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Influence of climate on the environmental and economic life cycle assessments of window options in the United States

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ABSTRACT

Life cycle assessments (LCA) of building materials often exclude the use phase due to variability in buildings and difficulties in isolating energy use for specific components of a building. For this study, a basic single-pane window was selected as a baseline to compare to two basic double-pane windows and four energy-efficient windows in a single-family home. Seventeen United States cities were investigated to represent 17 climate regions. Using energy simulations, along with life cycle inventory and economic data for windows, a cradle-to-grave LCA and life cycle cost (LCC) analysis were conducted. Environmental and economic impacts are normalized and weighted to identify the best overall performing windows. Environmentally, the low-solar gain windows always performed best due to the reduction in electricity needs, whereas economically they performed best in warmer climates but high-solar gain windows performed best in cooler climates. Thirteen of the seventeen cities had window options with a payback period less than five years when all retrofitting option were compared. When projecting the impacts of retrofitting a large number of homes, it was found that metro Atlanta could reduce CO_2 emissions by about a half a million metric tons of CO_2 annually with any of the energy efficient window choices.

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1. Introduction

Residential buildings contribute significantly to the United States (US) economy and environment impacts. The National Association of Home Builders cites that housing constituted 16% of the total US Gross Domestic Product in 2013 and averages around 18%, through residential investment and housing services [1]. Construction materials account for 75% of the total minerals and materials used for physical goods in the US [2], and 60% of the total square footage of infrastructure is residential [3]. Additionally, residential electricity contributes 20% of US' greenhouse gases to the atmosphere [4].

To better understand the environmental and economic effects of a building, a LCA and LCC should be conducted. A LCA for an entire building would include raw material extraction and manufacturing, transportation, on-site construction, use, and disposal at the end of life. However, knowing that analyses of buildings are quite difficult because of the interactive nature of the large and complex number of systems, it is useful to isolate particular components, as was done in this case study for windows. The Office of Energy Efficiency estimates that windows account for 10–25% of heat loss in a residential building [5], thus highlighting the importance of technological improvements in window design, and the importance of windows to the overall building LCA and LCC. Comparing energy savings as part of the LCA and LCC will allow renovating homeowners to weigh the cost as well as resource and manufacturing impacts of more energy-efficient windows against the energy savings provided over the window's life cycle. According to Energy Information Administration (EIA), 42% of homes have single-pane windows, and even for newer homes 20% of the homes constructed between 2000 and 2009 installed single-pane windows [6,7]. The objective of this study is to analyze the economic and environmental impacts associated with renovating windows in existing homes for 17 climate zones in the US.

2. Calculation methods

2.1. Background

Klöpffer [8] proposed that in order to consider the sustainability of a product, the three pillars of sustainability must be considered: environment, economic, and social issues. The paper noted that in order to do a complete life cycle sustainability assessment (LSCA),

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Table 1
The properties of seven windows compared in this study.[a]

Window Identifier	Glazing (no. of panes)	Solar gain (SHGC)	U[b]	VT[c]	Coating	Frame
1	Single (1)	Clear glass (0.64)	0.88	0.65	None	Aluminum-clad wood
2	Double (2)	Clear glass (0.57)	0.52	0.59	None	Aluminum-clad wood
3	Double (2)	Clear glass (0.57)	0.52	0.59	None	Polyvinyl chloride (PVC)
4	Double (2)	High (0.50)	0.29	0.57	Low-e	Fiberglass
5	Double (2)	Low (0.20)	0.27	0.46	Low-e	Fiberglass
6	Triple (3)	High (0.41)	0.20	0.50	Low-e	Fiberglass
7	Triple (3)	Low (0.18)	0.19	0.37	Low-e	Fiberglass

[a] Adapted from [21].
[b] The U-value of a window represents the rate of heat loss. Lower U-values demonstrate better insulating properties by having lower heat transfer.
[c] Visible transmittance (VT) is the fraction of visible light that passes through a window, with higher numbers indicating a high proportion of visible light.

three assessments should be completed with the same scope without overlapping (i.e., LCA, LCC, and social life cycle assessment – SLCA). After Klöpffer's paper was published, much of the discussion has been on how to properly integrate these scores [9–12], as well as the relevance of each assessment to total sustainability [13,14]. Currently, LCA is the only assessment of the three that has been standardized [15], and a code of practice has been developed for LCC [16,17]. In the case of the SLCA, it is difficult to find quantitative data to compare social impacts and SLCA standards are undeveloped at the moment [10,16]. For this study, we have chosen to focus on the two more developed pillars (LCA and LCC) to demonstrate which windows are both more environmentally and economically sound over the lifetime of a home.

There have been a number of studies on the impact of different window units on energy use [18–23], LCA [23–26], and payback period or economic performance [18,21,22,23,26]. The literature consistently suggests that increasing the number of panes in the window decreases the energy demand, however, the amount of energy savings depends strongly on the climate with more extreme climates seeing more energy savings [18–22]. Consistent with these finding, the payback periods and economic performances of efficient windows tended to be better in more extreme climates making double-pane windows a good choice in many climates, though the energy savings were often unable to make up for the initial cost of triple-pane windows [18,21]. The articles by Asif et al. [25] and Salazar and Sowlati [24] specifically address the life cycle assessment of windows with different frames. Both studies found polyvinyl chloride (PVC) frames to have worse environmental impacts than aluminum-clad frames, and Salazar's study additionally found PVC frames to be less environmental than fiberglass frames (fiberglass was not included in Asif's study). It should be noted that neither LCA study included energy use as a part of their environmental assessment. Additionally, others have looked at the impact of shading techniques and window area [19,23] on the total energy usage of a home. Both studies found significant reductions in energy use from shading for hot climates and warm climates. To limit the number of variable in our study, we did a sensitivity analysis of shading types in Atlanta, but did not include all shading types for all seventeen cities.

Many studies have looked at the combination of energy use with economic impacts, but few studies have considered these aspects with total environmental impacts from an LCA, despite the fact that both are important factors in deciding the sustainability of windows. Additionally, results are different with each climate, and this paper provides a more comprehensive study of the environmental and economic impact of windows in the United States than previous studies.

2.2. Functional unit and scope of study

In this study, seven window types were selected to compare different features, and the data were normalized by 1 ft^2 of window and frame. The data can be looked at in yearly intervals, as well as in cumulative terms for the mean lifetime of a window of 30 years [27,28]. Looking at the LCA and LCC for the entire lifetime of a window gives us a quick idea of performance over time, though a yearly timeframe may be useful for a person looking for the best performing window within a shorter timeframe than 30 years. The seven window types include a low-end, single-pane window (Window 1) which creates a baseline for comparison to two simple double-pane windows and four thermally-improved, energy-efficient windows, as seen in Table 1. This variety of windows allows us to compare framing materials, the impact of single versus double and triple-glazing, and the impact of high versus low SHGC. The two simple double pane windows, windows 2 and 3, are considered to be approximately the same in terms of energy performance and cost, with the only difference being the material of the frame. Two of the energy-efficient windows tested did not actually meet the code for ASHRAE 90.1-2013 Standard [29], the specific residential ASHRAE 90.2-2007 Standard [30], the 2012 International Energy Conservation Code (IECC) [31], or for Energy Star [32] requirements for many of the climate zones; however, the energy modeling demonstrated that they were the best performers under certain parameters. In fact, during the sensitivity analysis of shading, window area, and orientation, it was discovered that for in the best case scenario for energy modeling of a home in Atlanta, the window that results in the lowest overall annual energy cost (Window 6) has a higher SHGC than is allowed by the standards. Additionally, the baseline window is higher than the standards and requirements allow, but it is used as the comparison because we are considering retrofitting older windows that may have been installed long before the code was in place.

2.3. Data sources

To determine the environmental impacts of the product, an inventory of materials, manufacturing, and disposal is needed. Resource, manufacturing, and disposal inventory data were taken from values published by Salazar and Sowlati [24], who based their LCI on site-specific and published data acquired from three manufacturing sites in North America. For the LCC, the costs of the product are estimated using the National Renewable Energy Laboratory's (NREL) Residential Efficiency Measures Database (2013), which lists average window prices, for a variety of window types in USD per square foot. A report released by the US Department of Energy (DOE) notes that this price actually includes the demolition cost of $3 per square foot [21], so this study splits retrofitting cost into the cost of the product with installation and the demolition cost at the disposal phase.

To expand the scope of this study, we also considered maintenance and energy use attributable to windows. The maintenance impacts come from the amount of latex caulk needed every eight years, as specified in ATHENA's "Maintenance, repair and replacement effects for building envelope materials" manual [33] at a

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