

Life Cycle Assessment of Residential Windows: Saving Energy with Window Restoration

Katherine M. Switala-Elmhurst, Ph.D. Candidate, LEED AP and
Philip D. Udo-Inyang, Ph.D., PE
Temple University
Philadelphia, PA

New windows are rated based on their energy performance during the use phase and neglect the overall environmental impacts caused by manufacturing, maintenance and disposal. Due to the number of residential window replacements occurring today in the U.S., there is a growing need to quantify the sustainability of window preservation as an alternative to window replacement. This study assesses the environmental impact of wood window restoration versus replacement with the polyvinyl chloride (PVC) window and aluminum-clad wood window for the entire "cradle to grave" life cycle of the window assembly. A life cycle assessment (LCA) was conducted to evaluate the environmental impacts of historic wood window restoration versus window replacement. The life cycles were modeled using GaBi software with the construction extension database. Inventories were analyzed using TRACI 2.1 which translates the environmental consequences of the LCA processes into quantifiable environmental impacts. The results indicate that wood window restoration has less overall environmental impact when compared to a PVC and aluminum-clad wood replacement window. The sensitivity analysis revealed that window lifespan assumptions impact results and demonstrates the importance of proper wood window maintenance.

Key Words: Life Cycle Assessment, Wood Windows, Window Restoration, Residential Windows, Energy Efficiency

Introduction

Before the birth of modern technology, such as electric lighting and mechanical systems, buildings were designed to utilize natural systems, which made them inherently sustainable. A shift in building design started with the industrial revolution when new technologies began to be incorporated into buildings, and design came to rely more on energy dependent systems and less on natural systems. While some of the most unsustainable buildings were constructed during the latter half of the twentieth century, the practice of sustainable building design also reemerged.

Sustainable buildings, also known as green buildings, are designed to be more energy efficient than conventional buildings by incorporating sustainable materials and technology into their design. Existing historic buildings are often thought of as inefficient and less attention is given to their crucial role in conserving precious natural resources. According to the National Trust for Historic Preservation, building reuse can preserve embodied energy, avoid the environmental impact of new construction, reduce the use of new materials, and reduce greenhouse gas emissions. Studies have proven the value of building preservation and reuse by looking beyond the environmental impact of a building's use phase and examining the entire life cycle of buildings from raw material extraction to disposal. One recent study conducted by the Preservation Green Lab in 2011 found "that it takes 10 to 80 years for a new building that is 30 percent more efficient than an average-performing existing building to overcome, through efficient operations, the negative climate change impacts related to the construction process" (NTHP, 2011, p. 75). Applying a life cycle methodology to a building element, such as a window, could also show environmental benefits of preservation when compared to replacement. While only a few life cycle assessments have been conducted for new window assemblies, a life cycle assessment comparing the environmental footprint of window restoration versus window replacement has not been completed.

Life Cycle Assessment

According to International Organization for Standardization (ISO) 14040, a Life Cycle Assessment (LCA) is the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006, p. 2). The life cycle of a window includes: raw material extraction → manufacture of raw materials → distribution of materials between extraction and assembly → assembly of materials into windows → utilization and maintenance of windows → window disposal. A LCA consist of four stages (ISO, 2006):

1. Goal and scope definition: defines the system boundary and a functional unit.
2. Inventory analysis: the collection of data as defined by the study goals.
3. Impact assessment: translates environmental consequences into quantifiable environmental impacts.
4. Interpretation of the life cycle impact assessment.

Windows, Sustainability and Thermal Performance

Windows allow the interior building environment to connect with the exterior environment: they let light in and allow people to see out. They can also visually enhance building architecture. Retaining original windows in a historic building can be essential in maintaining building integrity and character.

Replacement windows have become a popular trend in the U.S. residential market. Polyvinyl chloride (PVC) windows accounted for 58% of residential replacement window sales in 2005 (Salazar & Sowlati, 2008) and 70% of residential replacement sales in 2010 (AAMA/WDMA, 2011). There is some perception that old windows are less energy efficient than new window replacements. It may be tempting for homeowners to replace old, leaky windows with low cost PVC or higher-end, aluminum-clad windows, even though replacement windows might not be the best all-around sustainable option. Property owners can be misinformed by the notion that replacing old windows will save them energy when often the payback period does not warrant replacement (Sedovic & Gotthelf, 2005).

Windows are affected by exterior and interior temperature, sunlight, wind and occupant use, and according to the U.S. Department of Energy, account for 10% to 25% of heating loss in an average home. The heat loss in windows is measured both by air infiltration around the frame and sash, and by thermal transmission (the rate of heat transfer). Energy flows through a window are a function of the following:

- U-value (Btu/hr-ft^2-°F): the measurement of the heat flow through the window which is dependent on the thermal properties of the window assembly and weather conditions. U-values typically range between 0.20 and 1.20 and a smaller value indicates a lower heat flow (better thermal performance).
- Solar Heat Gain Coefficient (SHGC): the fraction of solar radiation through a window. SHGC values range between 0 and 1 and a smaller value indicates less solar heat gain.
- Infiltration or air leakage (cfm/ft^2): the rate of air movement through a window assembly. Air leakage values typically range between 0.1 and 0.3 and the lower the value, the tighter the window.

Although replacement windows claim to be more energy efficient through lower U-values, studies (summarized later in this paper) have shown that window restoration and upgrades can achieve an energy performance indistinguishable from replacement windows.

Purpose of the Study

New windows are rated based on their energy performance during the use phase only and neglect the environmental impacts caused by the manufacture, maintenance and disposal of window assemblies. To date, there have only been a handful of comprehensive LCAs conducted on new windows; however, a LCA has not been performed to evaluate the environmental impact of preserving existing windows versus replacing existing windows. Due to the number of residential window replacements occurring today in the U.S., there is a growing need to quantify the sustainability of window preservation. This study assesses the environmental impact of historic wood window restoration versus replacement with the popular polyvinyl chloride (PVC) window and aluminum-clad wood window. The study evaluates a double-hung window, which is commonly found in the U.S. residential market, using four window configurations as follows:

1. Restored single-glazed, wood window with an existing aluminum exterior storm window.
2. Restored single-glazed, wood window with a new aluminum exterior storm window.
3. New double-glazed, PVC replacement window.

4. New double-glazed, aluminum-clad wood replacement window.

Literature Review

The life cycle assessment in this study excludes heat loss through the different window assemblies during the use phase. This assumption is backed by research that has shown that existing historic windows can be made to be as efficient as new windows through restoration and thermal upgrades. One recent study, conducted on an 108 year old home in Boulder, Colorado, concluded that it is possible to significantly improve energy performance by a factor of four through window restoration and the installation of a high performance storm window. The study conducted empirical and laboratory testing to evaluate different window and storm window configurations and their thermal performance. The original windows consisted of wood double-hung sash fitted with aluminum storm windows. Partial results of the U-value testing from the Colorado study are shown in Table 1 (Center for ReSource Conservation, 2011).

Table 1

Measurements of U-values from Boulder, CO Study

Description	**U-value**
Original double-hung window + original storm window	0.76
Restored double-hung window + new single-glazed storm window	0.40
New vinyl (PVC) window	0.45

Another recent study, conducted by the Preservation Green Lab, looked at the energy savings from retrofitting existing windows by analyzing a prototype house across five different climate zones (NTHP, 2012). One key finding from this study concluded that window retrofits, such as the addition of an exterior storm and weatherstripping, can increase thermal performance and make them comparable to new replacement windows.

These two recent studies confirm the results of an earlier study conducted in 1996 in Vermont (James, Flanders, Hemenway, & Shapiro, 1996). During this study, field testing was conducted on 151 windows to determine their infiltrative thermal losses. The results indicated that tightening the window can be a cost-effective measure for thermal enhancement and that the addition of a second glazing system, such as a storm window, can improve thermal performance of single-glazed windows.

Controlled testing in a laboratory has also revealed that window restoration and retrofits can increase the thermal performance of a window. Glasgow Caledonian University in Scotland conducted laboratory testing of an existing wood double hung window in poor condition. The test included thermal analysis of the window in its existing condition, in a restored condition and with certain window retrofits. The study found that window restoration along with the addition of a low-emissivity secondary glazing system (such as an exterior storm window) can improve a single-glazed, wood window’s thermal performance by as much as 58% (English Heritage, 2009). The testing also revealed that, with the addition of an exterior storm window, the restored window can achieve a U-value that meets EnergySTAR standards.

Methodology

The focus of this study was to conduct a comparative life cycle assessment (LCA) to show the environmental benefits of window preservation over window replacement. Data for this LCA was developed from a typical, mid-twentieth century housing development located in the northeastern U.S.

LCA Goal and Scope Definition

The LCA for this study was modeled using GaBi 6 Software along with the GaBi construction extension database. GaBi is one of the leading software technology suites for conducting LCAs and comes with an extensive database of construction processes and related environmental impacts. The LCA includes all life cycle stages from raw material extraction through disposal as detailed in Figure 1.

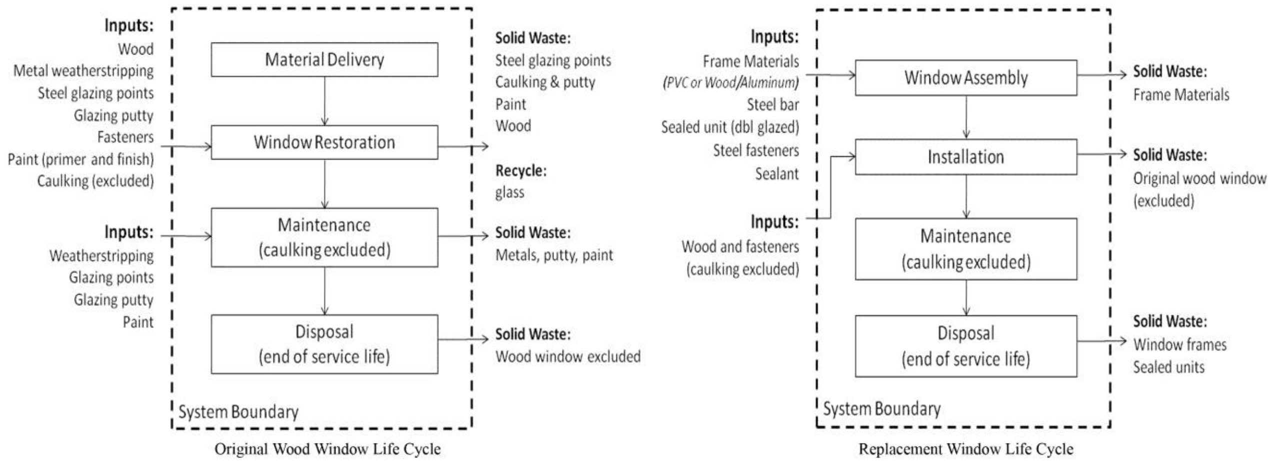

Figure 1: Original and replacement window life cycle.

A functional unit has to be determined in order to effectively conduct a LCA. The functional unit relates the product to an overall product system (Baumann & Tillman, 2004). Because windows make up part of a structure's building envelope, window life over the expected life of a building was used to determine the environmental impacts. Buildings have a typical lifespan range of 50 to 75 years. Due to the historic value of the property in this study, the building life was considered to be much greater than the typical lifespan. Assuming installation in a residential building with a 100 year life, the functional unit of this LCA was defined as 100 years of service per window assembly.

Window life expectancy is one parameter of this study that can vary due to maintenance habits and materials used. Wood windows constructed since the mid-twentieth century have an average life expectancy of 35 years, but a range of 6 to 100 years (Harvey, 2001). However, historic windows (windows constructed up through the mid-twentieth century) were constructed of old-growth wood and can last more than a hundred years with proper maintenance because they are denser, more rigid and rot resistant than newer replacement windows (Leeke, 2013). Exterior storm windows can further extend the service life of wood windows. Table 2 shows the results of a survey conducted in the United Kingdom which summarizes building owner's perceptions of window service life and maintenance characteristics (Asif, Davidson, & Muneer, 2002).

Table 2

Life expectancy of varying window types (Asif et al., 2002)

Window Type	Estimated Service Life (years)			Characteristics
	Mean	Median	Inter-quartile Range	
Aluminum	43.6	40	12.5	Low maintenance
PVC	24.1	22.5	15	Low maintenance, difficult to repair
Timber	39.6	35	16.3	High maintenance, easy to repair
Aluminum-clad	46.7	45	10	Low maintenance, easy to repair

In this study, the existing historic wood windows analyzed are in excellent condition due to the installation of storm windows approximately fifteen years after construction. Once restored, the study windows are considered "like new" and are expected to last at least 100 years with proper maintenance. Therefore, the baseline LCA model was based on the following:

- Wood window: 100 year life expectancy based on restored condition.

- PVC window: 18 - 24 year life expectancy based on perceived average service life and window quality (Athena, 2002).
- Aluminum-clad wood window: 43 - 46 year life expectancy based on perceived average service life and testing (Asif et al., 2002).

The baseline comparative LCA includes the life cycle of 1 wood window, 5 PVC windows and 3 aluminum-clad wood windows based on a building service life of 100 years.

Life Cycle Inventory Analysis

The windows and maintenance schedule for this comparative LCA are summarized in Table 3.

Table 3

Window assemblies and maintenance schedule

	Existing Wood Window	**New PVC Window**	**New Aluminum-clad Window**
Size	36" (W) by 56" (H)	36" (W) by 56" (H)	36" (W) by 56" (H)
Style	Double-hung	Double-hung	Double-hung
Sash Assembly	Single-glazed with storm	Double-glazed with Argon	Double-glazed with Argon
Length of Service	100+ years	24 years	46 years
Maintenance	Every 5 years: • Caulk; • Paint (exterior). Every 25 years: • Paint (interior); • Reglaze. Every 50 years: • Weatherstrip; • New storm window.	Every 5 years: • Caulk.	Every 5 years: • Caulk. Every 25 years: • Paint (interior).

Material quantities used for the wood window restoration inventory were determined based on routine maintenance (class I repair) per the National Park Service Technical Preservation Service (Myers, 1981) and actual field analysis and restoration of three windows. Routine window maintenance includes: Interior and exterior paint removal (use of hot air gun and/or putty knife), removal and repair of sash, repairs to the frame, metal spring weatherstripping installation, sash reinstallation (including reglazing), and repainting (including an oil-based primer).

Windows selected for restoration were noted to be in fair condition with failing window glazing putty, failing paint and some rot. However, the windows and frames were found to be structurally sound and no wood replacement was required. Epoxy was used to repair any wood rot and damage.

Quantities used for the manufacture of the replacement windows were obtained directly from the GaBi software database. Although this database is primarily European centric, the comparative nature of the study accounts for any differences between European and North American processes. Currently, the availability of U.S. emissions data for construction processes is extremely limited.

Ongoing window maintenance will be required during the utilization phase of all window options and was accounted for in the LCA model (Athena, 2002). Caulking maintenance for the wood and replacement windows was excluded from the LCA because maintenance will be the same regardless of window selection. Waste attributed to the wood window was excluded because it is expected to be thrown away in all LCA models. The model assumes no breakage of sealed glass units during the window's service life. Also, transportation was included through the manufacture stage, but was excluded from the remainder of the study due to the variability of project locations and window selections.

Life Cycle Impact Assessment

The aim of an impact assessment is to translate the environmental consequences of the LCA processes into quantifiable environmental impacts (Baumann & Tillman, 2004). The environmental impacts of material inputs, outputs and emissions for wood, PVC and aluminum-clad wood window processes were assessed using TRACI 2.1 (Tools for the Reduction and Assessment of Chemical and Other Environmental Impacts). Developed by the U.S. Environmental Protection Agency, TRACI uses the following impact categories: Ozone depletion, global warming, smog formation, acidification, eutrophication, human health cancer, human health noncancer, human health criteria pollutants, eco-toxicity, fossil fuel depletion, land use and water use.

Results and Interpretation

The life cycle impact category results for wood window restoration, PVC window replacement and aluminum-clad wood window replacement are shown in Table 4. The totals include all stages of the life cycle. The wood window restoration was modeled both with the existing exterior storm window and replacement of the storm.

Table 4

TRACI 2.1 impact category results for building with a 100 year service life

Impact Category TRACI 2.1	**100 Year Building Service Life**			
	Wood Window	**Wood Window New Storm**	**PVC Window**	**Aluminum-Clad Wood Window**
Acidification Air (kgSO2E)	0.282	1.82	3.02	2.19
Acidification Water (kgSO2E)	0.039	0.077	0.016	0.0648
Ecotoxicity (CTUeco)	0.0182	0.0713	0.213	0.0821
Eutrophication Air (kg N-Eq.)	0.0103	0.055	0.174	0.103
Eutrophication Water (kg N-Eq.)	0.00468	0.0281	0.109	0.0517
Global Warming Air (kgCO2E)	66.9	349	773	443
Human Health Particulate Air (kg PM2, 5E)	0.052	0.516	0.995	0.725
Human Toxicity, Cancer (CTUh)	3.68E-09	1.44E-08	3.80E-08	1.76E-08
Human Toxicity, Non Cancer (CTUh)	3.93E-10	8.87E-10	7.99E-09	1.32E-09
Ozone Depletion (kgCFC 11-Eq.)	1.87E-08	8.74E-08	7.37E-07	4.52E-07
Fossil Fuels (MJ)	95.7	412	1170	525
Smog (kgO3E)	4.39	20.9	52.2	33.7

The results indicate that wood window restoration has less overall environmental impact when compared to the replacement windows, even if a new exterior storm window is installed. The inclusion of the exterior storm shows a significant increase in global warming potential and fossil fuel use in the wood window restoration model. The PVC window has the greatest environmental impact when compared to all models except for the acidification of water.

A sensitivity analysis was conducted to test the effects certain assumptions made on the life cycle model. The most significant impact on this LCA is the service life assumption. An overall building service life of 100 years was modeled and during that time it was assumed that one wood window with an 100 year life-span, 5 PVC windows each with a 24 year life-span and 3 aluminum-clad windows each with a 46 year life-span would be used. Changes to window life-span (e.g. extended life of PVC window or poor maintenance of wood window) can affect the overall model. Table 5 shows the results of one window assembly. When comparing one window assembly, the global warming potential for the wood window with a new storm is only slightly lower than the two replacement window options.

Table 5

TRACI 2.1 impact category results for one window assembly

Impact Category TRACI 2.1	1 Window Assembly			
	Wood Window	Wood Window New Storm	PVC Window	Aluminum-Clad Wood Window
Acidification Air (kgSO2E)	0.107	0.618	0.585	0.71
Acidification Water (kgSO2E)	0.0231	0.0358	0.00276	0.212
Ecotoxicity (CTUeco)	0.00619	0.0239	0.0409	0.0257
Eutrophication Air (kg N-Eq.)	0.00318	0.018	0.0333	0.033
Eutrophication Water (kg N-Eq.)	0.00197	0.00974	0.0212	0.0168
Global Warming Air (kgCO2E)	25.7	120	148	141
Human Health Particulate Air (kg PM2, 5E)	0.0177	0.171	0.187	0.23
Human Toxicity, Cancer (CTUh)	9.22E-10	4.51E-09	6.99E-07	5.20E-09
Human Toxicity, Non Cancer (CTUh)	6.29E-11	2.28E-10	1.47E-09	3.10E-10
Ozone Depletion (kgCFC 11-Eq.)	6.98E-09	2.98E-08	1.46E-07	1.49E-07
Fossil Fuels (MJ)	29.4	135	224	165
Smog (kgO3E)	1.38	6.86	10.1	10.9

In TRACI 2.1, normalization and weighting of results analyzes each impact's respective share of overall damage by relating it to a common reference or unit. This process allows impact category results to be displayed as a single value. The developers of GaBi Software conducted a survey in 2012 of LCA researchers and practitioners to weight environmental impacts based on their perceived significance. The results in Figure 2 are based on North American responses using TRACI 2.1 impact categories. This interpretation method further illustrates the environmental benefits of window restoration over window replacements.

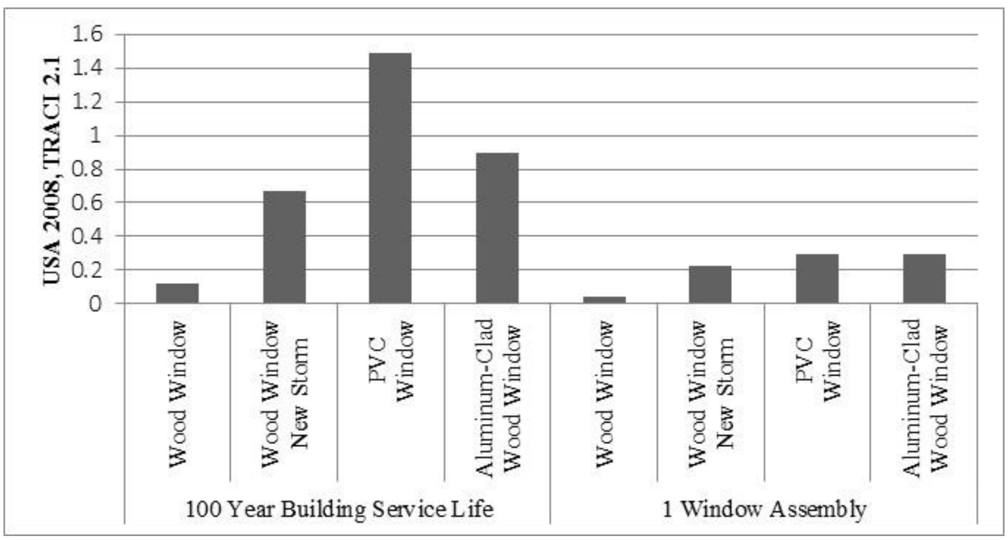

Figure 2: Normalization and weighting of environmental impacts.

Discussion

This study evaluated the environmental impact of window restoration versus window replacement using life cycle assessment as a means to quantify the sustainability of window preservation. Saving original building fabric is not only a means of preserving embodied energy and reducing the use of new materials, but is also essential in maintaining historic building integrity and character. This study helps make a case for window restoration and also informs homeowners of the environmental benefits of window restoration.

The results of this study indicate that wood window restoration has less overall environmental impact when compared to PVC and an aluminum-clad replacement window. For a service life of 100 years, wood window restoration is less damaging in all but one TRACI impact categories. The sensitivity analysis revealed that window lifespan assumptions impact life cycle results. Although wood window restoration is overall more environmentally friendly, when modeled together as one window assembly, the wood window with the installation of a new storm is comparable to the aluminum-clad wood window. This life cycle assessment demonstrates the importance of proper wood window maintenance to achieve the expected 100 year lifespan.

This study is limited to analyzing a specific residential case study and modeling assumptions made for the purposes of conducting the life cycle assessment. Assumptions such as, window and building lifespan, maintenance cycles, material quantities and the exclusion of material transportation to the site are likely to affect overall results.

The results of this life cycle assessment assume that all window efficiencies are comparable and further research is currently underway to validate energy efficiency improvements with restoration through field testing and computer energy modeling. While this study examines a single window unit, the results will be used to model whole house environmental impacts. Cost will likely impact a homeowner’s decision to replace or restore existing windows and will be evaluated in future research.

Although this is a comparative study, data quality is expected to impact results because it is European-centric and limited to certain window types and materials. Replacement of life cycle data with U.S. construction process emissions data is recommended as it becomes available. Also, this study is specific to a particular residential structure located in the northeast U.S. Further research of the environmental impacts of different window assemblies in different climate regions is recommended.

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