. E.g. biofuel at the sawn timber stage is used to dry timber in the kiln. Biofuel produced while selecting heartwood may be used to heat the factory and offices on the processing site. Other waste can be used for animal bedding or as raw material to the particleboard industry. This type of waste is assumed to have no residual EoL value or impact.

Timber carbon storage and forest stewardship

It is assumed that all timber used in the production of timber and timber based window frames are sustainably sourced. On 3 March 2013, the European Union (EU) Timber Regulation entered into force, making it a crime to introduce illegally harvested timber and products into the EU market. Importing companies are required to have a ***due diligence system*** to avoid this. According to the

British Standard, PAS2050, biogenic carbon storage must be fully accounted up to a period of 100 years. Any emission occurring after 100 years is not considered. In this study, the building life is taken to be 60 years and therefore all carbon sequestered during the growing phase of the trees, and the subsequent known release of this carbon through combustion or rotting in landfill are accounted for. Any carbon stored in wood products which are recycled at EoL remains; no residual value is assumed.

For 1000kg of felled timber, the sequestered carbon dioxide stored is assumed to be 1600kg. The carbon content of dried wood is approximately 50%. Using an assumed 12.5% retained moisture level and 50% of the dry weight as carbon, the carbon in 1000kg of wood weighs 436kg. The molecular mass of carbon is 12, while for oxygen is 16. This means that each kg of carbon in the timber has been drawn from 3.67kgCO_2. For sustainably sourced timber this leads to a carbon store of 436 x -3.67 = -1600kgCO_2. This value has been entered into the SimaPro model in a simulated opening balance manner.

Base Case End of Life Scenario

The base case EoL scenario is based on a recent update publication by WRAP [WRAP 2012]. For timber the baseline recycling rate for construction and demolition in 2008 was 78%. The remaining 22% is divided equally between incineration with electricity production (avoided electricity at UK grid production), and landfill with methane capping and electricity production. By 2015 WRAP makes recommendations under two policy options. The first is a restriction from landfill for different types of waste which would results in 86% of construction and demolition waste being recycled by 2015 and 50% of the remainder diverted to combustion; the second is to place a ban on unsorted waste which would results in 88% of construction and demolition waste being recycled by 2015 and 70% of the remainder diverted to combustion.

Current practice for PVC-U suggests that 12% of windows are crumbed and recycled (re-extruded for possible use in new PVC-U windows), 12% are incinerated, and 76% are landfilled [Davis Langdon, 2010]. According to the Ecoinvent database the degradability of PVC-U in landfill over 100 years is 1%. While the release of carbon and methane is therefore very small, the loss of fossil fuel based materials should be considered. Also, the capacity of landfill sites to “hide” all our refuse is of considerable ongoing concern. Reported by the Environment Agency in Zglobisz et al [2010], the landfill capacity in England and Wales is sufficient only until 2015.

4.6 Impact Assessment

SimaPro 7.3.2 gives a number of environmental impact categories and a full LCA appraisal, as listed in Table 2. Figure 5 shows the full range of impacts associated with each frame material for the base case scenario over a 60 year building life.

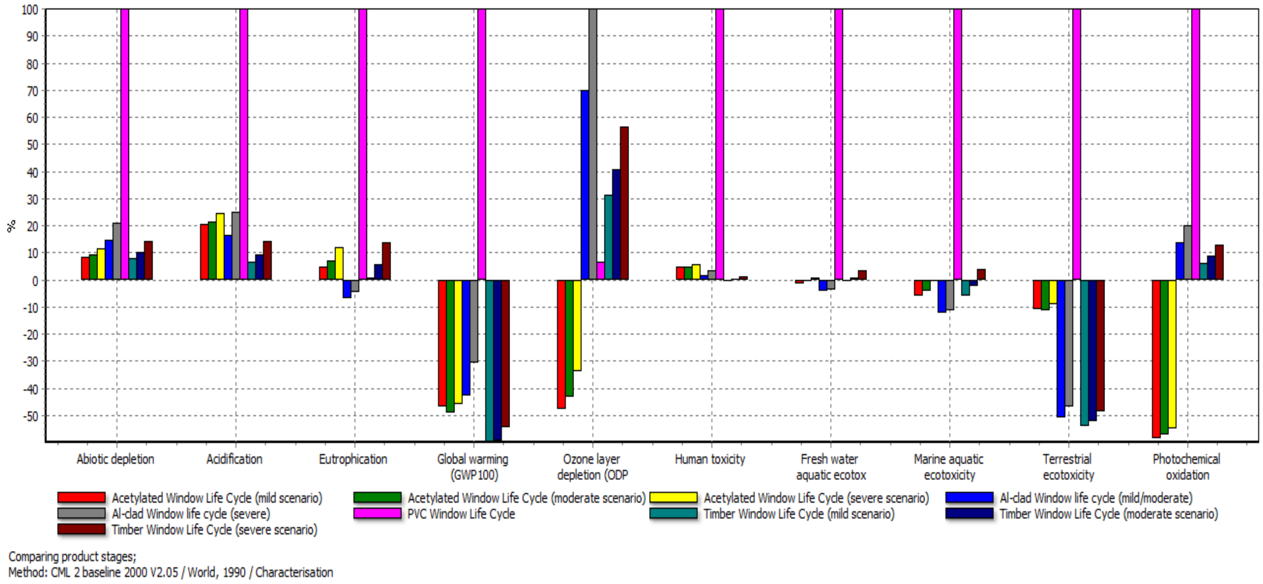


Figure 5. Full LCA results for base case scenario. Note this graph is indexed to 100% and does not show absolute values.

It is clear to see from Figure 5 that in nine of the ten impact factors calculated using SimaPro, PVC-U has a significantly increased impact (100% compared to 25% or less for other window frame options) than timber window frame options. Positive impacts, which are at a significantly lower level than for PVC-U (25% or less), are seen for some impact factors for timber based products. These can be attributed to the paint production process, to the acetylation process for modified timber options, to aluminium production processes, or to energy production processes. Strongly negative impacts are largely attributed to the carbon sequestration effect of growing trees, or where isolated to modified timbers, to the benefit of avoided acetic acid production created as a by-product of the acetylation process.

The exception is noted under the ozone layer depletion metric, where PVC-U has a significantly lower impact (less than 10% of the impact of Al-clad window frames in a severe environment) than both timber products and Al-clad timber products. This difference could be attributed to the paint applied both at the manufacturing stage and throughout the 60 year maintenance period of timber frame windows. The negative impact shown for modified timbers may be an arithmetic summing of the positive impact of paint used, and the negative impact of avoided acetic acid production. The strongly positive impact of Al-clad window options is likely attributed to the production of aluminium; the difference between timber and Al-clad timber frames is the addition of aluminium profiling and a reduced maintenance schedule over 60 years. i.e. less paint is applied, but two sets of aluminium profiles are accounted for.

In order to make a simplified basis for comparison across frame material choices and the various scenarios considered in Section 6.0 a focus is made on the Global Warming Potential (GWP) of each permutation, measured in $KgCO_2e$/window. GWP demonstrates the largest variation between scenarios and window options throughout the study and is selected as the most commonly used LCA/LCCA indicator. A focus on GWP only for the base case reveals the graph shown in Figure 6.

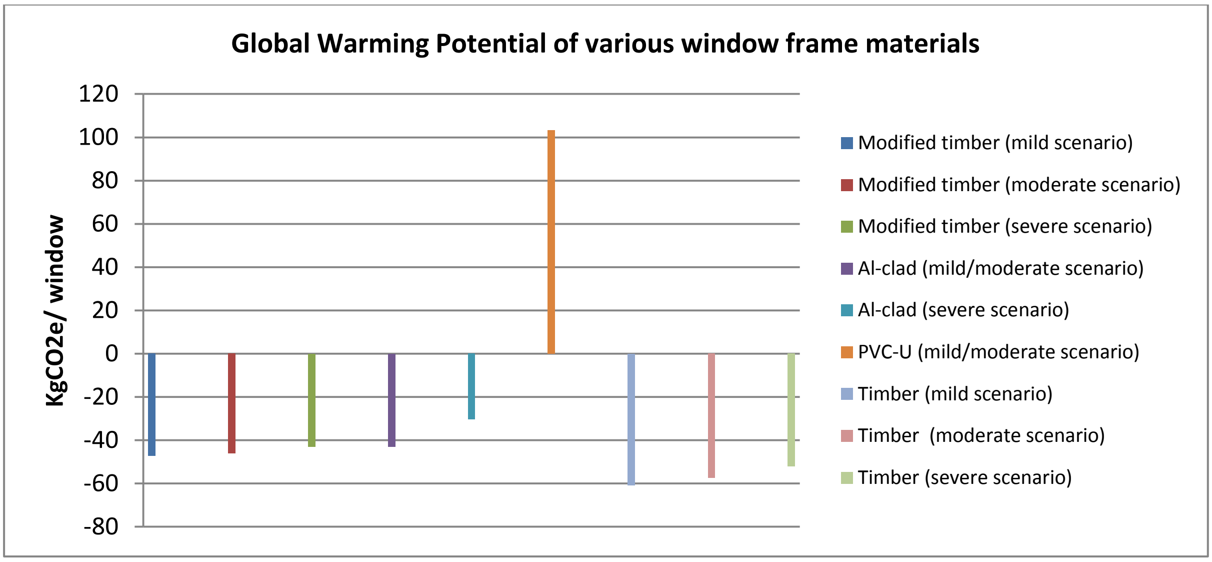


Figure 6: GWP for base case scenario

It is immediately noticeable that all timber based window options have negative values while the PVC-U option has a strongly positive impact. This is due to the carbon storage effect of timber during its growth phase. In the scenario analysis below it is shown how this negative impact is affected positively or negatively in relation to EoL assumptions and treatment, and whether timber is sustainably sourced.

It is also worth noting that Figure 6 represents the impact over a 60 year period. Each of the timber based options has a minimum service life which would service a 60 year building design life. The various exposure scenarios considered demonstrate the application of paint in maintenance events of timber and modified timber, and the replacement of aluminium cladding in Al-clad window frames over 60 years. According to the service life planning part of this study only PVC-U windows would require complete replacement within a 60 year building life. In a mild/moderate exposure scenario there would be one complete window replacement over a 60 year building life, while in a severe exposure scenario there may be two complete window replacements.

It is stressed that rather than focussing on the absolute values of GWP for each frame type and scenario that the results are used comparatively. For the reasons emphasised in the methodology section above it is rare for one LCA study to be directly comparable with another.

4.7 Waste Scenario Analysis and sensitivity

Using the SimaPro model for the base case described above, six scenarios were considered which test the sensitivity of assumptions made about timber sourcing and the end of life treatment of all materials. These scenarios are as follows:

1. Timber is not sustainably sourced and therefore cannot act as a carbon store since no replacement tree is planted when the raw materials are felled.
2. All materials are recycled at EoL on a Cradle to Grave basis, i.e. no residual value is given for materials which will enter a future product lifecycle.

3. All materials are recycled at EoL on a Cradle to Cradle basis, i.e. construction waste can be recycled and used to provide raw materials for re-manufacture of the same product, or new and different products. The benefit of providing reduced impact raw materials to a future lifecycle is counted in this lifecycle as a positive impact. This is outwith the recommendation of ISO 14040 but is included here to investigate if there are any strongly influencing benefits from the onward use of recycled materials.
4. All materials are incinerated at EoL and electricity produced is fully offset against the emissions generated, i.e. electricity is generated as an avoided product. This is an unlikely scenario given the recommendations set out by WRAP [2012], but is investigated to determine any strongly influencing results.
5. The outcomes in Scenario 4 are heavily dependent on the assumptions used to determine the carbon intensity of grid electricity in the UK. The current intensity factor published by Defra is 0.547 KgCo2e/kWh. As we move forward with the UK Government's aims to decarbonise grid electricity, this value is assumed to drop. The benefit to the lifecycle of avoided electricity production through waste incineration is therefore reduced as we progress towards a lower carbon intensity grid. Scenario 5 therefore includes avoided electricity from EoL incineration at 50% of the current grid carbon intensity.
6. Scenario 6 is similar to Scenario 5, but assumes a purely hypothetical analysis of a zero carbon intensity electricity grid in the UK.

Figures 7-12 show the GWP results for each of these six scenarios.

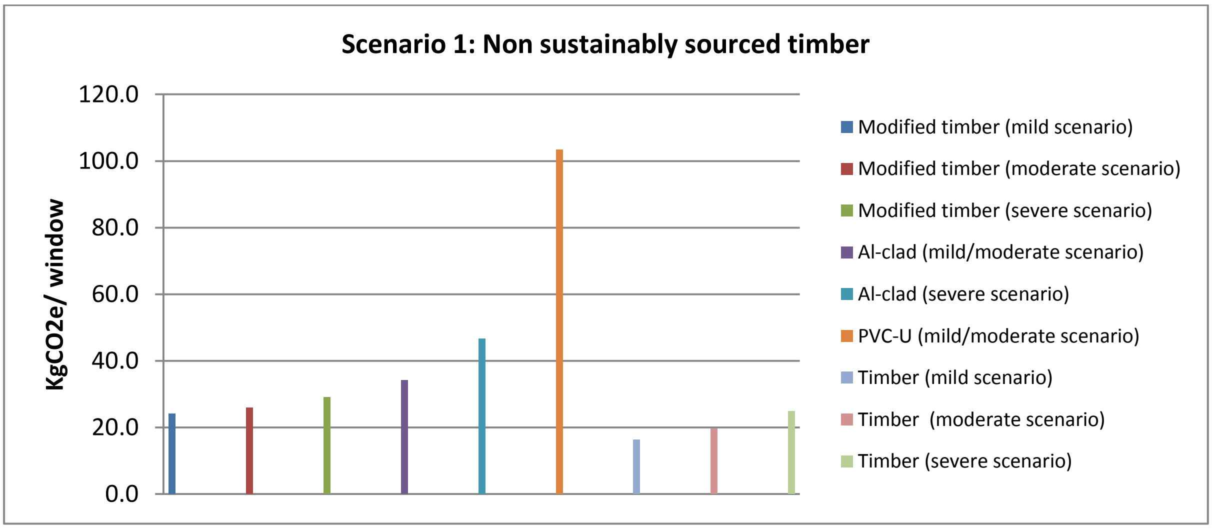


Figure 7: Scenario 1 GWP of unsustainably sourced timber (no carbon sequestered during growth)

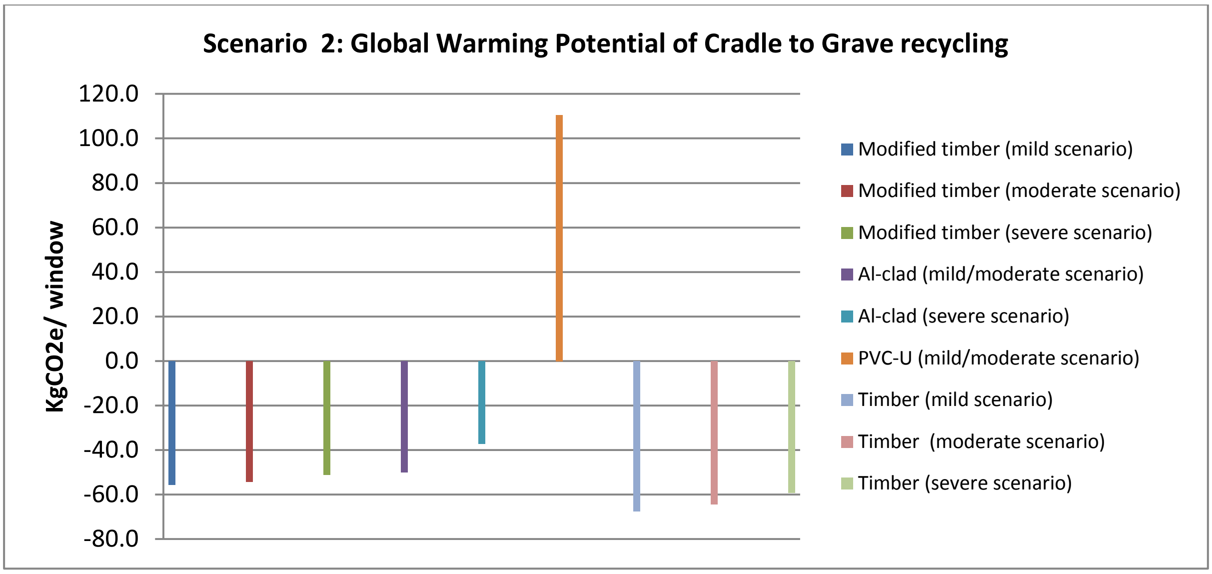


Figure 8: Scenario 2 GWP of Cradle to Grave recycling

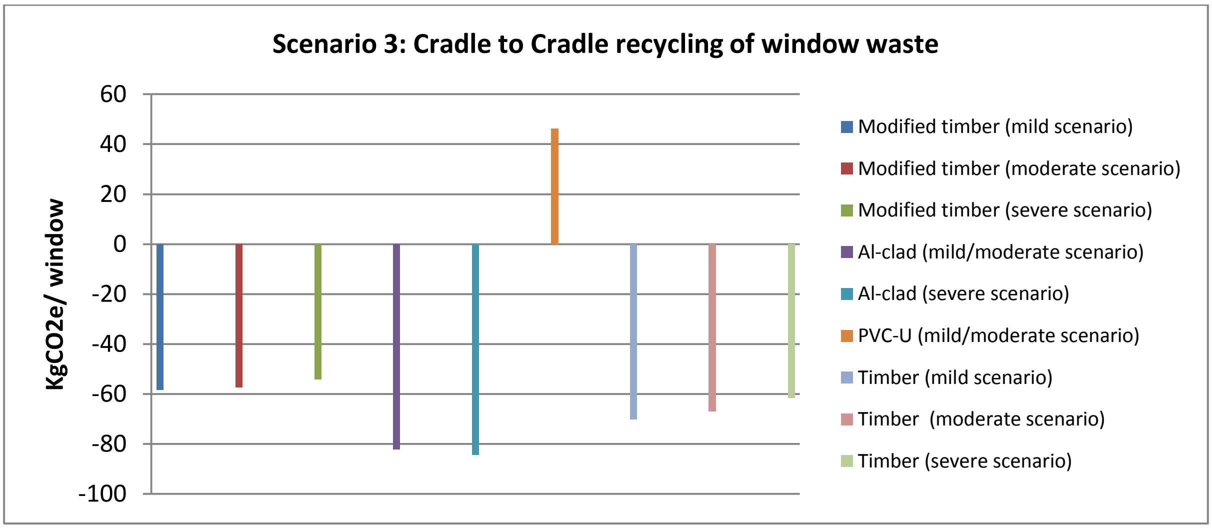


Figure 9: Scenario 3 Cradle to Cradle recycling of waste (includes benefit to next lifecycle)

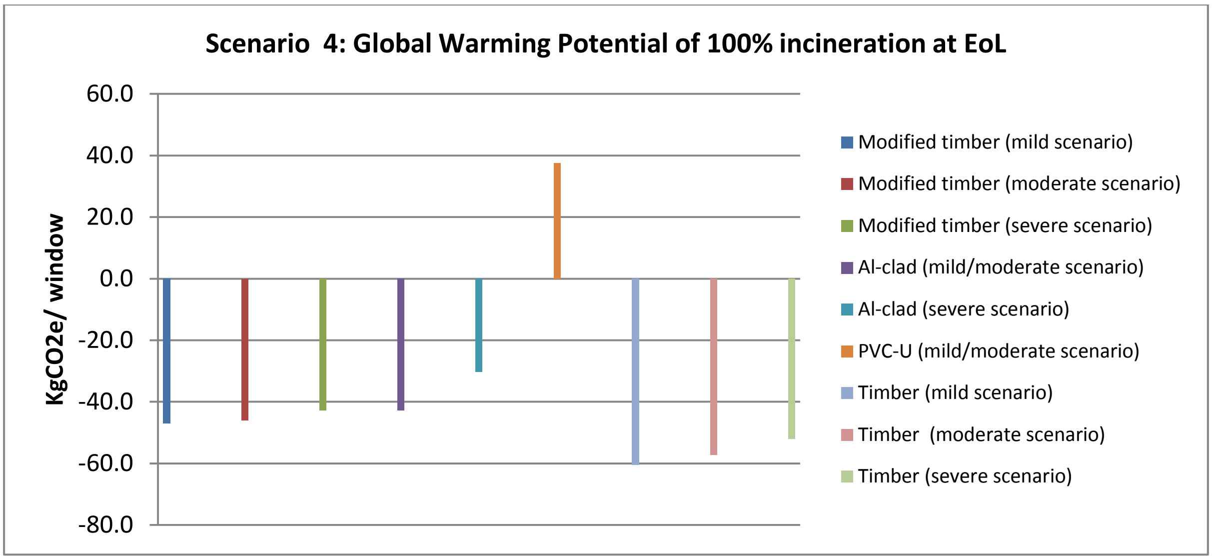


Figure 10: Scenario 4 All materials incinerated at EoL (current UK grid carbon-intensity)

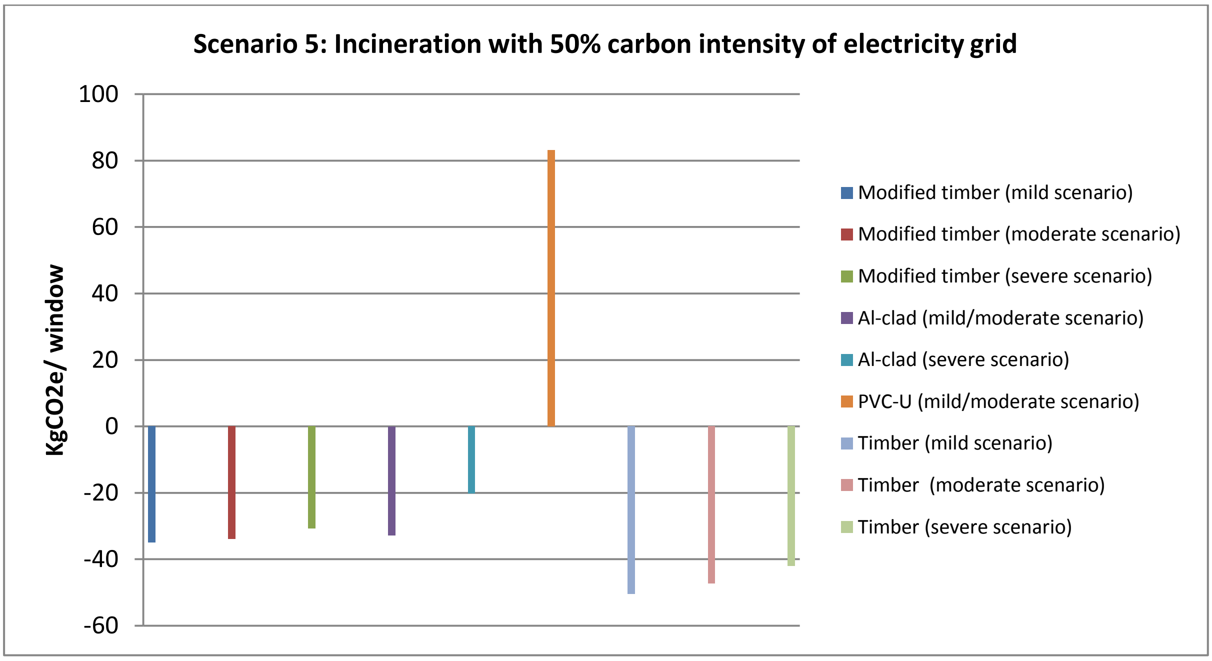


Figure 11: Scenario 5 All materials incinerated at EoL (50% UK grid carbon-intensity)

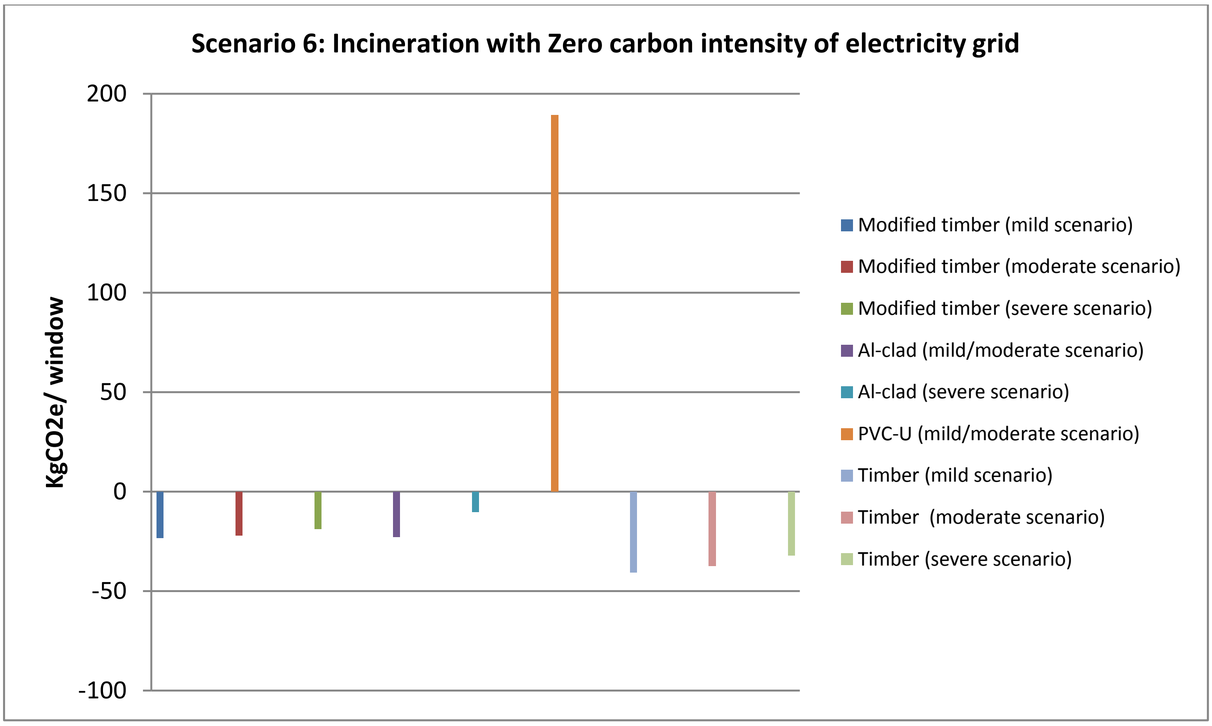


Figure 12: Scenario 6 All materials incinerated at EoL (Zero UK grid carbon-intensity)

Figure 13 attempts to capture these variances in one graph to show the potential shift in GWP results according to these scenario assumptions and investigations. Note that Figure 12 omits the effect of non-sustainably sourced timber (as this is now illegal under EU law), and the scenario for Cradle to Cradle analysis (as this is outwith ISO 14040 guidance).

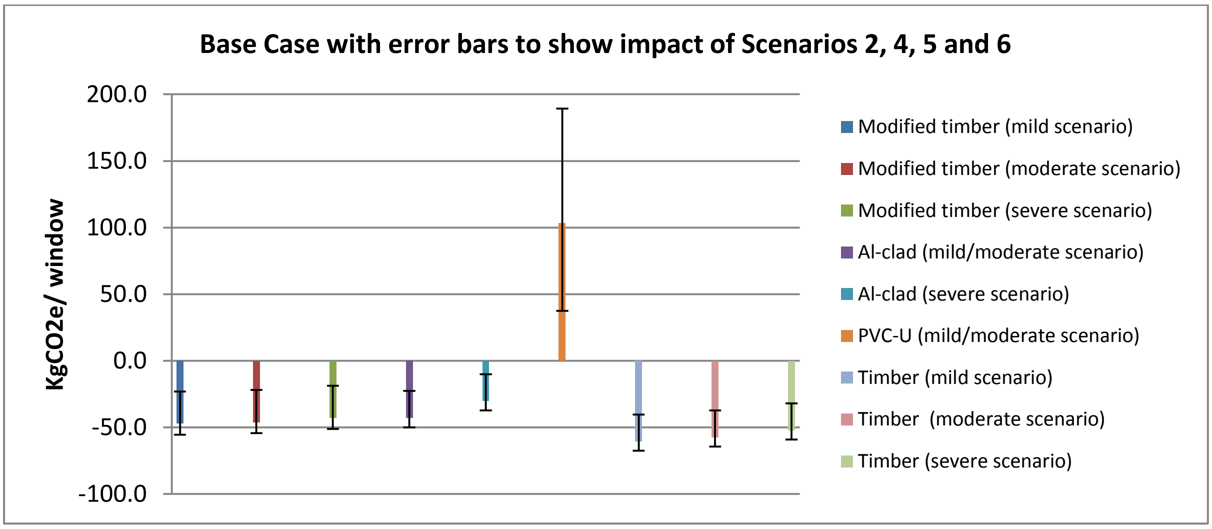


Figure 13: Base Case with error bars to show impact of Scenarios 2 and 4-6

4.8 LCA Discussion and Conclusions

In nine of the ten impact categories considered in this LCA report, timber based window frame options have a lower impact than PVC-U window frames. Where PVC-U is indexed to 100, the comparative impacts of timber frame options are 25% or less. The exception to this is noted under ozone layer depletion where PVC-U is less than 10% of Al-clad timber options.

Seven main discussions result from a scenario analysis which followed the full LCA results of a base case. These include the following issues and were performed to test the impact of EoL treatments on the overall GWP results:

- Sustainable sourcing of timber
- Recycling of materials
- End of life treatment
- Boundary inclusion
- Reducing intensity of grid electricity
- Service life impact
- Comparison of timber frame options

Sustainable sourcing of materials

The impact on the GWP of all timber based window frames which are sustainably sourced is clearly evident. The only scenario for which the GWP is positive for timber based options is seen when no carbon sequestration can be accounted for in the growing phase of the trees. New EU regulations from March 2013 ensure the legal obligation of timber users to source raw materials responsibly and ethically. This scenario is therefore purely hypothetical, but shows the sensitivity of the study to PAS2050 guidelines. The topic of carbon sequestration and its accounting is a subject of strong debate amongst researchers [Ostle et al, 2009]. This study highlights the importance of getting this right.

Recycling of materials

The optimum scenario for EoL treatment for timber products is shown to be recycling, with the largest negative GWP values seen in Scenarios 2 and 3. This is because the carbon remains stored in the timber and is not released through incineration or landfill decay.

In Scenario 2 (Cradle to Grave recycling) no significant benefit is seen for PVC-U windows over the base case scenario (largely landfill for PVC-U). This is because SimaPro deals with these processes in essentially the same way. Cradle to Grave analysis assumes no EoL residual value for PVC-U, while landfill assumes minimal biodegrading of PVC-U in landfill. Clearly it would be better to recycle PVC-U windows than landfill them, but as the lifecycle for the window has ended under Cradle to Grave analysis, this cannot be accounted in this lifecycle.

Scenario 3 (Cradle to Cradle recycling) is very different. The positive benefit to timber and PVC-U disposal is clearly evident with the best GWP values for all windows. This is a question of LCA boundary setting which must be consistent within a comparative LCA study. It is still seen, however, that timber based window frames perform better in GWP terms than PVC-U even when Cradle to Cradle boundaries are set.

End of Life Treatment

Clearly the EoL assumptions made are critical to the outcome of the study. Perhaps the best, and fairest, comparison which can be made at present is based on current EoL treatments for the various frame materials. In all scenarios, in terms of GWP, timber based window frames outperform PVC-U alternatives.

It is also seen that the optimum EoL treatment for timber is to recycle it. Initiatives like WRAP should therefore press on with their aims to improve recycling rates of timber, ensure waste segregation and continue steps to reduce landfilling of timber.

Boundary inclusion

LCA boundary inclusion/exclusion is well known to have significant impact on LCA results. This is particularly true when using a Process-LCA methodology, as in this report. The important factor is to ensure that boundaries are consistent within a comparative LCA. Treatment of avoided products and positive accounting of by-products can have significant effects on the overall results.

Reducing Intensity of Grid Electricity

Any analysis based on the “payback” of energy generated or carbon emitted either as a part of the use phase of a product (e.g. the installation of loft insulation or the manufacture of renewable technologies like photovoltaic panels) are sensitive to the long-term intensity of electricity supplies. Defra/Decc [2012] applies a five year rolling average of grid carbon dioxide equivalent intensity. The current value of 0.589 $kgCO_2e/kWh$ has dropped from 0.884 $kgCO_2e/kWh$ in 1990 due to efficiency of production and transmission, and use of alternative fuels. As part of the UK renewable energy strategy the CO_2 intensity of future electricity supplies should reflect a continuing downward trend.

It is seen in this study that if we were to achieve a hypothetical zero carbon grid intensity that all timber frame options would still be GWP negative. However it is noted that the UK is very unlikely to move towards a policy of wide scale incineration of wood waste.

Service Life Impact

The results of this LCA report are to be read in conjunction with the earlier work on Service Life Planning and Whole Life Costing. It was shown that PVC-U windows, even in a mild exposure scenario are unlikely to be serviceable beyond 35 years. This means that for a 60 year building life the GWP for the PVC-U scenarios considered above should be doubled. This further emphasises the environmental impact of fossil fuel based raw materials in construction.

Comparison of timber frame options

Removing PVC-U from the base case scenario reveals the results shown in Figure 13.

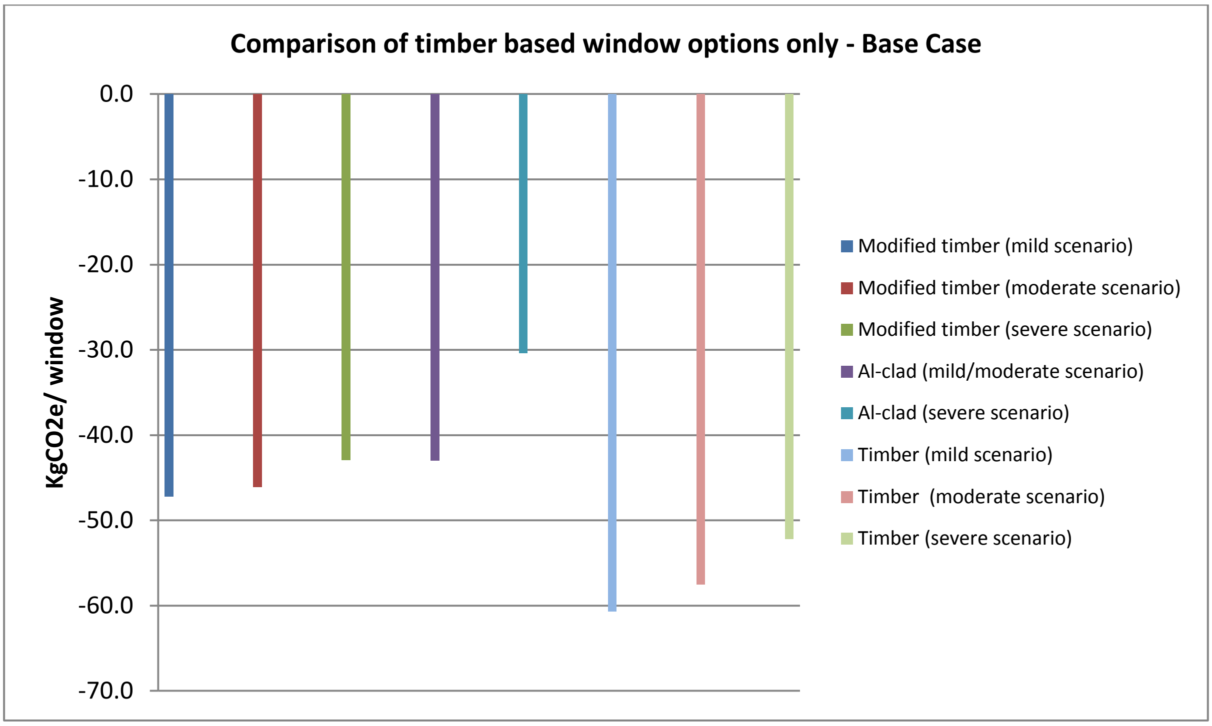


Figure 13: Base Case - comparison of timber based window options only

It can be seen that basic timber windows offer improved GWP values over 60 years for all exposure scenarios. Modified timber options for all exposure scenarios and Al-clad timber windows used in mild or moderate exposure scenarios are roughly equivalent. Al-clad timber windows used in severe exposure locations may have a higher GWP than alternatives, but this outcome is largely based on the assumption that the aluminium cladding will require replacement after 20 years of in-situ use. It is argued that the performance of the aluminium will not have been altered detrimentally after this time, but that replacement is deemed necessary for aesthetic reasons, i.e. perceived obsolescence.

5.0 Summary of Conclusions

This report considers the Service Life Planning (SLP), Whole Life Cost (WLC) and Life Cycle Assessment (LCA) of four window frame materials: timber, modified timber, aluminium-clad timber and PVC-U, under three exposure scenarios: mild, moderate and severe.

Applying a factor analysis, as set out in ISO 15686:8, predicts an expected service life for timber windows of between 56 and 65 years; for modified timber windows between 68 and 80 years; and for aluminium-clad timber windows 71 and 83 years. These are set against a base case for PVC-U of between 25 and 35 years.

Using NPV analysis it is shown that for mild exposures, timber windows offer the lowest lifetime cost option. For moderate and severe exposures the more durable modified timber and aluminium-clad windows gave more favourable lifetime cost outcomes. In all exposure conditions over 60 years, PVC-U window frames were shown to have the highest whole life cost.

In nine of the ten impact categories considered in this LCA report, timber based window frame options have a lower impact than PVC-U window frames. Where PVC-U is indexed to 100, the comparative impacts of timber frame options are 25% or less. The exception to this is noted under ozone layer depletion where PVC-U is less than 10% of Al-clad timber options. Sourcing of timber and end-of-life treatments were the most influential and critical factors in this LCA study, along with the drawing of study boundaries. Recycling at end-of-life offers the most environmentally sensitive solution and supports the aims of WRAP in pursuing greater waste segregation, and possible tighter restrictions on timber waste entering landfill sites.

6.0 References

1. Alcorn A. and Wood P., New Zealand Building Materials Embodied Energy Coefficients Database Volume II – Coefficients. Centre for Building Performance Research, Victoria University of Wellington, 1998
2. Asif (2005) Life Cycle Assessment of aluminium-clad timber windows, PhD thesis, Napier University, 2002
3. BRE Green Guide to Specification 4th Edition, Jane Anderson, David Shiers and Kristian Steele, ISBN 978-1-84806-071-5, 2009.
4. BSI 2011 PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services, British Standards Institute, 2011.
5. Buchanan, A.H. and Honey, B.G., Energy and carbon dioxide implications of building construction. Journal of Energy and Buildings, 1994, 20, 3, 205-217
6. Citherlet, S., Guglielmo, F. and Gay, J B, Window and Advanced Glazing Systems Life Cycle Assessment, Energy and Buildings, 32, pp 225-234, 2000
7. Consoli F, Allen D, Bousted I, Fava J, Franklin W, Jensen A, Oude A, Parrish R, Perriman R, Postlethwaite D, Quay B, Seguin J and Vigon, B (1993) Guide lines for life-cycle assessment: a 'code of practice', SETAC
8. Davey, A. Inform: Information for historic building owners, Technical Conservation, Research and Education Group, Historic Scotland, 2007
9. Davis Langdon, Comparison of environmental impact (CO_2e) of timber and PVC-U windows, 2010.
10. Defra/DECC (2012) Guidelines to Defra DECC's GHG Conversion Factors for Company Reporting, available at http://www.defra.gov.uk/publications/files/pb13773-ghg-conversion-factors-2012.pdf accessed on 21 March 2013.
11. HAPM, Housing Association Properly Manual, London, 1996.
12. ICE, 2011 Embodied Carbon - the Inventory of Carbon and Energy (ICE) (BG 10/2011), BSRIA
13. ISO 14040 Environmental management Life cycle assessment Principles and framework: International Organisation for Standardisation, Geneva, Switzerland, 1996
14. ISO 15686:8 Buildings and constructed assets -- Service-life planning -- Part 8: Reference service life and service-life estimation, 2008.
15. Lenzen, M. and Treloar G. Endogenising capital: a comparison of two methods. *Journal of* Applied Input-Output Analysis, 2005, 10, 1-11
16. Ostle NJ, Levy PE, Evans CD and Smith P (2009) UK land use and soil carbon sequestration, Land Use Policy 26 (1) S274-S283.
17. Selmes, D. G. (2005) Towards sustainability: direction for life cycle assessment, Edinburgh, Heriot Watt University, PhD thesis
18. SimaPro LCA software, Pre Consultants, Netherlands, http://www.pre.nl/simapro
19. Smith P. F., Architecture in a climate of change: a guide to sustainable design. Architectural Press, Oxford; Boston, 2005

20. Sonnemann G., Castells F. and Schuhmacher M. (2003) Integrated life-cycle and risk assessment for industrial processes, CRC Press
21. WCC, Comparative Assessment of Window Types, Worcester City Council, 1990
22. Wood C, Bordass W, Baker P, Research into the thermal performance of windows: timber sash windows, English Heritage Research Report, June 2009
23. WRAP 2012 Landfill restriction feasibility research: wood update August 2012, Waste and Resources Action Programme, available at http://www.wrap.org.uk/sites/files/wrap/Landfill%20restriction%20-%20Wood%20Waste%20update.pdf accessed on 21 March 2013.
24. Zglobisz, N,Castillo-Castillo A, Grimes S, Jones P (2010) Influence of UK energy policy on the deployment of anaerobic digestion, Energy Policy, 38 (10).

Appendix 2.1 Service Level Factors

			Factors and Factor categories					
			A	**B**	**C**	**E**	**G**	**Baseline**
WWA Specified Timber Window Frames			**Inherent Performance Level**	**Design Level**	**Work execution level**	**Outdoor environment**	**Maintenance level**	**Expected Service Life (Years)**
Individual Factors and Cumulative* factor effects		Original service life assumption	Modified materials	Design Improvement	Standards and Controls	Exposure external	Cycle frequency	Modified service life
BRE		**35**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**35**
High Quailty softwood BS EN 942 - assumed to be 'normal'	A		1.00	1.00	1.00	1.00	1.00	35
Enhanced substrate (defect free etc)	A		1.03	1.00	1.00	1.00	1.00	36
Endgrain sealing	A		1.03	1.00	1.00	1.00	1.00	36
Construction joint sealing	A		1.03	1.00	1.00	1.00	1.00	36
Preservative treatment BS EN 599 / BS 8417	A		1.04	1.00	1.00	1.00	1.00	36
Modified bottom beads BS EN 644	A		1.03	1.00	1.00	1.00	1.00	36
Sub-total Materials	A		***1.15***	***1.00***	***1.00***	***1.00***	***1.00***	***40***
Cill extension < 70mm	B		1.00	1.05	1.00	1.00	1.00	37
Min 7° angle on horizontal surfaces	B		1.00	1.05	1.00	1.00	1.00	37
rounded arrisses: min 3mm round	B		1.00	1.05	1.00	1.00	1.00	37
installed in recess	B		1.00	1.07	1.00	1.00	1.00	37
Sub-total Design	B		***1.00***	***1.22***	***1.00***	***1.00***	***1.00***	***43***
Factory glazed BS 8000	C		1.00	1.00	1.03	1.00	1.00	36
Factory coated: min 120µ dft BS EN 927	C		1.00	1.00	1.03	1.00	1.00	36
Quality Standard: ISO 9001 or equivalent	C		1.00	1.00	1.03	1.00	1.00	36
Sub-total Work execution	C		***1.00***	***1.00***	***1.10***	***1.00***	***1.00***	***38***
Sheltered	E		1.00	1.00	1.00	1.05	1.00	37
Exposed	E		1.00	1.00	1.00	0.95	1.00	33
Severe	E		1.00	1.00	1.00	0.90	1.00	32
Annual wipe-down/wash	G		1.00	1.00	1.00	1.00	1.05	37
Follow manufacturers recommendation, redecorate 5 to 7 yrs = Expected	G		1.00	1.00	1.00	1.00	1.10	39
Sub-total Manufacturer Expected Maintenance	G		***1.00***	***1.00***	***1.00***	***1.00***	***1.15***	***40***
All factors under WWA control CUMULATIVE	AM	Mild	***1.15***	***1.22***	***1.10***	***1.05***	***1.15***	***65***
All factors under WWA control CUMULATIVE	AM	Moderate	***1.15***	***1.22***	***1.10***	***0.95***	***1.15***	***59***
All factors under WWA control CUMULATIVE	AM	Severe	***1.15***	***1.22***	***1.10***	***0.90***	***1.15***	***56***

			Factors and Factor categories					
			A	**B**	**C**	**E**	**G**	**Baseline**
Modified Timber Window Frames			**Inherent Performance Level**	**Design Level**	**Work execution level**	**Outdoor environment**	**Maintenance level**	**Expected Service Life (Years)**
Individual Factors and Cumulative* factor effects		Original service life assumption	Modified materials	Design Improvement	Standards and Controls	Exposure external	Cycle frequency	Modified service life
BRE		**35**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**35**
Laminated acetylated timber	A		1.30	1.00	1.00	1.00	1.00	46
Enhanced substrate (defect free etc)	A		1.03	1.00	1.00	1.00	1.00	36
Endgrain sealing	A		1.03	1.00	1.00	1.00	1.00	36
Construction joint sealing	A		1.03	1.00	1.00	1.00	1.00	36
Preservative treatment BS EN 599 / BS 8417	A		1.00	1.00	1.00	1.00	1.00	35
Modified bottom beads BS EN 644	A		1.03	1.00	1.00	1.00	1.00	36
Sub-total Materials	A		***1.41***	***1.00***	***1.00***	***1.00***	***1.00***	***49***
Cill extension < 70mm	B		1.00	1.05	1.00	1.00	1.00	37
Min 7° angle on horizontal surfaces	B		1.00	1.05	1.00	1.00	1.00	37
rounded arrisses: min 3mm round	B		1.00	1.05	1.00	1.00	1.00	37
installed in recess	B		1.00	1.07	1.00	1.00	1.00	37
Sub-total Design	B		***1.00***	***1.22***	***1.00***	***1.00***	***1.00***	***43***
Factory glazed BS 8000	C		1.00	1.00	1.03	1.00	1.00	36
Factory coated: min 120µ dft BS EN 927	C		1.00	1.00	1.03	1.00	1.00	36
Quality Standard: ISO 9001 or equivalent	C		1.00	1.00	1.03	1.00	1.00	36
Sub-total Work execution	C		***1.00***	***1.00***	***1.10***	***1.00***	***1.00***	***38***
Sheltered	E		1.00	1.00	1.00	1.05	1.00	37
Exposed	E		1.00	1.00	1.00	0.95	1.00	33
Severe	E		1.00	1.00	1.00	0.90	1.00	32
Annual wipe-down/wash	G		1.00	1.00	1.00	1.00	1.05	37
Follow manufacturers recommendation, redecorate 10 to 12 yrs = Expected	G		1.00	1.00	1.00	1.00	1.10	39
Sub-total Manufacturer Expected Maintenance	G		***1.00***	***1.00***	***1.00***	***1.00***	***1.15***	***40***
All factors under WWA control CUMULATIVE	**AM**	Mild	***1.41***	***1.22***	***1.10***	***1.05***	***1.15***	***80***
All factors under WWA control CUMULATIVE	**AM**	Moderate	***1.41***	***1.22***	***1.10***	***0.95***	***1.15***	***72***
All factors under WWA control CUMULATIVE	**AM**	Severe	***1.41***	***1.22***	***1.10***	***0.90***	***1.15***	***68***

			Factors and Factor categories					
			A	B	C	E	G	Baseline
Al-Clad Timber Window Frames			Inherent Performance Level	Design Level	Work execution level	Outdoor environment	Maintenance level	Expected Service Life (Years)
Individual Factors and Cumulative* factor effects		Original service life assumption	Modified materials	Design Improvement	Standards and Controls	Exposure external	Cycle frequency	Modified service life
BRE		35	1.00	1.00	1.00	1.00	1.00	35
High Quailty softwood BS EN 942 - assumed to be 'normal'	A		1.00	1.00	1.00	1.00	1.00	35
Aluminium material EN AW-6063, EN AW-6060 or simular	A		1.05	1.00	1.00	1.00	1.00	37
Meets performance Class C3(DS 418): external	A		1.25	1.00	1.00	1.00	1.00	
Meets performance Class C2(DS 419): internal	A		1.05	1.00	1.00	1.00	1.00	37
Heat treated aluminium to T5 or better	A		1.03	1.00	1.00	1.00	1.00	36
Pre-treatment of aluminium to meet GSB AL 631	A		1.03	1.00	1.00	1.00	1.00	36
Anodizing treatment to DS/EN 12373-1	A		1.03	1.00	1.00	1.00	1.00	36
Sub-total Materials	A		***1.43***	***1.00***	***1.00***	***1.00***	***1.00***	***50***
Cill extension < 70mm	B		1.00	1.05	1.00	1.00	1.00	37
Min 7° angle on horizontal surfaces	B		1.00	1.05	1.00	1.00	1.00	37
rounded arrisses: min 3mm round	B		1.00	1.03	1.00	1.00	1.00	36
Min Al thickness of 1.8mm where loadbearing hardware fitted	B		1.00	1.03	1.00	1.00	1.00	36
installed in recess	B		1.00	1.07	1.00	1.00	1.00	37
Sub-total Design	B		***1.00***	***1.23***	***1.00***	***1.00***	***1.00***	***43***
Factory glazed BS 8000	C		1.00	1.00	1.03	1.00	1.00	36
Aluminium coating to meet (Powder) 100-120µm	C		1.00	1.00	1.05	1.00	1.00	37
Quality Standard: ISO 9001 or equivalent	C		1.00	1.00	1.03	1.00	1.00	36
Sub-total Work execution	C		***1.00***	***1.00***	***1.12***	***1.00***	***1.00***	***39***
Sheltered	E		1.00	1.00	1.00	1.05	1.00	37
Exposed	E		1.00	1.00	1.00	0.95	1.00	33
Severe	E		1.00	1.00	1.00	0.90	1.00	32
Annual wipe-down/wash	G		1.00	1.00	1.00	1.00	1.05	37
Follow manufacturers recommendation, refurbish 20 to 30 yrs = Expected	G		1.00	1.00	1.00	1.00	1.10	39
Sub-total Manufacturer Expected Maintenance	G		***1.00***	***1.00***	***1.00***	***1.00***	***1.15***	***40***
All factors under WWA control CUMULATIVE	**AM**	Mild	***1.43***	***1.23***	***1.12***	***1.05***	***1.15***	***83***
All factors under WWA control CUMULATIVE	**AM**	Moderate	***1.43***	***1.23***	***1.12***	***0.95***	***1.15***	***75***
All factors under WWA control CUMULATIVE	**AM**	Severe	***1.43***	***1.23***	***1.12***	***0.90***	***1.15***	***71***