Saving Windows, Saving Money:

Evaluating the Energy Performance of Window Retrofit and Replacement

A REPORT BY:

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CASCADIA GREEN BUILDING COUNCIL

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Cascadia, the leading green building organization in the Pacific Northwest, is dedicated to making deep and lasting change within the building industry for positive environmental impact. A chapter of the U.S. and Canada Green Building Councils, Cascadia is a cross-border education, research and advocacy organization that brings a bioregional approach to problem solving and market transformation. Cascadia is housed within the International Living Future Institute (ILFI), a U.S.-based NGO committed to catalyzing a global transformation toward true sustainability.

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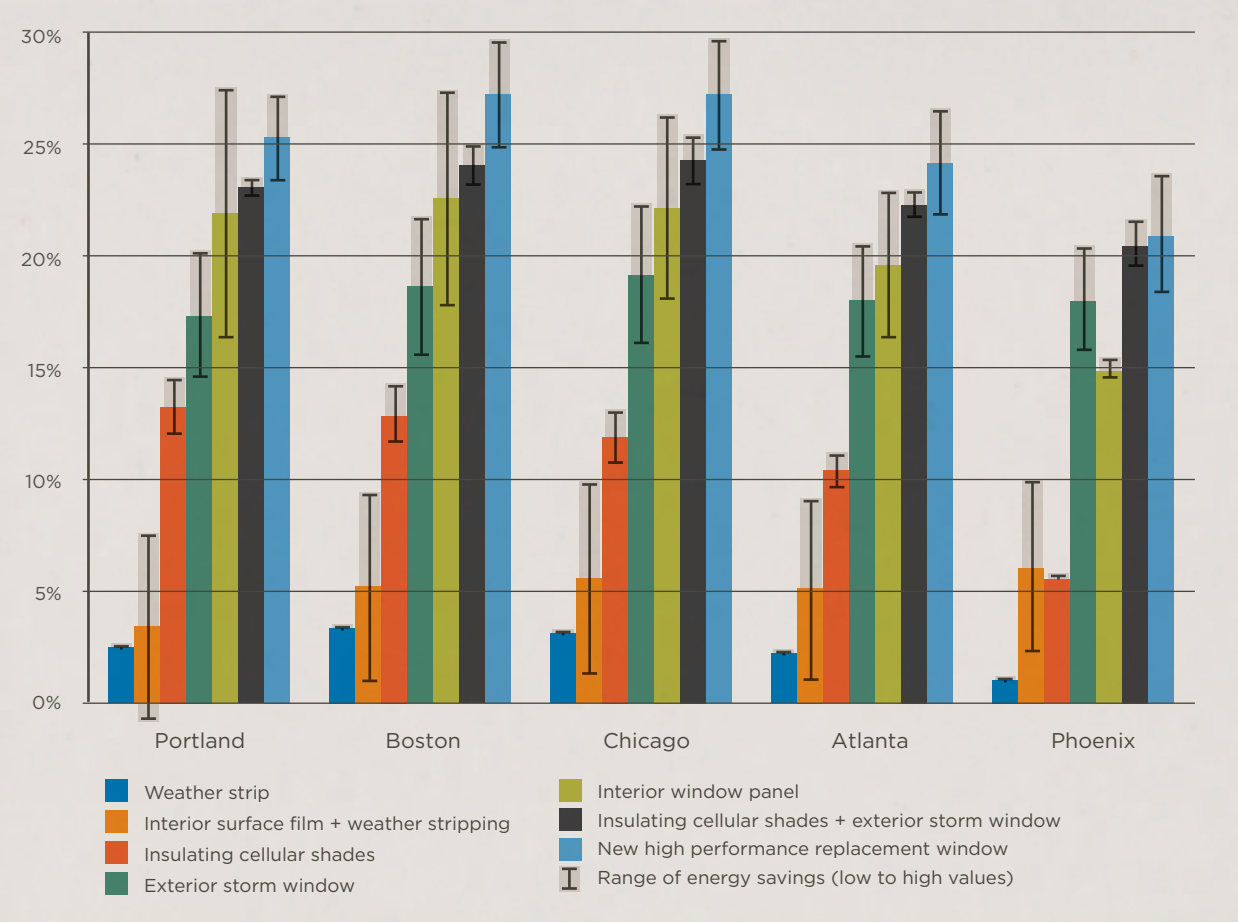
EXECUTIVE SUMMARY

Homeowners and design professionals seeking to upgrade the performance and efficiency of existing windows are faced with many choices—from simple, low cost, do-it-yourself solutions such as window films and weather stripping to replacing older windows with new ones that require investments costing tens of thousands of dollars. Often these decisions are made without a clear understanding of the range of options available, an evaluation of the ability of these options to provide energy and cost savings, or proper consideration for the historic character of the existing windows.

This study builds on previous research and examines multiple window improvement options, comparing the relative energy, carbon, and cost savings of various choices across multiple climate regions. *Results of this analysis demonstrate that a number of existing window retrofit strategies come very close to the energy performance of high-performance replacement windows at a fraction of the cost.*

Annual Percent Energy Savings For Various Window Upgrade Options



Note: Percentage savings are not intended to predict actual savings. Instead, the results are meant to be used to evaluate the relative performance of measures where other more cost-effective energy saving strategies have been implemented first.

KEY FINDINGS

RETROFIT MEASURES CAN ACHIEVE PERFORMANCE RESULTS COMPARABLE TO NEW REPLACEMENT WINDOWS.

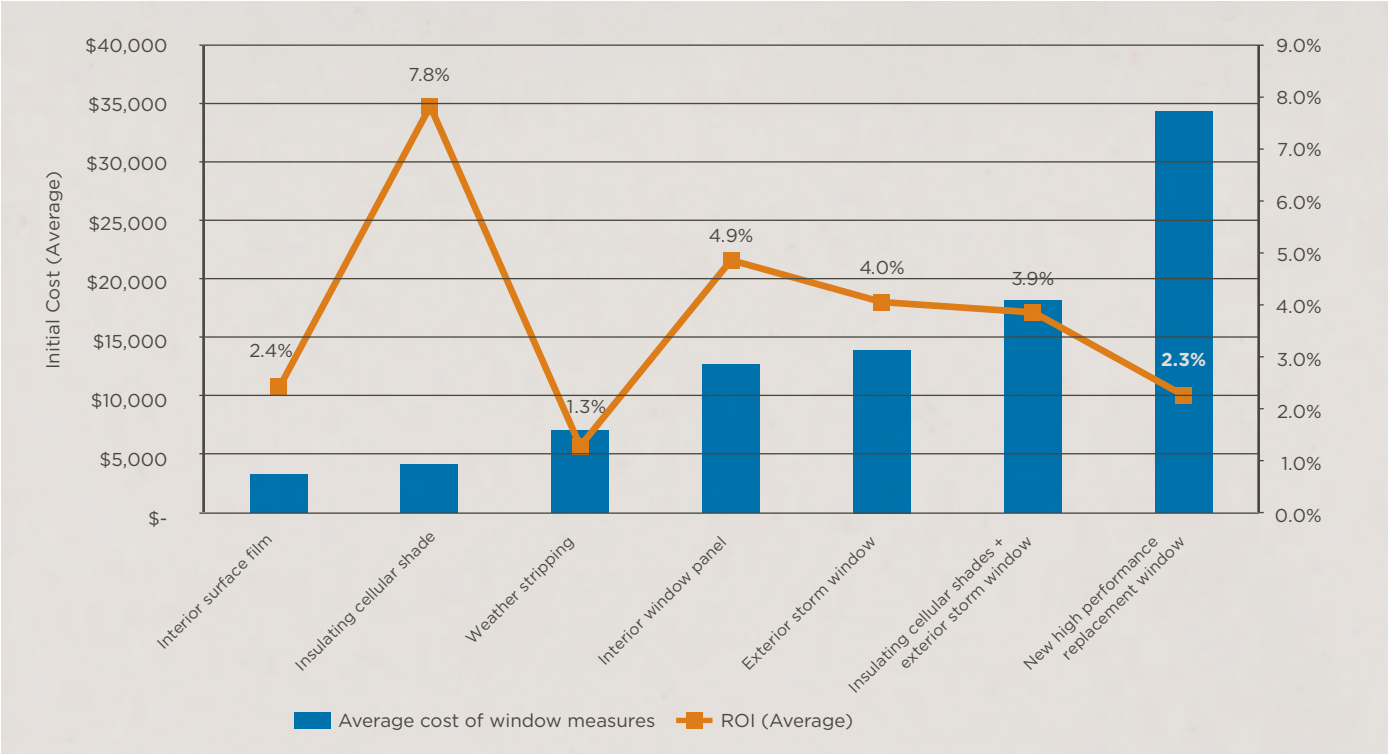
There are readily-available retrofit measures that can achieve energy savings within the range of savings expected from new, high performance replacement windows. This challenges the common assumption that replacement windows alone provide the greatest benefit to homeowners.

The figure on the previous page shows that for all cities, at least one and often two of the selected measures can achieve energy savings within the range of savings expected from new, high performance replacement windows. Specifically, interior window panels, exterior storm windows combined with cellular blinds, and in some cases even exterior storm windows alone fall within the range of performance for replacement windows.

ALMOST EVERY RETROFIT OPTION OFFERS A BETTER RETURN ON INVESTMENT THAN REPLACEMENT WINDOWS

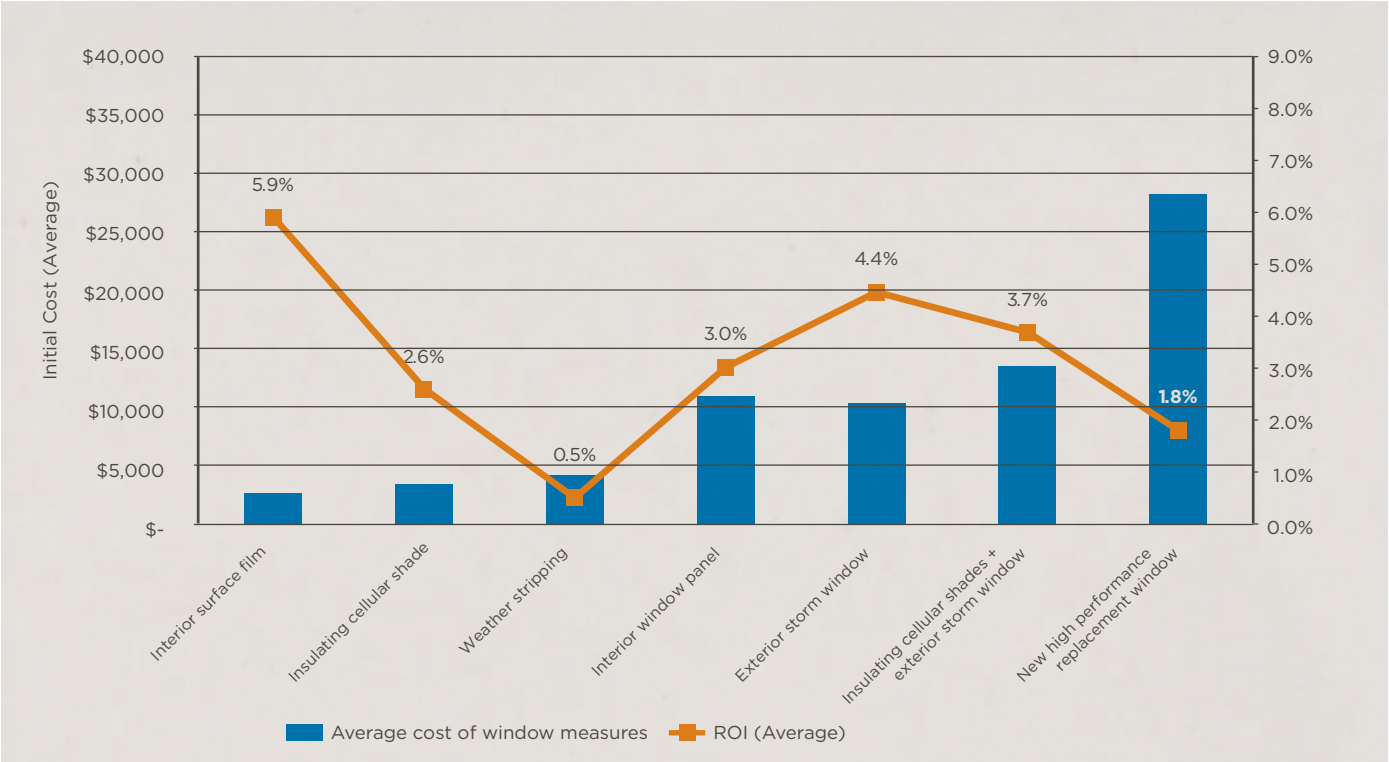
Energy savings alone should not influence decisions to upgrade windows without consideration of initial investment. For all climates, the cost analysis shows that new, high performance windows are by far the most costly measure, averaging approximately $30,000 for materials, installation, and general construction commonly required for an existing home. In cold climates, all other retrofit measures, with the exception of weather stripping and heat reducing surface films, offer a higher average return on investment when compared to new, efficient replacement windows. In hot climates, all of the study retrofit measures offer a better average return on investment than new windows, with the exception of weather stripping.

Financial Comparison of Various Window Upgrade Options for Boston



Due to high utility costs and high heating and cooling loads, window upgrade options in Boston generally produced the highest return on investment of any of the regions studied. Simple financial analysis such as Return on Investment (ROI) provides a decision making framework to allow informed choices between options for a given location.

Financial Comparison of Various Window Upgrade Options for Phoenix



STUDY OBJECTIVES AND APPROACH

In recent years, awareness around energy use and its financial and environmental impacts have placed buildings in the spotlight. Residential buildings alone are responsible for approximately 20 percent of total U.S. energy use and carbon dioxide emissions. The vast majority of these buildings are single-family homes where heating and cooling represent the largest use of energy. Windows are one important aspect of how heat loss (and gain) affects a home's operational efficiency and cumulatively represent over $17 billion in annual U.S. household expenditures on heating and cooling.

In this study, computer simulation is used to model energy use in a typical, prototype home both before and after window improvements. Several commercially available window improvement options were analyzed ranging from simple, low cost applications to more expensive options representing the highest energy performance on the market.

The study analyzed energy, cost, and carbon savings for seven selected measures: weather stripping existing windows; interior window panels; exterior storm windows; insulating cellular shades; a combination of exterior storm windows and insulating cellular shades; interior-applied surface films; and new, high performance replacement windows.

Variations in climate and regional energy grids were addressed by evaluating the home's performance in five U.S. cities—Boston, Atlanta, Chicago, Phoenix, and Portland. A thorough cost analysis allowed for the comparison of average return on investment for each window option in each of the cities.

RECOMMENDATIONS AND CONCLUSION

Findings from this study demonstrate that upgrading windows (specifically older, single-pane models) with high performance enhancements can result in substantial energy savings across a variety of climate zones. Selecting options that retain and retrofit existing windows are the most cost effective way to achieve these energy savings and to lower a home's carbon footprint. Due to the cost and complexity of upgrading windows, however, these options are not likely to be the first intervention that homeowners undertake. For many older homes, non-window-related interventions—including air sealing, adding insulation, and upgrading heating and cooling systems—offer easier and lower cost solutions to reducing energy bills.

In addition to providing insights into the energy performance and investment costs of window options, the study's findings reinforce several additional benefits in choosing to retrofit existing windows rather than replace them. Retrofits extend the life of existing windows, avoid production of new materials, and reduce waste. Additionally, wood windows are often a character defining feature of older homes, and conserving them helps to preserve the historic integrity of a home. *The Secretary of the Interior's Standards for the Treatment of Historic Properties* and *The Secretary of the Interior's Illustrated Guidelines on Sustainability for Rehabilitating Historic Buildings* offer guidance on how best to approach the preservation of windows in historically designated homes, or homes that may be eligible for listing.

Selecting the most appropriate measure for upgrading windows requires a detailed understanding of climate and energy costs in addition to window performance and installation costs. This study provides a valuable analysis of these variables that can be used to help inform the decision to improve the energy performance of and reduce the carbon dioxide emissions from older and historic single-family homes.

I. INTRODUCTION AND BACKGROUND

INTRODUCTION

Growing interest in improving the energy efficiency of residential buildings inevitably raises questions about what to do with existing windows. Homeowners often assume that replacing older, leaky windows is the only way to save energy, an assumption actively promulgated and reinforced by companies selling replacement windows and by the availability of federal tax incentives for installing new, high performance windows. The confusion is often compounded by a lack of easily accessible information on the range of window improvement options available and the ability of these options to provide meaningful energy savings. This study examines window replacement and retrofit objectively, evaluating the energy-saving potential of each approach in various climate regions.

While windows are an important consideration for achieving substantial energy savings in a home, homeowners should consider other energy-efficiency measures first. Options such as air sealing, added insulation, or improving the efficiency of Heating, Ventilation and Air Conditioning (HVAC) systems may offer a greater return on investment. This study, however, focuses solely on windows and assumes that an upgrade to the performance of windows is planned. It is therefore intended as a resource to help inform homeowners and/or building professionals about the best options based on the energy and cost savings potentially offered by selected window upgrade choices.

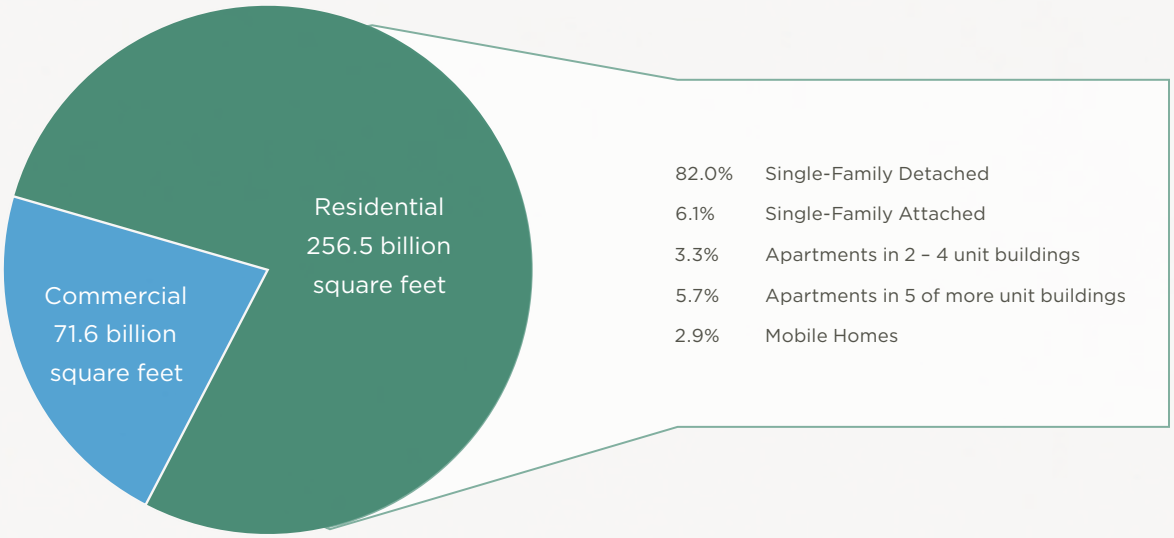
This study is a follow-up to a report published by the National Trust for Historic Preservation in 2012 titled *The Greenest Building: Quantifying the Environmental Value of Building Reuse*. The previous research evaluated whole-building life cycle impacts including those from both material and energy use, finding that reusing existing buildings and retrofitting them for greater energy-efficiency offers immediate reductions in CO2 emissions and other environmental impacts. Specifically, the research shows that it can take from 38 to 50 years for a new, energy-efficient home to compensate for the initial carbon expended during the construction process.[1] While the study does not evaluate specific material choices, it indicates that a greater understanding of the environmental impacts of material selection is needed to highlight best practices to retain and retrofit our existing building stock.

RESIDENTIAL ENERGY USE

In recent years, much attention has been directed to the residential energy-efficiency market as a way to create local construction jobs and reduce the carbon emissions from buildings. With housing comprising the vast majority of the U.S. building stock, as shown in Figure 1, the opportunity for investment in energy savings has the potential for a broad positive contribution to the U.S. economy.

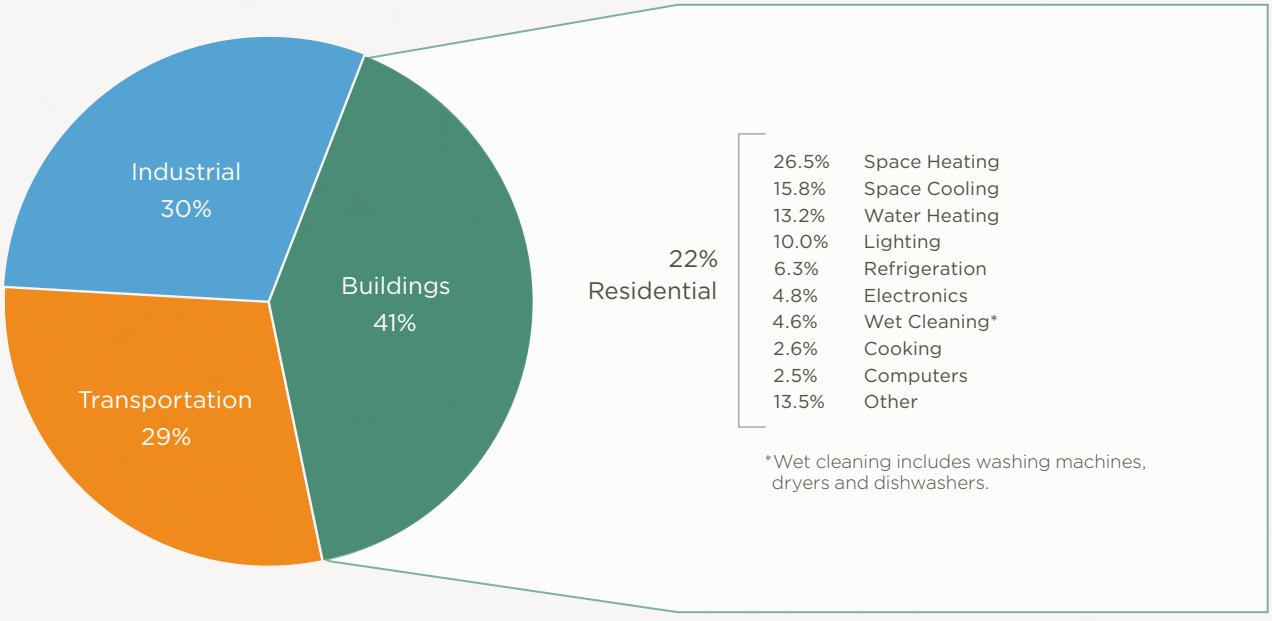
The residential building sector consumes approximately 22 percent of all U.S. primary energy, and is responsible for 21 percent of U.S. energy-related carbon dioxide emissions.[2] As shown in Figure 2, space heating and cooling consume the largest amount of residential energy.

Figure 1: Square Footage of U.S. Building Stock by Type



Source: U.S. Energy Information Administration

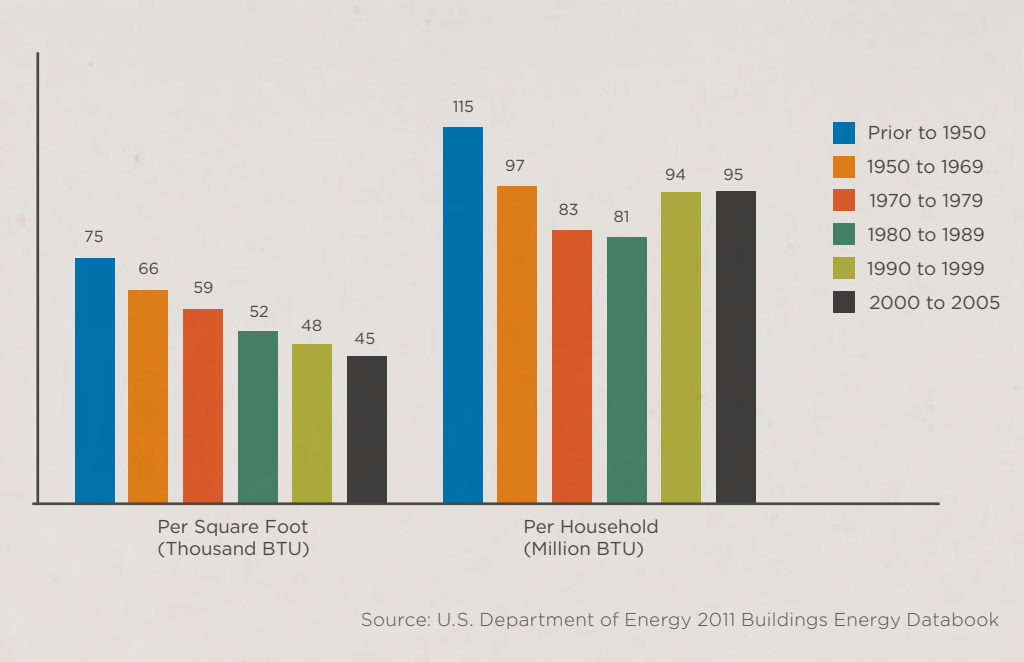
Figure 2: U.S. Energy Consumption by Sector



Source: U.S. Energy Information Administration and U.S. Department of Energy

Older homes, particularly those built before the existence of energy codes, tend to use more energy than their newer counterparts. Figure 3, from the U.S. Department of Energy's 2011 Buildings Energy Databook, shows that pre-1950s homes have the highest energy use (both on a per square foot basis and a per household basis), since these homes are more likely to have less efficient heating systems and little or no insulation.[3]

Figure 3: Annual Energy Intensity by Housing Vintage



Source: U.S. Department of Energy 2011 Buildings Energy Databook

The chart on the left shows that newer homes are more energy efficient on a square foot basis compared to older homes. The trend toward larger home sizes in recent decades, however, has offset their improved efficiency, showing higher energy use per household. According to the Department of Energy, pre-1950s homes have the highest per-household energy consumption of all home vintages. This is because they are on average 11 percent larger than those built between 1950 through 1979 and that they typically have older, less efficient systems and little or no insulation.[4]

As the image below illustrates, windows can be a source of heat loss. It is estimated that 50.7 million residential homes in the U.S. have single-pane windows.[5] According to the U.S. Department of Energy, *Energy Savers Guide,* windows account for 10 to 25 percent of heating and cooling costs in the typical American home.[6] Windows cumulatively represent approximately $17 billion in annual U.S. household utility costs for heating and cooling. However, they are not the only culprit. Un- or under-insulated walls, roof, wall and roof penetrations (e.g., vent stacks), doors, and foundation also substantially contribute to heat loss as illustrated by the bright yellow areas in the illustration.

Photo: Morgan Heater

Thermal imaging of an older home shows typical areas responsible for heat loss through a home's enclosure. Exterior elements of the home with greater heat loss to the outside are shown as yellow and orange, whereas areas with lower heat loss are shown as violet and purple.

CHALLENGES WITH SELECTING WINDOW UPGRADES

There are many options for improving the energy efficiency of existing windows. While the body of information and objective data about window upgrade options is growing, few resources are tailored to provide guidance about which options are best suited for a particular home. Homeowners, designers, and those in the building trades have few tools to evaluate how various strategies for retrofitting of existing windows compare to replacing them with new windows.

Homeowners upgrade windows for a variety of reasons. Some are motivated strictly by energy cost savings, while others want to improve the comfort of a drafty house or reduce their carbon footprint by decreasing the greenhouse gas emissions associated with their home's energy consumption.[7] Still others elect retrofit strategies over replacement to extend the life of existing windows, to avoid adding valuable resources to landfills, and to preserve a home's original materials, such as old growth wood, which is now scarce. Owners renovating an older or historic home will retain the original windows to keep the historic character and aesthetic charm of the home intact through the upgrade process.

Upfront investment costs can ultimately drive (or deter) a homeowner's decision to upgrade residential windows. Without expert energy analysis, however, homeowners are frequently misinformed on whether specific window retrofit or replacement measures will pay off in terms of ongoing utility savings. With the average U.S. household spending more than $2,200 annually on energy,[8] investments to upgrade the performance of existing single-pane windows (the focus of this study) may offer acceptable financial returns, especially during times of rising energy costs.

When considering whether to retrofit or replace a window, questions arise about what is more important: saving money, saving energy, retaining historic character, or reducing negative environmental effects. This study focuses solely on energy savings, associated utility cost savings, and the potential for reducing carbon emissions, acknowledging that many other factors must also be considered. While outside the scope of this study, additional important considerations include:

- Characteristics of the window materials selected (such as toxicity, location of raw material extraction, manufacture, and the potential for reuse, recycling, or disposal at the end of their service life),
- Maintenance and longevity of the window upgrade measure.
- Stimulation of the local economy through construction expenditures.
- Reparability.

II. STUDY OBJECTIVES

This study analyzes the potential energy savings related to common practices for upgrading older, existing single-pane residential windows. Variables such as climate, regional energy costs, heating system efficiency, and window system performance are evaluated to understand which options provide the greatest energy savings for homeowners.

The objectives of this study are to:

- Characterize the typical performance of older, leaky, single-pane residential windows in terms of thermal resistance, solar heat gain, and airtightness, and identify the range of common practices for upgrading performance through window retrofit and replacement options.
- Using computer simulations, compare the relative energy savings from window upgrade measures for a prototype single-family home.
- Based on the results of energy modeling, provide recommendations for improving window performance across different U.S. climate regions.
- Apply regionally adjusted construction cost estimates, demontrate the relative cost effectiveness of the measures studied.

A number of previous studies have evaluated the energy efficiency of window retrofit and replacement measures. These studies have included both empirical testing and computer simulations of the thermal performance and air leakage for various options including interior and exterior storm windows, weather stripping, and insulating shades. A list of previous research referenced in this study is located in Section VIII.

This study builds upon the data developed in these earlier studies to develop a single data-set that evaluates and allows a comparison of the most effective window retrofit options. The results from this study are intended to add to the existing body of research in this field, providing greater insight into the anticipated relative energy, carbon, and cost savings between window retrofits compared to window replacement across different climate regions. Ultimately, this study is intended to help influence practice and policy around upgrading older windows for energy efficiency and to help homeowners, designers, and building professionals make more informed decisions.

III. OVERVIEW OF HEAT TRANSFER THROUGH WINDOWS

Three principal factors affect heat loss/gain through windows. Each factor is sensitive to different aspects of window design and specifications and contributes differently to a home's overall energy use depending on the climate in which the house is located.

I. **Air Leakage/Infiltration:** Air leakage involves movement of air through unintentional cracks between window components within the window frame itself or between the window assembly and the building structure. Driven by air pressure differences, outside air infiltrates through these cracks in the high-pressure zone of the house, while conditioned inside air escapes in the low-pressure zone. Pressure differences to drive this infiltration can come from wind, stack effects that cause heat to rise in the house, or pressure imbalances from the installed heating and cooling equipment. Infiltration has its greatest energy impact during cold weather in heating-dominated climates when winds can be most severe and where the temperature of outside air is significantly colder than inside air.

   Air leakage depends on the size of infiltration cracks, which can be evaluated with a blower door test. Leakage is minimized by filling cracks and/or using an overall barrier, such as a storm window, to block airflow paths.

II. **Temperature Driven Heat Transfer (Conduction and Convection):** Heat moves through materials from warm to cold; therefore, differences in temperature (ΔT) between the outside and inside air provide a forcing function for the movement of heat through window materials. This heat transfer happens through all parts of the window—both the glazing and the frame—and its energy impact is specified by the U-factor of the window assembly. The overall effect of these losses depends on the total window area and its U-factor and the inside/outside temperature difference. Since this difference is usually greatest during cold weather, when ΔT may exceed 60 degrees F, this heat transfer mechanism is usually most significant during heating-dominated times of the year.

   Reducing heat flow through windows results in interior surfaces that are closer to the interior air temperature and not cold to the touch in winter. This greatly improves thermal comfort of occupants and reduces condensation along with providing energy savings. Keeping the interior surface of the window warmer and more consistent from top to bottom also reduces convection, further contributing to occupant comfort. Heat flow through glazing units is minimized by using multiple glass layers, low emissivity (low-e) coatings, inert gas fill, and warm edge spacers between all sealed glazing layers. For window frame components, U-factor is minimized by using low conductivity (or thermally broken) frame

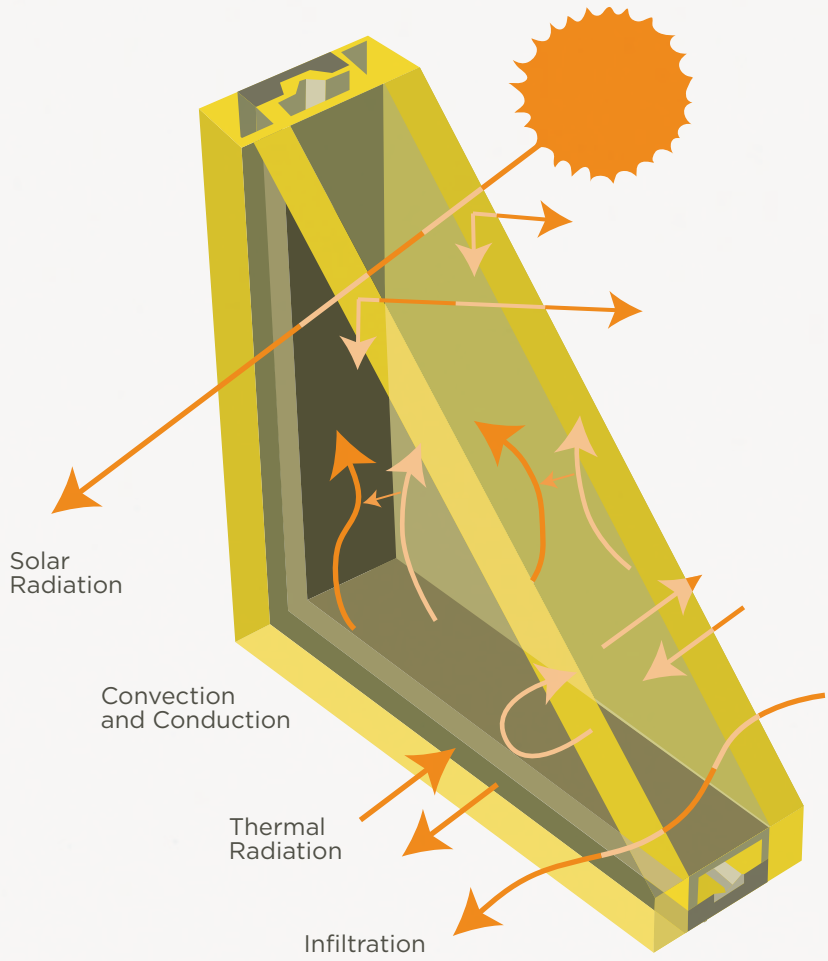
WINDOW PERFORMANCE CHARACTERISTICS EVALUATED IN THIS STUDY

Air-leakage Rate: A measure of the rate of air infiltration around the window due to pressure differences on either side, expressed in units of cubic feet per minute (cfm). The lower a window's air-leakage rating is, the better its airtightness.

Solar Heat Gain Coefficient (SHGC): Measures transmission of direct radiation from the sun through a window, expressed as a number between 0 and 1. The lower a window's SHGC, the less solar heat it transmits, and the greater its shading ability. Windows with low SHGC are beneficial in cooling-dominated climates but may potentially conflict with passive heating strategies in heating-dominated climates.

U-factor: A measure of the rate of non-solar heat loss or gain through a window, expressed in units of Btu/hr-sq ft-°F. The lower the U-factor, the greater a window's resistance to heat flow and the better its insulating value.

Figure 4: Heat Transfer Through Windows



Source: U.S. Department of Energy

materials. For example, wood has a lower conductivity than metal. External measures such as adding insulating curtains, blinds, or interior shutters will also reduce heat transfer.

III. **Solar Gains (Radiation):** Solar gains happen through the transparent window glazing components and can have both positive and negative effects on the energy performance of windows. During the heating season, solar gains deliver heat to spaces and offset the need for mechanical heating, but during the cooling season, these same solar gains will increase the energy needed to cool the space. The Solar Heat Gain Coefficient (SHGC) quantifies of the transmission of solar radiation through the window. The amount of solar gain depends on the area of transparent

window glazing oriented toward the sun, the SHGC of the glazing, the amount of shading, and local solar conditions (sun angles, cloudiness, window cleanliness, etc.).

Solar radiation is divided into three components: visible light (roughly 45 percent), infrared (roughly 52 percent), and ultraviolet rays (roughly 3 percent). Although solar heat gains happen from all three components, only the visible light portion of the spectrum can be seen. Since the primary function of windows is to allow natural light in and provide views out, the transmission of visible light is a vital consideration.

Low-e coatings added to windows decrease the effective U-factor of the window and reduce the SHGC. These coatings or films are designed to trap beneficial heat (infrared energy) inside the house and reflect unwanted solar rays (infrared energy) away from the house while simultaneously letting a large fraction of the visible light pass through to the inside. However, where passive solar heating is desirable, such as in heating-dominated climates, these films can reflect away more solar energy than they trap.

While visible transmission is not linearly related to the U-factor or SHGC, many low-e films used to improve a window's thermal performance or control solar gains also decrease the visible light transmission, sometimes making the glass appear deeply tinted or reflective. This not only affects views and natural light, it can also jeopardize the historic integrity of a home. For this reason, test conditions evaluated in this research are limited to products that maintain a reasonably high visible transmission (greater than 40 percent) and an acceptably low visible reflection (less than 12 percent). Interior shades, blinds, and films and external measures such as awnings, vegetation, or exterior shutters all help to reduce unwanted solar heat gain through windows.

IV. STUDY METHODOLOGY AND TEST CONDITIONS

OVERVIEW OF METHODOLOGY

In this study, a set of test conditions for various window upgrade measures were applied to a prototype home. Researchers then compared these measures by simulating the energy performance of the house before and after the energy-efficient window interventions. A typical single-family home with older, leaky single-pane windows serves as the baseline case study for the analysis. The energy performance of the house, both before and after window improvements, is estimated using a whole-house, hourly, energy simulation computer program.

The results are expressed in terms of energy savings (kWh/yr), energy costs ($/yr), and reductions in carbon dioxide emissions (lbs CO2/yr) associated with increased operational efficiency for a prototype single-family home in four climate regions—cold, temperate, hot/humid, and hot/arid. A representative range of low and high heating system efficiencies is modeled to determine how results may be influenced if window interventions take place before or after a homeowner has elected to upgrade the heating system.

For the purposes of this study, it was assumed that the owners of the Pettygrove Residence had already performed many common energy retrofits, including insulation in the walls and attic, air sealing, and an upgraded HVAC system. This assumption was made because it has been widely demonstrated that these retrofit strategies offer better energy savings at less cost than window retrofit or replacement options. In addition, it was assumed that the window upgrades were part of a whole-house, substantial effort to improve energy efficiency, but as one of the last measures applied to a home. *Because the prototype had already substantially reduced its total energy consumption through these strategies, window interventions made a greater percentage impact in both cost and CO2 savings than if the house had not already completed the other energy efficiency measures.* Under these conditions, savings associated with window improvements may appear greater than is found in many other studies assessing window options.

Importantly, this study also assumes that the Pettygrove Residence has leaky double-hung windows, because past research has shown that substantial air infiltration from this window type contributes to energy loss.[9] This study sought to simulate how various retrofit and replacement options would perform in this context. The analysis also assumes that high quality retrofit or replacement measures are applied as part of a comprehensive, whole house effort to improve energy performance. *Together, assumptions about the poor performance of leaky windows and the application of high quality retrofit/replacement strategies produces energy, carbon and cost savings may not be typical of an average home or lower quality improvement measures.* However, it is expected that data from this study describing the *relative difference* in cost and performance between different window measures will help design professionals and homeowners understand what solutions are most appropriate for a given home.

PROTOTYPE HOUSE AND ASSUMPTIONS

The prototype home used in the analysis (known as the Pettygrove Residence) is a two-story, Queen Anne style home located in Portland, Ore. Constructed in 1896, the home was most recently remodeled in 2009.

By using an actual, rather than a theoretical house, the analysis is grounded in a real-life example allowing the team to simulate an existing house with a variety of window interventions. While the home is located in Portland, for the purposes of this study it is "traveled" to four other cities to determine how variations in climate and energy cost affect potential window choices.

Table 1 describes the data inputs and assumptions for the baseline home used in the analysis. A range of low and high baseline conditions is used to model both the windows (U-factor, SHGC, airtightness) and the heating system efficiency (equipment efficiency, duct leakage) for the home. These ranges are based on the cited research and on the prevalent heating/cooling system type and efficiency for each region. The values are intended to represent a range of existing conditions in a typical older U.S. home. According to the *Energy Savers Guide*, air sealing, adding insulation, and upgrading old, inefficient equipment are the most cost-effective energy upgrades for an older home. The prototype home assumes that the furnace performs to minimum national efficiency standards, that an average level of whole-house air sealing was performed, and that insulation has already been installed in all un-insulated wall and under-insulated attic spaces.

The research findings and study methodology in this report are meant to guide the application of energy-efficiency improvements in older homes. However, homeowners or professionals working with a historically-designated home, a home that is eligible for designation, or a home that is located in a historic district should consult the Energy Efficiency section of the *Guidelines for Preserving Historic Buildings* and the technical brief on weatherization issued by the National Park Service for guidance regarding the appropriate application of air sealing, insulation, window treatments, and mechanical equipment upgrades. In particular, the proper approach to adding wall insulation depends on the construction of the historic wall assembly, the climate conditions to which the home is exposed, and the materials and techniques chosen to insulate and seal the wall cavity.

TABLE 1: PROTOTYPE SINGLE FAMILY RESIDENCE

PETTYGROVE RESIDENCE		
Square Footage	1,579 s.f.	
Unheated Basement	900 s.f.	
No. of Stories	2 plus basement	
Year Built/Year Renovated	1896 / 2009	
Description	3-BR, 2.5 BA	
Number of Occupants	3	
ENVELOPE		
Envelope and Framing	2x4 stick frame @ 16" on center, cedar lap siding, asphalt roofing	
Above grade walls (R values)	R-13 (blown-in insulation & existing wood siding & plaster in full dimensional 2x4 wall)	
Roof Construction (R values)	R-30 (blown in insulation above ceiling)	
Basement	Un-insulated 6" concrete	
Basement Ceiling/Level 1 Floor	R-4 (wood & carpet)	
WINDOWS		
Window Type	Double hung, single pane wood windows, no storm windows or panels	
% Glazing (window:wall)	14%	
SHGC	0.74[a]	
	LOW	**HIGH**
U-Factor	0.77[b]	1.05[c]
Air Leakage	646 cfm @ 50 pa[d]	1360 cfm @ 50 pa[d]
HVAC SYSTEMS		
Heating System Type	Gas furnace	
Heating System Capacity	Heating System Capacity – 62 KBTUH	
	HIGHER PERFORMANCE	**LOWER PERFORMANCE**
Heating Efficiency	0.92 AFUE	0.78 AFUE
Ducts	Located in heated space, tight	Located in unheated space, leaky
Cooling System Type	Window Units	
Cooling Efficiency	SEER 9.4	

*Window Air Leakage rates in this table and throughout this report are expressed as total air leakage resulting from all windows in the home. Total air leakage of the entire home (including windows plus all other envelope infiltration) for the baseline is assumed to be 4,000 cfm50 before window intervention and less than 3,000 cfm50 after. For the baseline, "high value" window air leakage represents about one-third of the home's total, which falls within the expected performance range of untreated windows in a home that has been insulated and sealed to average levels.

Sources:

a ASHRAE Handbook Fundamentals, 2005, Table 19, pg 31.48 for residential single clear.

b Measured Winter Performance of Storm Windows. Joseph Klems. 2002. Table 4, "Prime only," single-glazed double-hung.

C DOE-2 Glass Library Listing for Single Clear (code 1000) with wood frame.

d Testing the Energy Performance of Wood Windows in Cold Climates. Brad James, Andrew Shapiro, Steve Flanders, Dr. David Hemenway. 1996. (Extensive study on air leakage.) Page 27, Table 4 "tight window" and "loose window" leakage rates normalized to CFM.

CITIES AND CLIMATE REGIONS ANALYZED

Researchers analyzed five cities representing various climate types and geographic regions to characterize the typical climate conditions that occur within the continental U.S. (temperate, cold, hot/humid and hot/arid). The cities analyzed in the study were:

- **Boston** (cold)
- **Chicago** (cold)
- **Portland** (temperate)
- **Atlanta** (hot/humid)
- **Phoenix** (hot/arid)

Typical Meteorological Year (TMY3) climate data for each of these cities was used in the computer simulations of the baseline and for each window upgrade test condition. Table 2 shows these representative cities and their comparative heating degree days (HDD), cooling degree days (CDD),[10] estimated regional rates for natural gas and electricity, and a carbon equivalent multiplier that represents the regional fuel mix used to generate electricity.

TABLE 2: CLIMATE AND FUEL CHARACTERISTICS FOR CITIES ANALYZED

CITY	HDD[8] (65°F)	CDD (65°F)	EST. GAS RATE ($/ MMBTU)[a]	EST. ELEC. RATE ($/KWHR)[b]	CO2 CONVERSION (ELEC) (LBS/KWH)[c]
Boston	5630	777	1.410	0.1459	0.828
Chicago	6498	830	0.873	0.1152	1.552
Portland	4400	390	1.265	0.0887	0.859
Atlanta	2827	1810	1.607	0.1107	1.495
Phoenix	1125	4189	1.543	0.1097	1.253

[a] U.S. Energy Information Administration. Average Price of Natural Gas Sold to Residential Consumers, by State, 2009-2011.
[b] U.S. Energy Information Administration. 2010 Electric Sales, Revenue, and Average Price.http://www.eia.gov/electricity/sales%5Frevenue%5Fprice/
[c] U.S. EPA, Clean Energy calculator. Accessed April 2012. http://www.epa.gov/cleanenergy/energy-and-you/how-clean.html

SIMULATION PROGRAM

Energy simulations for the baseline house and each window upgrade measure were carried out using the SEEM (Simple Energy and Enthalpy Model) program. Designed to specifically model residential building energy use, this program conducts concurrent hourly simulations of heat transfer, moisture (humidity), and infiltration. These simulations interact with each other as well as duct specifications, equipment, and weather parameters to calculate the annual heating and cooling energy requirements of the building. The program is based on algorithms consistent with current American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), American Heating and Refrigeration Institute (AHRI), and International Organization for Standards (ISO) calculation standards. Widely accepted as a residential simulation program, SEEM is used to support state building energy code revisions in Washington and Oregon and the U.S. EPA's Northwest Energy Star Homes program.

SEEM offers a number of advantages over other simulation programs. The step-by-step hourly thermal calculations accurately model both air temperature and mean radiant temperature using a highly efficient forward difference algorithm. Similar to the Lawrence Berkeley National Laboratory infiltration model, SEEM infiltration simulations realistically allow airflow to fluctuate with changing weather and mechanical ventilation and have been generalized to include the effects of exhaust fans and duct leakage. This program was specifically selected for this study due to its ease of use and its ability to produce reliable outputs for residential energy use.

For more information and to download the free program visit:
http://www.nwcouncil.org/energy/rtf/measures/support/SEEM/Default.asp

WINDOW TEST CONDITIONS

The range of energy-efficiency retrofits evaluated in this research study encompasses the improvements to window unit and glazing that might be undertaken by homeowners to improve the energy efficiency and comfort of their homes. The measures selected address infiltration, temperature driven heat losses, and solar gains, which were explained in Section 3. While homeowners have many options to choose from (or combinations of options), this study evaluates seven commonly employed approaches. The selected measures include readily available, off-the-shelf products ranging from simple, low cost do-it-yourself applications to more expensive options requiring professional installation. The following window upgrade test conditions were studied:

- Weather stripping for existing window
- Exterior storm window
- Interior window panel
- Insulating cellular shade
- Combination of exterior storm window and insulating cellular shade
- Interior surface film (including weather stripping)
- New, high performance replacement window

This study only considers specific retrofits/improvements to the glazing and the window frame and does not address additions of exterior architectural and landscaping elements. The addition of exterior architectural shading elements (overhangs, awnings, shutters, etc.) and landscaping elements (trellises, vines, trees, etc.) can have a substantial effect on the contribution of windows to residential energy use (especially to reduce solar gains during cooling conditions). These measures were outside the scope of this study. The energy simulations did, however, assume a standard “shading factor” of 65 percent to account for shading from buildings, trees, curtains, etc. It should also be noted that this study does not provide a comprehensive assessment of all window improvement measures or all combinations of measures, but rather is an assessment of those that are typically used.

The following pages describe each test condition used in the analysis and assumptions for thermal performance, SHGC, and airtightness values. For each test condition, “low value” and “high value” assumptions are used to represent the typical range of performance expected from that particular measure. “Low” value refers to the lower end of values for U-factor, SHGC, and airtightness, whereas “high” value refers to the larger values for these characteristics. These values are derived from an extensive review of data from prior studies. Empirical testing of window retrofit/replacement options was outside the scope of this study.

COST ANALYSIS METHODOLOGY

A thorough cost analysis was performed to compare the average return on investment (ROI), defined as the annual energy cost savings divided by the initial installation cost, of the test conditions in each city. Estimates were performed by volunteer industry experts within each installation practice, and include the cost of labor, materials, and contractor mark-up for the prototype home in Portland, Ore. Results were then regionally adjusted for each city using the R.S. Means 2012 Residential Construction Cost Estimator. Low- and high-cost values were established using the specifications defined in the Summary of Study Assumptions listed below for each test condition. The low-cost scenarios for the following three test conditions were assumed to be installed by the homeowner and included only material costs: weather stripping for existing window, insulating cellular shade, and interior surface film including weather stripping. The high-cost test conditions used specifications for commercially available products that were assumed to provide maximum potential energy savings for the given condition.

ROI was chosen as the preferred measure of cost effectiveness of the test conditions over simple payback, which is the mathematical inverse of ROI. The primary reason for using ROI is to allow homeowners to compare investments in home-energy efficiency to other, long-term financial investments. However, because ROI and simple payback are inversely related, the relative difference between window options will be equivalent using either method.

While an important consideration in extending a window’s useful life, window repairs were not considered within the scope of this study, except in the case of the high-cost exterior storm window test condition. In this case, repairs to the primary window that improved operability and fit of the sashes were required in order to accomplish the very low U-factor assumed in the Summary of Study Assumptions for that test condition.

WEATHER STRIPPING

Weather stripping improves the airtightness of an existing window by sealing gaps at head, sill, meeting rail, and at vertical edges to reduce air leakage.

The red arrows indicate metal weather stripping that fits into a routed channel along the sides and bottom of the sash.

OPTIONS

- The four common types of weather stripping are spring-metal, plastic strips, compressible foam tapes, and sealant beads.
- Common materials are felt, open and closed-cell foams, vinyl, and metals (bronze, copper, stainless steel, and aluminum).
- Tension seal options block drafts by pressing against the sides of a crack to create a seal. Magnetic and interlocking metal channel options are very effective at air sealing.

BENEFITS

+ Improves comfort by reducing drafts.
+ Improves airtightness by reducing both air infiltration and exfiltration.
+ Maintains aesthetics of existing window.
+ Reduces entry points for insects and moisture.

DRAWBACKS

- Self-stick version may be difficult to install.
- Some options may require professional installation.
- No thermal insulation benefit.

ADDITIONAL CONSIDERATIONS

Installation methods vary by product type. Many use self-stick adhesives; others must be stapled, glued or tacked in place. Weather stripping comes in varying depths and widths and must be applied such that it does not interfere with the operation of the window. Some products are more durable than others. Replacement frequency will vary depending on material type, friction, weather, temperature changes, and normal wear and tear. Metal options (bronze, copper, stainless steel, and aluminum) can last for many years.[11]

SUMMARY OF STUDY ASSUMPTIONS

WEATHER STRIP	LOW VALUE	HIGH VALUE
Specifications	Metal interlocking gaskets and T-rail, professionally installed.	Homeowner installed rubber or felt gaskets
Window U-Factor	0.77	1.05
SHGC	0.74	0.74
Window Air Leakage (CFM @ 50 pa)	156	812

EXTERIOR STORM WINDOW

Exterior window unit applied over an existing window to protect from weather and to improve energy performance.

A traditional wood storm window fastened by hangers at the top. This storm window is also secured by four screws along the perimeter.

OPTIONS

- Wood, aluminum, and vinyl are the most common frame materials.
- Single- or double-pane glass.
- Clear or low-e coatings.
- Panel options are:
  - *Triple Track:* two operable glass panels with operable screen
  - *Double Track:* one operable glass panel with operable screen
  - *Fixed:* one, non-operable glass panel

BENEFITS

+ Improves thermal performance and air-tightness of window assembly (fixed panels are most airtight).
+ Protects and may extend the life of existing windows.
+ Low-e coatings may decrease solar heat gain in cooling-dominated climates.
+ Improves indoor comfort near windows.
+ Reduces noise infiltration.

DRAWBACKS

- Fixed-panel models need to be installed/removed seasonally if window is to be opened.
- May affect egress requirements.
- May conflict with codes/regulations that prohibit changing exterior window appearance if low-e glazing is used.
- May interfere with existing window operation (i.e., outswinging casement and awning windows).

ADDITIONAL CONSIDERATIONS

Exterior storm windows can be homeowner or professionally installed and caulked in place with “weep holes” at the bottom of the frame to allow any moisture that collects between the primary window and the storm window to drain out. Windows may be difficult to install on upper floors of multi-story houses. Exterior storm windows provide added life to existing window sash, paint finish, and historic glass. Maintenance and service life for the storm windows will depend on frame material. Exterior storm windows provide added life to existing window sash, paint finish, and historic glass. Maintenance and service life for the storm windows themselves will depend on frame material.

SUMMARY OF STUDY ASSUMPTIONS

EXTERIOR STORM WINDOW	LOW VALUE	HIGH VALUE
Specifications	Low-E double pane operable exterior storm; aluminum triple-track frame	Single-Clear operable exterior storm; aluminum triple-track frame
U-Factor	0.21	0.55
SHGC	0.27	0.31
Window Air Leakage (CFM @ 50 pa)	307	1027

INTERIOR STORM PANEL

Plastic or glass panels mounted on the indoor side of an existing window to improve energy performance.

Interior storm panel.

Image courtesy of: Environmental Window Solutions, LLC

OPTIONS

- *Mounting:* Face-mounted onto window casing or inset and mounted on window jamb.
- *Glazing:* Usually clear acrylic or polycarbonate; glass with or without low-e coating.
- *Frame:* Aluminum most common; steel, vinyl, and wood frames available.
- *Operability*: Most are fixed panels but operable versions are available.

BENEFITS

+ Improves thermal performance, airtightness and comfort.
+ Easier to install than exterior storm windows.
+ Do-it-yourself friendly.
+ Require less maintenance than exterior storm windows because they're not exposed to the elements.
+ Doesn't affect exterior aesthetics — an important consideration for historic homes.
+ Reduces noise infiltration.

DRAWBACKS

- Reduced visibility with plastic panels.
- Fixed-panel models need to be installed/removed and stored seasonally if window is to be opened.
- May affect egress requirements.
- Potential ventilation/condensation issues.
- Does not protect or extend the life of primary window.

ADDITIONAL CONSIDERATIONS

Interior window panels can be installed by a homeowner or professional. Glass pane types offer better visibility and longer life than plastic pane types, but glass is heavy and fragile. Plexiglas and acrylics are tougher and lighter than glass, but may scratch easily when stored and may turn yellow over time when exposed to sunlight.

SUMMARY OF STUDY ASSUMPTIONS

INTERIOR WINDOW PANEL	LOW VALUE	HIGH VALUE
Specifications	Low-E single pane fixed interior storm	Single-Clear operable interior window panel
U-Factor	0.36	0.48
SHGC	0.39	0.60
Window Air Leakage (CFM @ 50 pa)	203	456

INSULATING CELLULAR SHADES

Pleated shades applied to the inside of the window opening to improve thermal performance.

Cellular shade with interior tracks. Image © Comfortex Window Fashions

OPTIONS

- Accordion-like shade folds up or both up and down.
- Optional side tracks in which the edges of the shades run and weather stripping to improve airtightness.
- Manual or motorized (wireless electronic) operation.
- Cell configuration: Single or dual cell.
- Fabric: light filtering or opaque in a range of textures and colors.

BENEFITS

+ Improved thermal performance when deployed.
+ Minimizes drafts near windows.
+ Provides daylight control and privacy.
+ Can be combined with air sealing and repair of existing window and with exterior storm windows.
+ Minimal interference with existing window operability and egress.

DRAWBACKS

- Requires proper deployment daily.
- Views and daylighting reduced when deployed.
- No energy benefit when shades are raised for light and views.

ADDITIONAL CONSIDERATIONS

May be owner or professionally installed. Most fabrics repel dust and are inherently anti-static, but light vacuuming or dusting is routinely required. Many shades are also fully washable. Service life depends on the fabric selected and care in operation. Many shades carry a 10-year warranty on the mechanisms and a 5-year warranty on the fabric, but can last longer with careful use.

SUMMARY OF STUDY ASSUMPTIONS

INSULATING CELLULAR SHADES	LOW VALUE	HIGH VALUE
Specifications	Shades with side tracks + existing Single Clear glazing Assumes shades deployed 70% of nighttime hours; at other hours performance matches baseline.	Shades without side tracks + existing Single Clear glazing Assumes shades deployed 70% of nighttime hours; at other hours performance matches baseline.
U-Factor (night/day)	Assumes shades deployed 70% of nighttime hours; at other hours performance matches baseline.	0.58/1.05
SHGC	0.74	0.74
Window Air Leakage (CFM @ 50 pa)	156	1360

INTERIOR SURFACE FILM

Self-adhesive polyester film (2-7 mil) applied to the interior surface of glass to reduce solar gains and glare, improve U factor (low-e options only) and increase security.

Homeowner installation of low-e interior surface film.

OPTIONS

- *Dyed/tinted films*: Reduce SHGC by absorbing solar energy. These have a neutral visible color (bronze or grey) which also reduces visible light transmission.
- *Reflective or metalized films:* Reduce SHGC by reflecting and absorbing solar energy. Their mirror-like appearance also reduces visible light transmission.
- *Low-e films:* Reduce both U-factor and SHGC. These vary widely in color, reflectivity, and visible light transmission.
- *Security films:* Deter vandalism but have negligible impact on U factor and SHGC.

BENEFITS

+ Reduces unwanted solar heat gain.
+ Reduces UV transmission (reduced fading).
+ May reduce radiant heat loss (low-e coating only).
+ Only window attachment option rated by National Fenestration Rating Council.
+ No operation or maintenance required.

DRAWBACKS

- Reduces visible light transmission (darkens views and may increase need for electric lighting).
- High reflectance and darkly tinted coatings may be not be desirable aesthetically.
- May conflict with historic regulations that prohibit changing exterior window appearance.
- Reduces beneficial winter solar heat gain in heating-dominated climates.

ADDITIONAL CONSIDERATIONS

Depending on the film, installation may be done by the homeowner, or may require professional installation (with added cost). Weather stripping should be completed before the film installation.

Although durable, films may scratch or bubble over time and need to be removed/replaced. Most films carry a 5 to 10 year warranty, but can last longer with good care.

SUMMARY OF STUDY ASSUMPTIONS

INTERIOR SURFACE FILM	LOW VALUE	HIGH VALUE
Specifications	Professionally-applied low-e film; tight existing window	Homeowner-applied tinted film; leaky existing window
U-Factor	0.55	1.05
SHGC	0.47	0.61
Window Air Leakage (CFM @ 50 pa)	156	812

NEW HIGH PERFORMANCE WINDOW

Replacement with new, high performance window to improve thermal performance and airtightness.

OPTIONS

- *Frame:* Wood, metal (thermally broken), fiberglass, polycarbonate, or vinyl options.
- *Glazing:* Double and triple-insulated glass units (IGU) with clear or tinted glass, low-e coatings and/or inert gas fill.
- *Operation:* Fixed, double-hung, casement, sliding, awning, and hopper options.

BENEFITS

+ Predictable performance with a warranty when installed correctly.
+ May be specified to accommodate high performance glazing units.
+ Frame or cladding materials may require less maintenance than wood windows.
+ Installation process can uncover and repair long-term water intrusion issues around window.

DRAWBACKS

- May conflict with codes/regulations that prohibit changing exterior window appearance.
- Original window material and character is permanently destroyed upon removal.
- Non-wood frame options are difficult to repair. Replacement of failed IGU seals can be costly.
- New wood frames may not last as long as old growth wood windows. High performance glazing and frames can be two to four times more expensive than other retrofit options with comparable energy savings potential.

ADDITIONAL CONSIDERATIONS

Installation requires professional expertise. Maintenance and expected service life varies. Warranties range from 10 years to “lifetime” and are often limited once a home is sold. New windows possibly carry a National Fenestration Rating Council (NFRC) performance specifications for U-factor, SHGC, airtightness, etc.

SUMMARY OF STUDY ASSUMPTIONS

NEW HIGH PERFORMANCE WINDOW	LOW VALUE	HIGH VALUE
Specifications	Double-glazed, double-hung fiberglass/wood/vinyl window with suspended low-e film; inert gas fill; warm edge spacer system and insulating foam filled frame	Double-glazed, double-hung vinyl window with low-e film
U-Factor	0.24	0.35
SHGC	0.39*	0.24*
Window Air Leakage (CFM @ 50 pa)	38	44

*In the case of the replacement window, a low U-factor window was selected with a higher SHGC to optimize performance in cold climates.

V. RESULTS

The energy analysis calculated low and high values for the prototype home's energy use based on a range of input values for each test condition. Table 3 below summarizes the simulation inputs. These input values were sourced from existing research (see References section) to characterize the range of performance values for typical installations. Assumptions and sources for each test condition can be found in Appendix A.

TABLE 3: SUMMARY OF TEST CONDITION SIMULATION INPUTS

TEST CONDITIONS		Thermal Performance (U-factor, SHGC)		Air Leakage (Window leakage CFM @ 50 pa)	
		(LOW VALUE)	(HIGH VALUE)	(LOW VALUE)	(HIGH VALUE)
1	**Baseline: double hung single pane window**	0.77, 0.74	1.05, 0.74	646	1360
2	**Weather strip existing window**	0.77, 0.74	1.05, 0.74	156	812
3	**Exterior storm window**	0.21, 0.27	0.55, 0.31	307	1027
4	**Interior window panel**	0.36, 0.39	0.48, 0.60	203	456
5	**Insulating cellular shades,* night-time/daytime values**	0.26/0.77, 0.74	0.58/1.05, 0.74	156	1360
6	**Insulating cellular shades* with exterior storm, night-time/daytime values**	0.12/0.21, 0.27	0.22/0.55, 0.31	156	1360
7	**Interior surface film + weather stripping**	0.55, 0.47	1.05, 0.61	156	812
8	**New high performance replacement window**	0.24, 0.39**	0.35, 0.24	38	44

*Assumes shades are deployed correctly 70 percent of the time.

**In the case of the replacement window, a low U-factor window was selected with a higher SHGC to optimize performance in cold climates.

KEY FINDINGS AND ANALYSIS

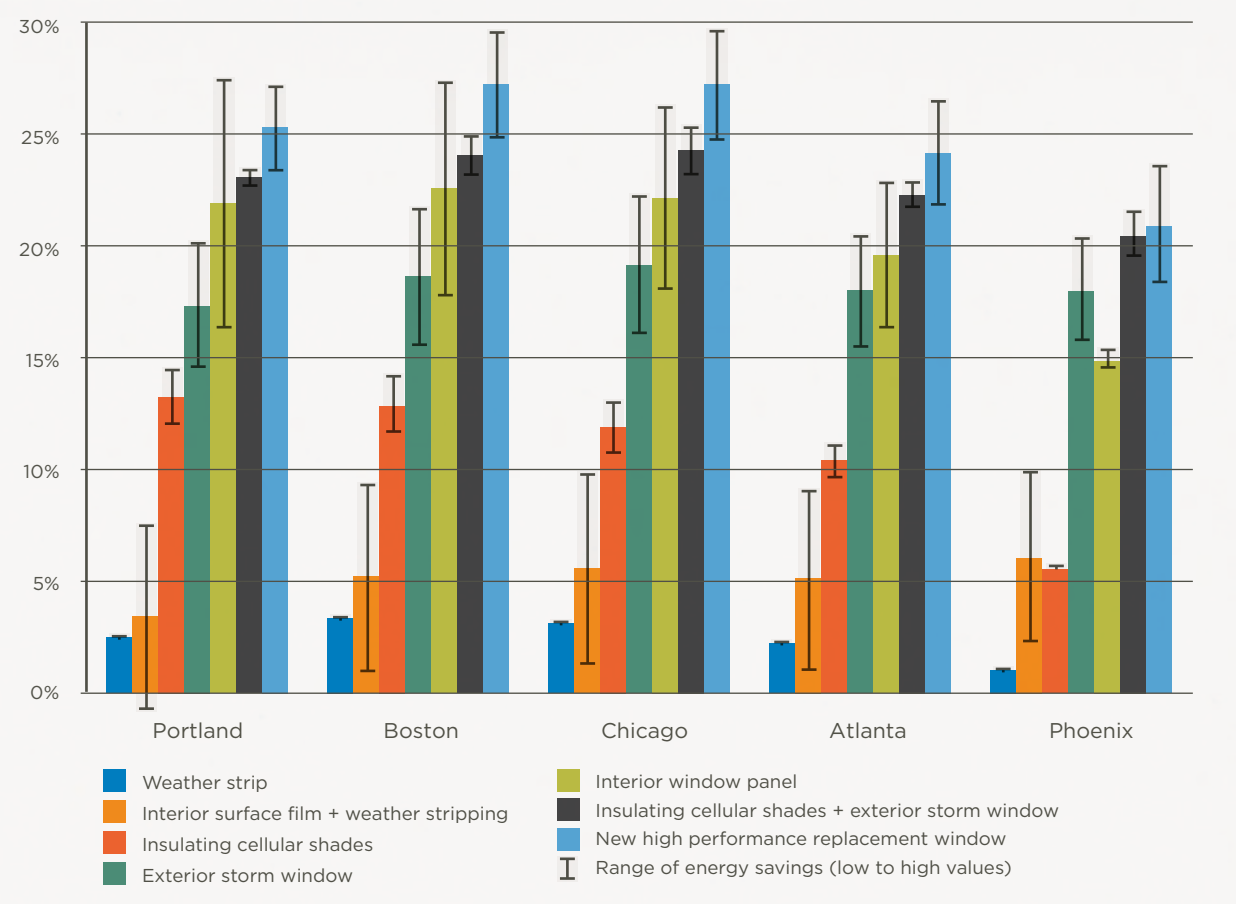
The results from the simulation analysis provide valuable information about the range of savings available for window upgrade measures in a variety of climates and the relative performance of the various options in each climate. The most significant trends that were observed include the following:

1. Retrofit measures can achieve performance results comparable to new replacement windows.

Importantly, Figure 5 shows that for all cities, at least one and often two of the selected measures can achieve energy savings within the range of savings expected from new, high performance replacement windows. This is noteworthy as it is typically assumed that replacement windows offer the best option for performance improvements. Figure 5 shows that interior window panels, exterior storm windows combined with cellular blinds, and in some cases even exterior storm windows alone fall within the range of performance for replacement windows.

At least one and often two of the selected measures can achieve energy savings within the range of savings expected from new, high performance replacement windows.

Figure 5: Annual Percent Energy Savings For Various Window Upgrade Options



The bars on this graph show the average percentage of energy savings for the prototype home with each window upgrade measure applied. The black bars represent the range of possible savings expected based on the high and low value assumptions for each measure. For instance, clear operable interior window panels in Portland show a 16 percent whole-house energy savings when applied to existing, leaky, single-pane windows, whereas low-e, fixed interior window panels in the same city show a 27 percent whole-house energy savings. Note that the savings predicted in Figure 5 are not additive for the individual measures and are not intended to predict actual savings. Instead, the results are meant to be used to evaluate the relative performance of measures where other more cost-effective energy saving strategies have been implemented first.

2. The range of energy performance for retrofit options varies significantly.

Window upgrades demonstrate the potential for significant energy savings in all the cities studied as shown in Figure 5. This graph shows the average percent energy savings for each measure in each city, along with the range of high and low savings that might be expected depending on the measure's anticipated installed performance. Percent energy savings is highly dependent on the baseline, whole-house energy consumption of the model. This analysis assumed that the prototype house had already been upgraded to a better than average level of energy performance before simulation. The intent of this analysis is to show the relative performance of the different window retrofit options while maximizing the cost effectiveness of the investment.

More specifically, this study shows that the range of energy savings for a set of upgrade measures applied to existing windows demonstrates as little as 1 percent savings and as much as 30 percent savings when considering options with the most ideal values for U-factor, SHGC, and air leakage. The highest performing test conditions demonstrate potential savings between 15 to 30 percent energy savings in all cities and across the full range of installation conditions studied, approximately double the energy performance of the mid-range options and 6 to 10 times the lowest performing measure.

The highest performing measures include exterior storm windows, interior window panels, the combination of insulating shades plus exterior storm windows, and high performance replacement windows. Two of the measures studied (insulating cellular shades alone and interior surface films) perform in the mid-range of results, showing between 5 to 15 percent energy savings over the baseline. The performance of these measures varies significantly depending on the climate in which they are installed. The measure showing the least effectiveness is weather stripping, which results in less than 5 percent energy savings across all climate regions.

3. Improving window airtightness alone is not enough.

The simulation analysis that showed the least amount of energy savings over the baseline was weather stripping, resulting in an energy savings of only 1 to 3 percent for all the cities studied. Actual savings from this measure will vary widely depending on the condition of the existing window before installing the weather stripping, but the relative difference in energy savings between options should remain consistent.

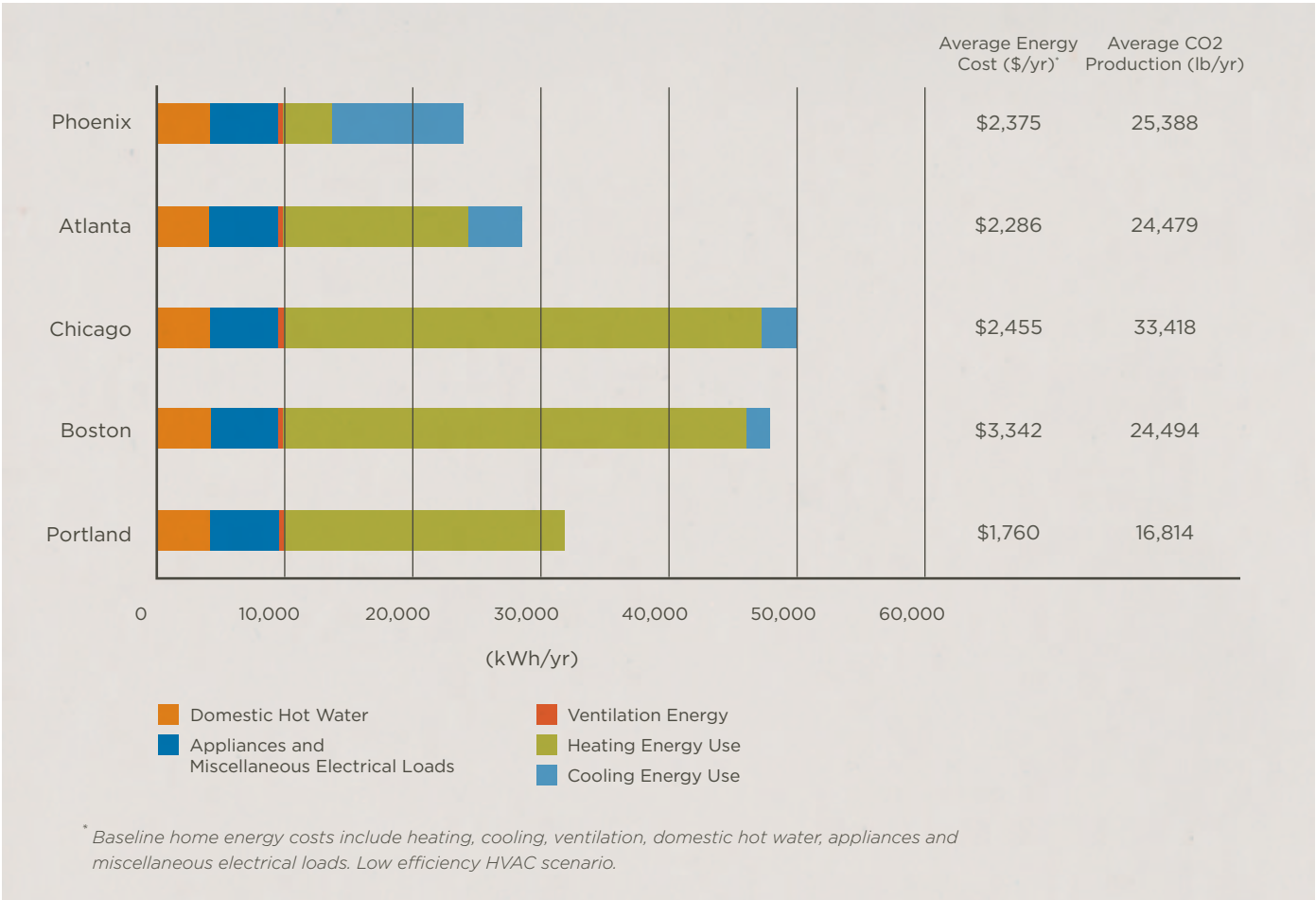
These results, however, indicate that reducing air infiltration from windows has only a minor contribution to energy savings in all the climates studied. This is consistent with other research[12] and suggests that energy savings from reduced infiltration may be secondary to other considerations that improve the functionality and extend the life of the window, such as reduction of drafts, elimination of water infiltration, and window preservation.

4. Energy cost and carbon savings varies by city and climate.

Figure 6 shows the baseline energy use established by SEEM for the prototype home in each of the five cities studied. Not surprisingly, energy use varies significantly from heating- to cooling-dominated climates. All of the cities studied are heating-dominated (shown by the larger orange bar in Figure 6) except for Phoenix, which uses 2.5 times more energy for cooling than for heating.

In addition, Figure 6 shows annual energy costs and operational CO2 emissions for each of the five cities. Variations in gas and electricity costs and the regional fuel mix for electricity from city to city shows a non-linear relationship between the energy cost and the CO2 emissions among the cities. For example, although the baseline home has substantially higher energy cost in Boston ($3,342/yr) than in Chicago ($2,455), the Chicago home has a greater carbon impact (33,418 lb/yr, versus 24,494 lb/yr for Boston).

Figure 6: Baseline Annual Energy Use, Energy Cost and CO2 Emissions for the Prototype Home by City



* *Baseline home energy costs include heating, cooling, ventilation, domestic hot water, appliances and miscellaneous electrical loads. Low efficiency HVAC scenario.*

Due to these variations in climate, fuel costs, and fuel mix, the results from window improvement measures show interesting results not just in energy savings, but also in energy cost and CO2 emissions reductions across the different locales. Table 5 documents the average energy cost savings (in $/yr) for each measure compared to the baseline. When comparing cities, such as Boston and Portland, the savings more than double.

TABLE 5: AVERAGE ENERGY COST SAVINGS OVER THE BASELINE

	AVERAGE ENERGY COSTS SAVINGS OVER BASELINE ($/YR)*				
WINDOW UPGRADE MEASURE	PORTLAND	BOSTON	CHICAGO	ATLANTA	PHOENIX
Weather strip existing window	$38	$90	$57	$41	$20
Interior surface film + weather stripping	$52	$178	$143	$136	$170
Insulating cellular shades	$197	$324	$198	$167	$85
Exterior storm window	$258	$565	$424	$404	$453
Interior window panel	$326	$620	$426	$379	$326
Insulating cellular shades + exterior storm window	$342	$702	$508	$473	$494
New high performance replacement window	$376	$778	$555	$502	$499
*low efficiency HVAC scenario					

These findings are based on study assumptions that the Pettygrove Residence has leaky, double-hung windows and that high performance retrofit and replacement measures have been applied; these savings may not be typical of an average home or standard lower performance improvement measures.

Regional variations in energy cost savings affect the potential energy cost savings of each measure, because higher or lower energy costs have a multiplier effect on the energy savings. As noted earlier, the cost of electricity for the cities used in this study is much greater (2 to 3.9 times higher) than the cost of gas on a per kWh basis. In addition, the cost of electricity and gas varies considerably city to city. So even though energy savings in Chicago are a little higher than in Boston, the higher gas prices in Boston as compared to Chicago (62 percent higher) create greater cost savings for each test condition, yielding the highest cost savings on installed measures. It should be noted, however, that these results are based a prototype home with a gas furnace. Other fuels and heating systems, such as oil furnace or electric resistance heating, will yield different results (i.e., a home in Portland might show lower returns for window upgrade measures if it had an electric heating system since electricity prices there are low).

In analyzing the energy cost savings for retrofit versus replacement options, Table 5 also shows that the average cost savings from the cellular shade plus exterior storm option is only slightly less than the cost savings generated from the replacement windows. Table 6 shows a similar comparison, documenting the average operational CO2 savings for each measure over the baseline. This demonstrates that while replacing existing, single pane leaky windows with new high performance options has the greatest potential for reducing operational CO2 emissions, comparable savings are offered by the exterior storm window, interior window panel, or insulating cellular shades plus exterior storm window combination.

TABLE 6: AVERAGE CO2 SAVINGS OVER THE BASELINE

TEST CONDITION	AVERAGE CO2 SAVINGS OVER BASELINE (LB/YR)*				
	PORTLAND	BOSTON	CHICAGO	ATLANTA	PHOENIX
Weather strip existing window	363	727	776	359	201
Interior surface film + weather stripping	491	1,290	1,939	1,616	1,918
Insulating cellular shades	1,873	2,677	2,714	1,273	739
Exterior storm window	2,457	4,293	5,775	4,302	4,955
Interior window panel	3,096	4,911	5,820	3,581	3,411
Insulating cellular shades + exterior storm window	3,255	5,418	6,931	4,830	5,318
New high performance replacement window	3,570	6,054	7,580	5,034	5,358
*low efficiency HVAC scenario					

*These findings are based on study assumptions that the Pettygrove Residence has leaky, double-hung windows, and that high performance retrofit and replacement measures have been applied; these savings may not be typical of an average home or standard lower performance improvement measures.

5. Climate is an important factor in determining the appropriate application of interior surface film.

Passive solar heating occurs when beneficial solar energy is absorbed through windows to offset at least part of a building's heating load. All heating-dominated cities benefit from direct solar exposure on windows during cooler months. Windows on elevations facing the sun with high SHGC values or clear glass will pass more beneficial energy into the house, whereas low-e interior surface films reduce the amount of solar energy that can enter the house through these windows.

Since Phoenix is cooling-dominated (shown by the larger blue bar in Figure 6), it receives the most significant benefits from low SHGC (low-e) windows by reducing solar gains during the long cooling season. However, climates with extreme hot and cold, such as Chicago, also benefit from the application of low SHGC treatments. In contrast, the reduction in beneficial winter solar gains from low SHGC (low-e) window treatments has the reverse effect in Portland, which is entirely heating dominated and has no mechanical cooling in these simulations. In this instance, the interior surface film applied to the higher U-factor window uses more energy than the baseline scenario (shown as negative savings in Figure 5) because beneficial solar energy is reflected away from the house during the heating season.

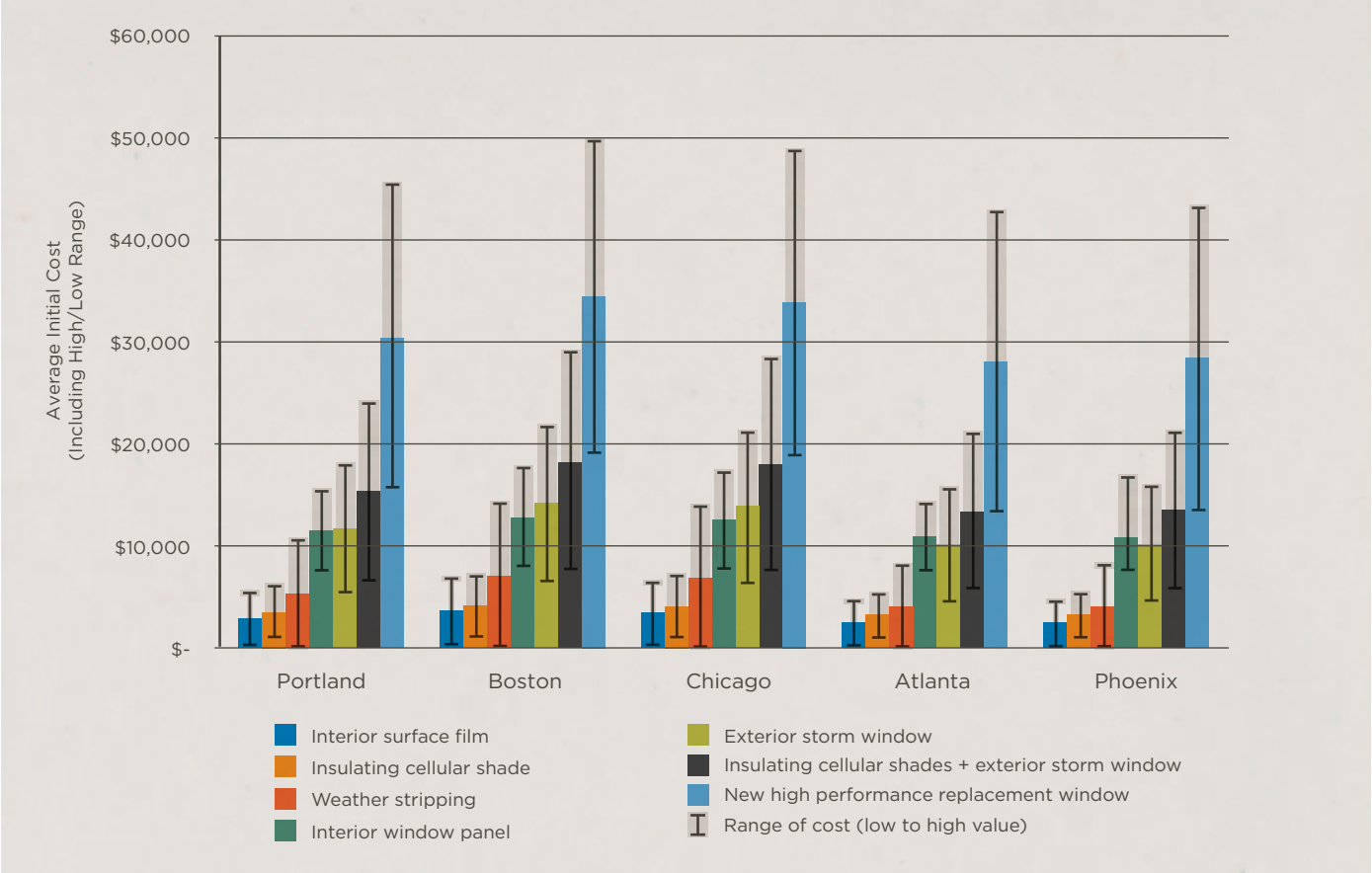
These varied simulation results for interior surface film show that selecting window upgrade options based on optimal SHGC, designed appropriately for a the climate and solar conditions of the site, is crucial to maximizing energy savings. The influence of SHGC values on net energy savings over the course of a year is particularly important in properly selecting different window options. For instance, the exterior storm windows as modeled in this study both had very low SHGC (0.27 to 0.31) compared to the interior window panels (SHGC = 0.39 to 0.60).

6. Almost every retrofit option offers a better return on investment than replacement windows.

A detailed analysis identified the costs of each retrofit or replacement measure and was adjusted based on differences in regional material and labor costs. Full cost data can be seen in Appendix C. While every attempt was made to gather accurate pricing for the prototype house, actual costs may vary depending on the number and size of windows. This study focused on commercially available window options that yield the highest possible energy performance improvement. It should be noted that far less expensive materials are available on the market. More affordable options, however, are likely to offer reduced energy savings. This analysis also includes a comprehensive estimate of the full cost of window replacement, factoring in the cost of siding repair and replacement, sheetrock repair and replacement, and the paint touch-ups that are typically required with window replacement. For these reasons, costs may appear higher than what is typically quoted in the market, which is often based on material-only pricing.

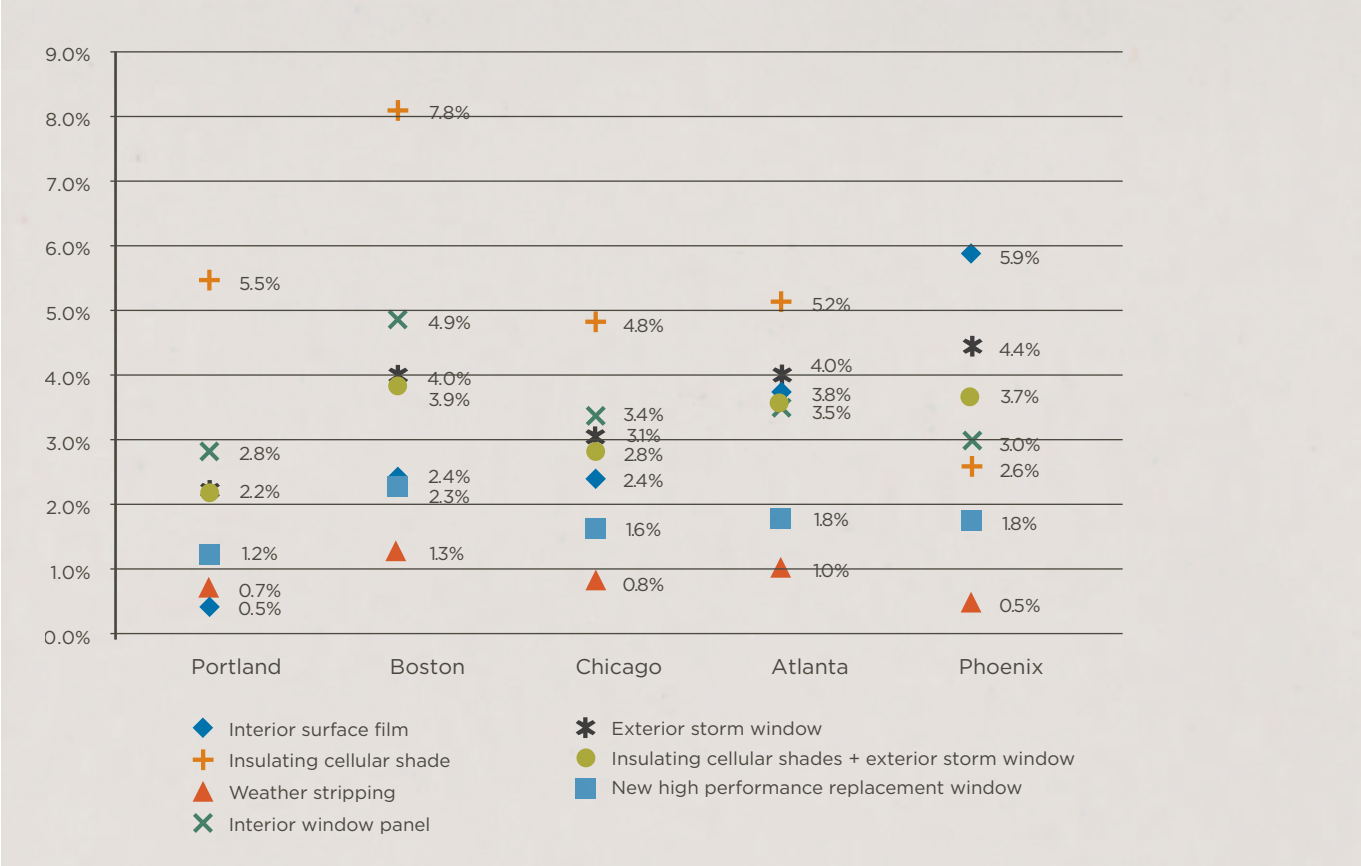
As can be seen in Figure 7, new windows are by far the most costly retrofit measure for the prototype house. The full cost of replacing existing windows with high performance (very low U-factor) windows averages about $30,000 per home. The high performance exterior storms and insulating shade combination costs about half of new windows at about $15,000 per home, while exterior and interior storms cost around $12,000 per home. Of note, insulating shades offer a less expensive solution, costing about $3,000 per home on average and provide the additional benefits of privacy and room shading.

Figure 7: Average Initial Costs of Window Options For All Cities



While included together in the energy simulation, interior surface film and weather stripping were separated for the purposes of calculating costs of installation. Costs for these two options have the highest variability of all window options, since the low range of cost assumed homeowner installation and the high range assumed professional installation. Excluding labor, they are the least costly strategies to achieve energy savings of any of the window retrofit options. Yet upfront cost data alone should not be the only consideration when selecting the best window strategies for a given application—first costs should be analyzed based on the return that can be expected from utility bill savings. A comprehensive graph of average return on investment for the various test conditions and adjusted regionally for energy costs and construction costs is shown in Figure 8.

Figure 8: Average Return on Investment of Window Options For All Cities



Figures 9, 10, and 11 offer a more in-depth return on investment analysis for three cities considered in this study, Boston, Portland, and Phoenix. With its harsh climate and high fuel costs, window retrofit or replacement measures in Boston offer the highest ROI of any of the locations analyzed. At the other extreme, window measures in Portland in general yield the lowest rate of return, with its mild climate and lower energy costs. Phoenix represents the range of results that may be expected in warmer climates.

In heating-dominated climates, insulating cellular shades offer by far the highest average ROI, from 4.8 and 7.8 percent; this low cost measure offers fairly significant energy performance returns, making this approach the clear winner in terms of return on investment. At the other end of the spectrum, new high performance windows offer a poor average rate of return, from 1.2 to 2.3 percent, depending on location. While new windows significantly improve performance, the upfront costs are substantial.

In a cooling-dominated climate, interior surface film offers the greatest ROI at 5.9 percent; insulating shades offered considerably less benefit than in heating-dominated climates, with return on investment of only 2.6 percent. Notably, between the three climates, interior surface film offers the most variable ROI, as it depends on the extent of cooling needed during the year.

Interior window panels offer a 4.9 to 2.8 percent return in all climate conditions studied, and exterior storm windows produce a similar ROI. The combination of insulating shades and an exterior window storm offers ROIs of between 3.9 to 2.2 percent.

Figure 9: Average Annual Return on Investment — Boston

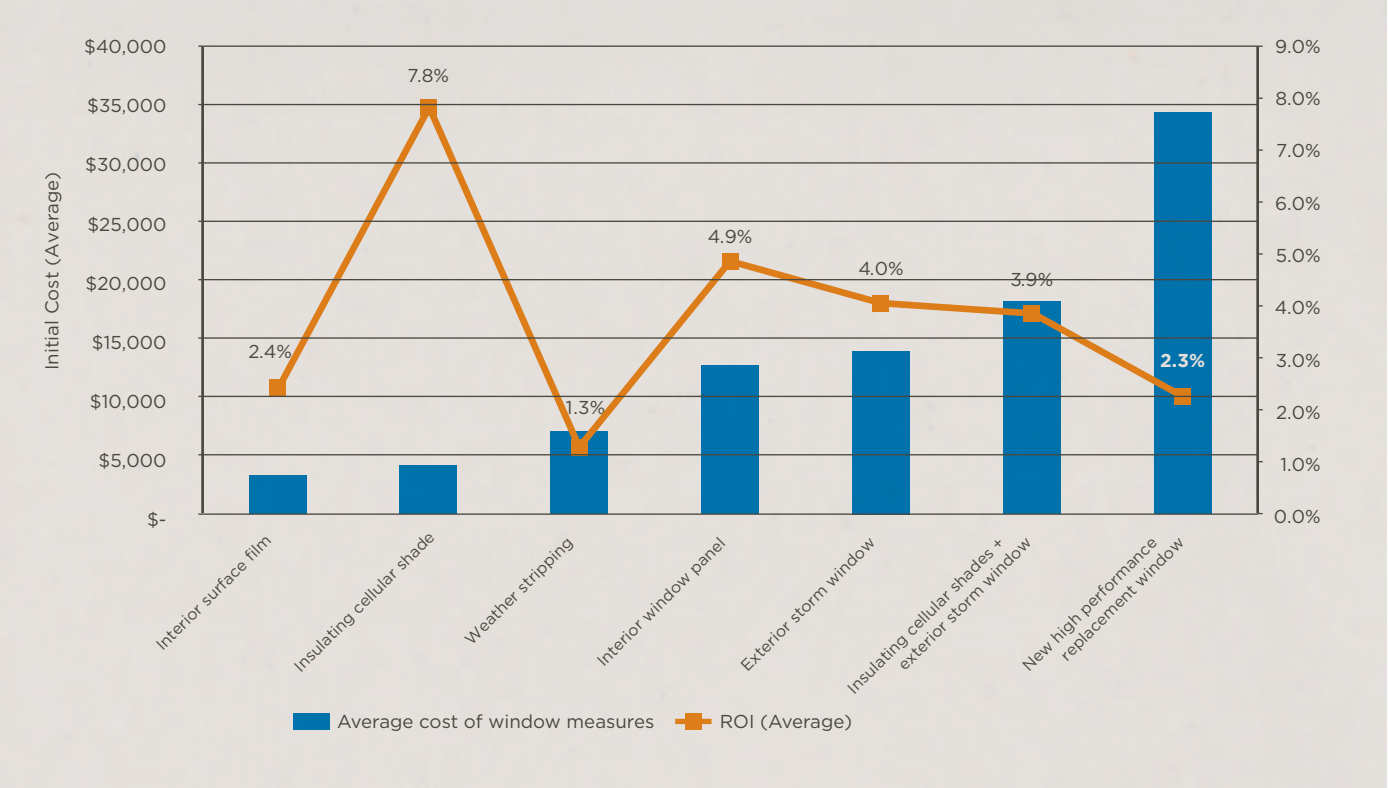


Figure 10: Average Annual Return on Investment — Portland

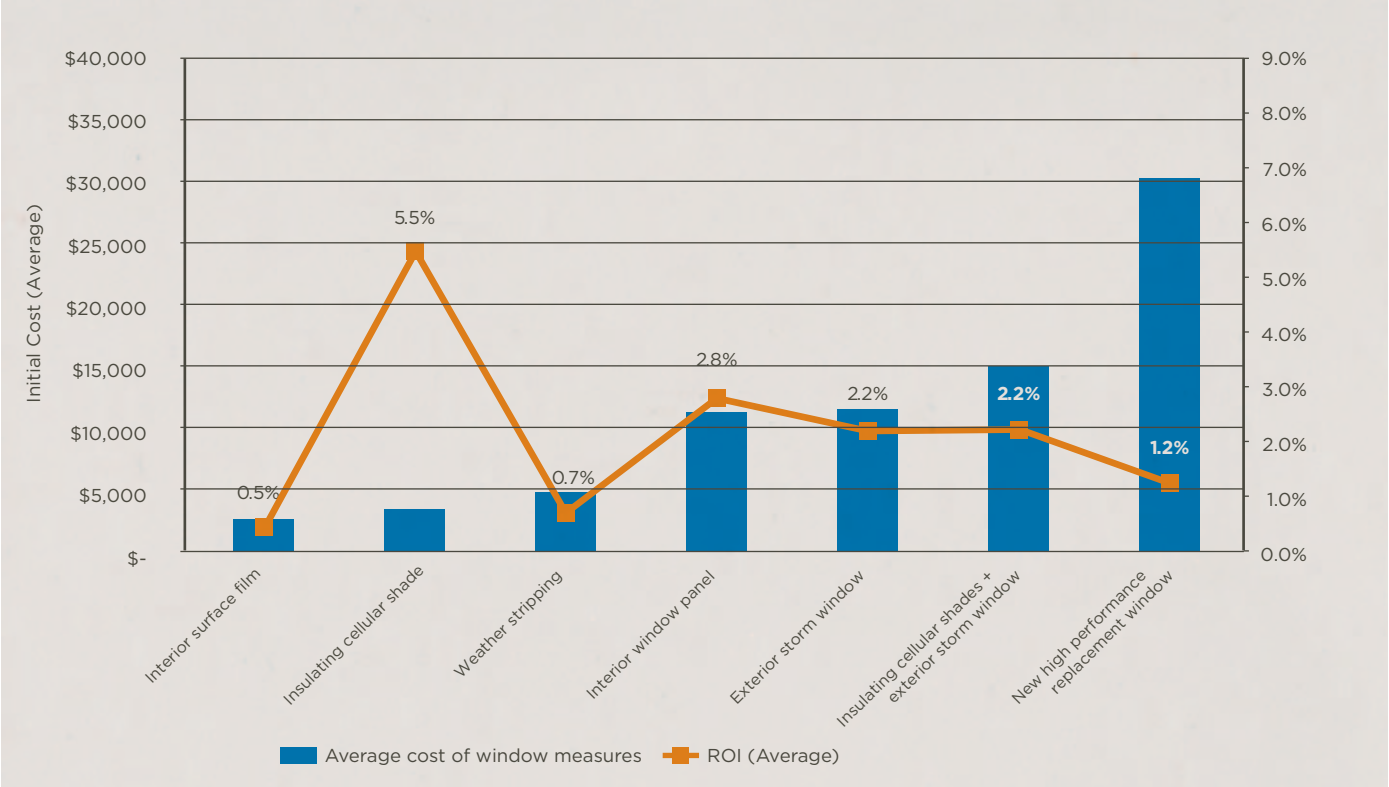
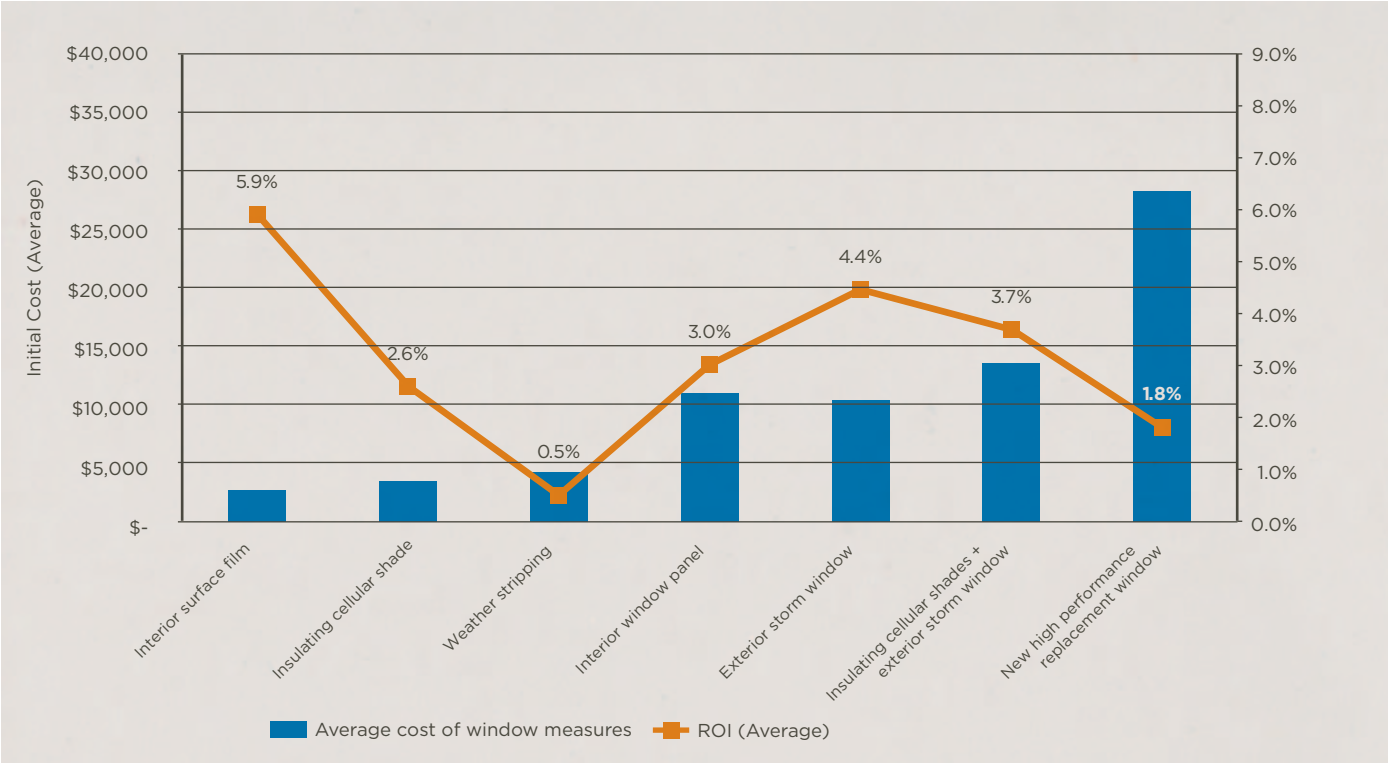


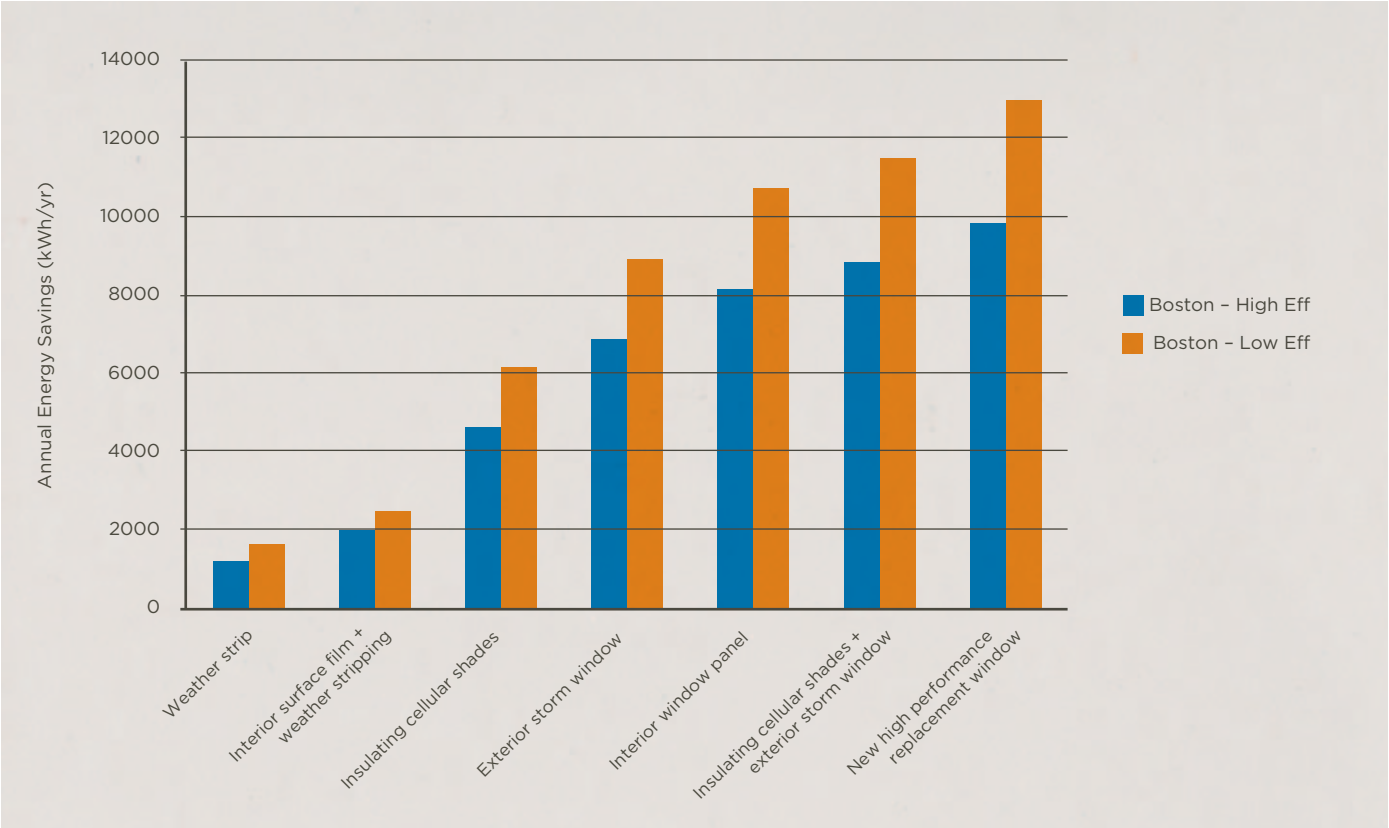
Figure 11: Average Return on Investment — Phoenix



7. Impact of window improvements are diminished if heating system has already been upgraded.

The results of this analysis assume a gas furnace with a minimum federal efficiency rating of 0.78 Annual Fuel Utilization Efficiency (AFUE) and relatively leaky ducts. Additional results were generated using a higher efficiency furnace with 0.92 AFUE and tight, well-insulated ductwork. In the Boston example, the average energy savings in kWh/yr for the higher efficiency furnace scenario are compared below in Figure 12 for all test conditions. As these results indicate, the total annual energy savings from various window upgrades are consistently lower when a more efficient furnace is selected. Even though the heat loss through the windows is the same in both efficiency scenarios, less total energy is needed to run the high efficiency furnace. As the total energy needed for heating is reduced, the potential savings from the windows is also reduced proportionally. Improvement of cooling system efficiency will have a comparable impact on reducing window savings in areas that use air conditioning.

Figure 12: Average Energy Savings (kWh/yr) over baseline for low and high efficiency HVAC

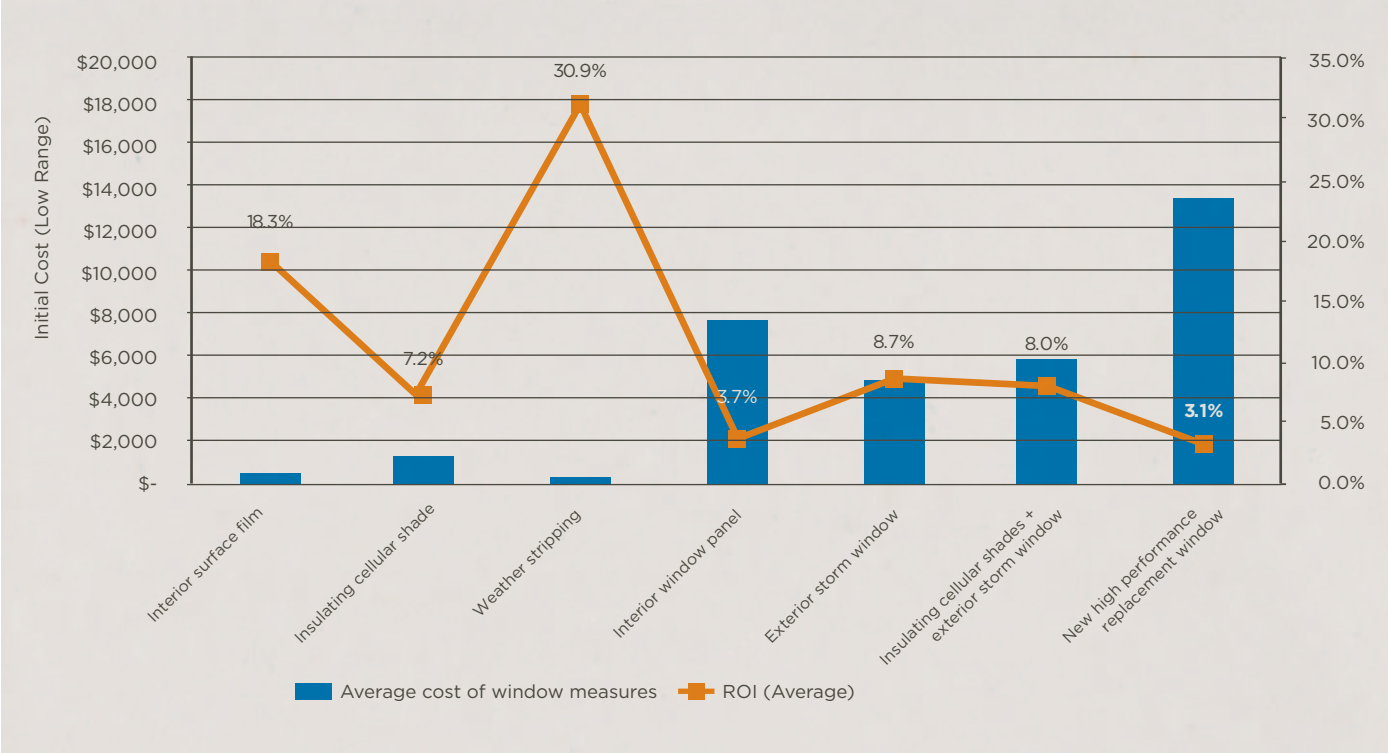


This graph charts the average kWh savings per year that the baseline home is expected to realize with various window improvement measures. The blue bars represent energy savings when the home is assumed to have a high efficiency heating system; the red bars represent savings for the home with a low efficiency heating system. These results show that the savings from upgrading windows is diminished if a home's heating system has already been upgraded. While this graph shows simulation results for Boston, the influence of equipment efficiency on the window savings applies to the other cities studied in proportion to their heating load.

8. The best returns on investment are generated for do-it-yourself measures such as simple weather stripping and interior surface film.

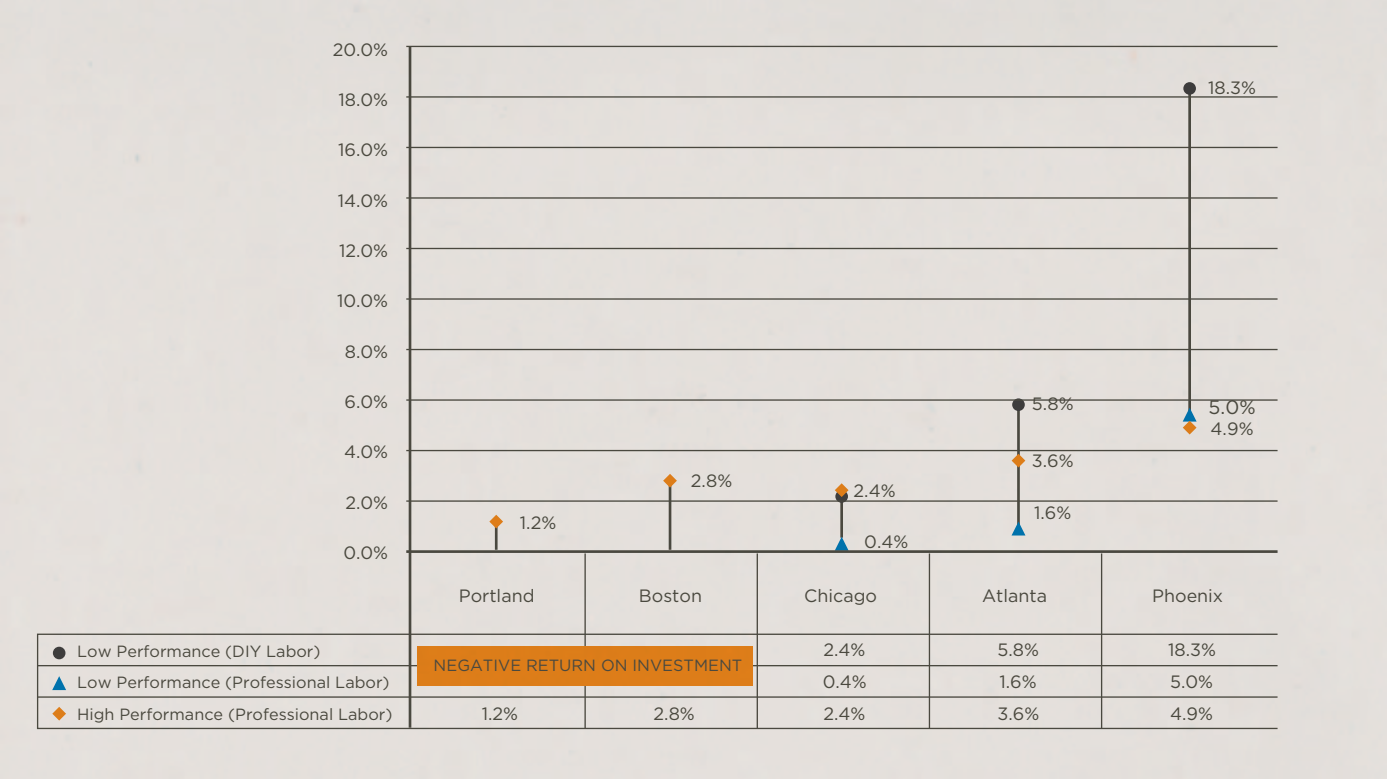
Even though the weather stripping option has the lowest energy cost savings and a low average ROI relative to other window improvement strategies, Figure 13 shows that these savings can be cost effectively captured through homeowner installation, producing higher returns than any of the other window options studied. In Phoenix, the city that showed the lowest total energy savings from weather stripping, owner-installed weather stripping can still realize a substantial return on investment. Hiring a professional, however, to install weather stripping, quickly drives the return on investment to the lowest level of any window option.

Figure 13: Return on Investment Soars For Do-It-Yourself Installation



As demonstrated in Figure 14, returns for the interior surface film options are influenced by the cost of installation and by solar design practices. For example, a homeowner installation in a cooling-dominated climate such as Phoenix can produce returns exceeding 18 percent, far more than most of the other window options presented in this study. However, even this low-cost approach produces negative returns in Portland, where no summer cooling is needed, underscoring the importance of correctly selecting a window's SHGC for its climate.

Figure 14: Variability in Return on Investment for Interior Surface Film



	Portland	Boston	Chicago	Atlanta	Phoenix
● Low Performance (DIY Labor)	NEGATIVE RETURN ON INVESTMENT		2.4%	5.8%	18.3%
▲ Low Performance (Professional Labor)			0.4%	1.6%	5.0%
◆ High Performance (Professional Labor)	1.2%	2.8%	2.4%	3.6%	4.9%

VI. RECOMMENDATIONS

This report presents computer-simulated results of estimated energy use that indicate the value of individual retrofit measures relative to each other in a variety of climates. *The energy savings noted (whether as a percentage or as an annual estimate of energy cost or CO2 savings) should only be used to compare options, not to predict the final savings that a retrofit will achieve.* In reality, savings will vary widely depending on the actual house retrofitted (size, condition, number of windows, construction characteristics, etc.) and occupant behavior (windows/doors left open, temperature set points, nighttime setbacks for HVAC systems, etc.). Nonetheless, this study offers useful guidance for homeowners and industry professionals choosing among window retrofit or replacement options.

The energy savings noted (whether as a percentage or as an annual estimate of energy cost or CO_2 savings) should only be used to compare options, not to predict the final savings that a retrofit will achieve.

The following recommendations set out best practices for selecting window retrofit and replacement options.

1. Don't start with windows: Tackle other energy-efficiency measures first.

As discussed in Section 4 of this study, whole-house air sealing, improving insulation, and upgrading HVAC systems are often suggested as first measures homeowners should consider from a cost-effectiveness and energy efficiency perspective. Although investigating the sequence of all the possible energy retrofits in an existing house was outside the scope of this study, Figure 12, which compares the savings from the minimum-efficiency and high-efficiency HVAC systems, reinforces the importance of considering window interventions within the context of other possible energy-efficiency measures. Homeowners who desire to maximize return on investment should consult an experienced energy professional, a house designer or architect, and a contractor who is familiar with energy saving retrofits to help evaluate applicable energy-saving solutions, proper sequencing, and estimated construction costs for a specific house.

The Pettygrove Residence modeled in this study was assumed to have already performed many common energy retrofits, including insulation, air sealing, and an upgraded HVAC system. Because the prototype had already substantially reduced its total energy consumption through these strategies, window interventions made a greater percentage impact in both cost and CO2 savings than if the house had not already completed the other energy efficiency measures. While window retrofits and replacement typically should not be the first intervention considered by homeowners, they do offer efficiency gains and energy savings, and are a significant part of a whole-house approach to achieving energy efficiency.

2. Choose window retrofits over replacements.

Window retrofits can achieve comparable energy savings at a much lower cost.

Many homeowners may be surprised to learn that enhancing the performance of existing windows can offer nearly the same energy performance improvement as replacement windows.

For all cities studied, at least one and often two of the improvements to the existing windows can achieve energy savings within the range of savings expected from new, high performance replacement windows.

For all cities studied, at least one and often two of the improvements to the existing windows can achieve energy savings within the range of savings expected from new, high performance replacement windows.

The results of this study show that interior window panels, exterior storm windows combined with cellular blinds, and in some cases even exterior storm windows alone fall within the range of performance for replacement windows. Importantly, not all retrofit/replacement window options are equal: To achieve the highest total energy performance for a window retrofit, use a product and installation method that is at the highest performance end of the range for that measure (lowest U-factor, most appropriate SHGC for the climate condition, and lowest air leakage rate).

Furthermore, retrofitting existing windows is far less costly than installing high performance replacement windows. Figures 9, 10, and 11 demonstrate that replacement windows have comparatively low returns on investment for homeowners. While replacement windows may offer high energy performance improvement, the upfront costs are substantial and are not rapidly recovered through savings in energy bills. Installing cellular shades typically offers the highest return on investment, while the use of storm windows and/or the use of storm windows with insulating shades also offers a solid return on investment. Interior storm windows offer other advantages as well, including reduced potential exposure to lead-based paint, while exterior storm windows help extend the useful life of historic windows by offering protection from the elements.

Saving existing windows avoids the environmental impacts associated with new windows production.

Reusing existing windows has other advantages beyond operational energy and cost savings. Keeping existing windows saves the energy and resources that would be needed to create a new window. Like any product, the production of replacement windows requires materials, and these materials generate CO2 and other environmental hazards from the extraction, manufacture, transport, and disposal processes. Retrofit measures also require materials, but are often less materials intensive and have less of an environmental impact than an entire window replacement.

A full life cycle assessment was outside the scope of this report, and is needed to further evaluate this issue. In the absence of such analysis, high performance green building standards such the Living Building Challenge can also serve as a useful guide for material selection for homeowners, providing stringent

standards for eliminating "Red-List" materials and chemicals found in building materials (such as PVC, a common material used in window products, both replacements and retrofits), using only sustainably sourced wood products, and selecting locally manufactured materials to reduce transportation energy and support regional economies.[13]

Finally, anticipated lifespan is also an important consideration when selecting materials. Many old windows are made from old growth wood, an increasingly scarce resource, which is extremely durable and easily repaired. Replacement windows do not offer such durability or reparability. To extend the life of the existing window, other upgrade measures should be considered when addressing the performance of the existing window, regardless of the energy savings produced. These include general sash and frame repairs such as replacing and rebalancing the counter-weight system, adjusting the stops, checking that the sash lock is drawing the meeting rails tight, and repairing failed glazing.

Saving windows preserves a home's character.

Historic windows were custom fit to their original openings and often have sizes, shapes, and muntin patterns not found today. Replacing them often requires changing the size and/or shape of the opening. Standard-sized new windows, with or without applied muntins, might save on operational costs but will compromise the character and historic integrity of a home. For this reason, repairing existing windows and/or choosing attachments to improve their thermal performance and occupant comfort is generally less expensive than custom replacements and preserves the character of the home.

Retrofits extend the life of existing windows, avoid production of new materials, and reduce waste. Additionally, wood windows are often a character defining feature of older homes, and conserving them helps to preserve the historic integrity of a home. *The Secretary of the Interior's Standards for the Treatment of Historic Properties* and *The Secretary of the Interior's Illustrated Guidelines on Sustainability for Rehabilitating Historic Buildings* offer guidance on how best to approach the preservation of windows in historically designated homes, or homes that may be eligible for listing.

3. Take climate into consideration.

The best retrofit option for Phoenix may not be right for Chicago.

The results from both the energy simulation and the investment analysis show that for all climates and cities studied, interior window panels and exterior storm windows are recommended options for reducing the energy loss from existing single-pane windows. In many cases, these two storm window measures have comparable energy performance to new, high performance replacement windows at a fraction of the cost.

The Living Building Challenge can also serve as a useful guide for material selection for homeowners, providing stringent standards for eliminating "Red-List" materials and chemicals found in building materials

In heating-dominated climates, insulating cellular shades helped reduce heat loss, especially when using a side track and in conjunction with exterior storm windows. As the need for winter heating decreases and summer cooling increases, the benefits of insulating cellular shades decline.

Interior surface films that reduce solar heat gain produced the best savings and greatest return on investment in cooling-dominated climates. Further, the application of low-e coatings to exterior storm windows substantially improved simulated energy performance for cooling-dominated climates. However, in heating-dominated climates the energy simulation showed an increase in energy used due to beneficial solar energy being reflected away from the house during the heating season. Thus, interior surface films or low-e coatings should be selected for these climates that simultaneously maintain a medium-to-high solar heat gain coefficient and a low U-factor. In climates with no summer cooling, such as Portland, facades that face the sun during the winter may maximize beneficial solar gain by using clear glass without any film or low-e coating. Homeowners should consult with an energy consultant familiar with passive solar design during the design phase of a project to make sure that the complex interaction between the sun and a home's heating and cooling needs is considered.

An important climatic consideration when selecting window enhancements is whether existing exterior shading from overhangs, trees, or other nearby buildings will reduce the impact of installing an upgrade measure with a low SHGC in cooling climates. If windows are already shaded by exterior elements, or if windows are not oriented toward the sun, they will receive minimal or no cooling benefit from the addition of a low SHGC retrofit.

4. Take matters into your own hands.

Perform high-return, do-it-yourself installations first, where possible.

Weather stripping and interior surface film generate immediate, low-cost savings and don't preclude future installations of other window measures that may produce additional savings. However, expected returns from weather stripping are highest where the windows are old and drafty, so focus on those first for immediate energy savings. Interior surface films are an excellent option for homeowner installation, especially for homes with big cooling bills in hot climates. Use care in applying films or low-e coatings to windows in colder climates, consulting a designer or energy professional to assist with the proper selection of materials and window locations that may produce the best year-round savings.

Create a plan that saves the existing windows and saves energy.

1. Get blower-door test.
2. Repair existing windows.
3. Install cellular shades with tracks.
4. Save money.
5. Buy exterior storm windows.

While not directly related to energy savings, a comprehensive window renovation that includes repairing the counterbalance mechanism, adjusting for proper fit, and repairing weather-damaged window components can substantially extend the life of the window and improve window tightness. Care should be taken to properly assess and abate lead-based paint during any window repair activities. As resources allow, simple enhancements such as cellular shades, especially those with side tracks to reduce air infiltration, can substantially improve the energy performance of windows over time. A combination of measures such as cellular shades with exterior storm windows in a cooler climate or interior surface film in a warmer climate can produce dramatic energy savings. Taking a phased approach to window upgrades, focusing on the highest returns first and using savings to pay for future improvements, can eventually lead to long-term savings of money, energy, and carbon emissions for older homes, even for households that are on a tight budget.

VII. CONCLUSIONS AND FUTURE RESEARCH

The results of this study show that window retrofit and replacement options have the potential to significantly improve the energy efficiency of a home with existing leaky, single-pane windows. How much varies substantially among retrofit options, energy costs, and climate variations. Several retrofit options fall into the range of expected performance that a replacement window might achieve (specifically exterior and interior storm windows, especially when combined with cellular shades), showing that retrofit options should be a first consideration before replacements.

This study identified a number of future research opportunities that could provide a more comprehensive understanding of window retrofit and replacement options for older leaky, single-pane windows. These include:

LIFE CYCLE ASSESSMENT

This study evaluated only the energy savings of various test conditions and did not address impacts to the environment or to human health associated with material production, transportation, maintenance, replacement, or disposal over the anticipated life span of the retrofitted or replacement windows. Further research is needed to understand how each test condition compares based on these impacts. Due to the wide range of material choices that exist for window retrofit/replacement measures, this type of analysis was outside the scope of this current study. However, the energy results from this analysis could provide a basis for a more comprehensive study on life cycle impacts in the future.

VARIATIONS IN HEATING SYSTEM OR FUEL TYPE

This study was limited to an evaluation of a baseline home assumed to be served by a natural gas-powered furnace and electrical window/wall air conditioning units. Variations in the type and efficiency of the heating/cooling system as well as the fuel type could potentially change the results of this study. More research is needed to understand how these variables affect the decision to replace or retrofit windows in different climate regions.

UNDERSTANDING WINDOW UPGRADES IN CONTEXT OF WHOLE HOUSE RETROFIT CHOICES

In many cases, choosing to retrofit or replace windows may not be the most cost-effective or efficient way to improve the energy performance of an older home. A much more detailed analysis is needed to evaluate how to prioritize window upgrades in the context of other energy-efficiency measures such as adding insulation, whole-house air sealing, and upgrading existing heating and cooling equipment.

PASSIVE SOLAR DESIGN GUIDANCE FOR WINDOW RETROFITS

The energy simulations for this study used assumptions for window performance that were assembled from a meta-review of past windows reports. The selections of U-factor, SHGC, and air infiltration characteristics were based

upon previously tested or modeled conditions for actual assemblies. Low and high performance assumptions did not reflect exact climate conditions in the five cities selected. A follow-up study is needed to provide guidance about how to properly select low-e coatings, films, and glazing for the different window retrofit options presented, ideally for each of the climate zones identified in the International Energy Conservation Code.

IX. ENDNOTES

1. *The Greenest Building: Quantifying the Environmental Value of Building Reuse.* National Trust for Historic Preservation, 2012. http://www.preservationnation.org/information-center/sustainable-communities/sustainability/green-lab/lca/The_Greenest_Building_lowres.pdf

2. U.S. Department of Energy, *2011 Buildings Energy Databook*, Residential energy use based on 2009 data, accessed April 2012 at http://buildingsdatabook.eren.doe.gov/ChapterIntro2.aspx. U.S. Energy Information Association, Carbon Dioxide Emissions by End-Use Sector, Table 6, 2008 data. http://205.254.135.24/oiaf/1605/ggrpt/carbon.html. Accessed April 2012.

3. U.S. Department of Energy, accessed March 2012. http://buildingsdatabook.eren.doe.gov/ChapterIntro2.aspx.

4. Ibid.

5. U.S. Census Bureau. American Housing Survey for the United States, 2007. On-Line, www.census.gov/prod/2008pubs/h150-07.pdf., Department of Energy. Buildings Energy Data Book, Table 5.2.6, "2005 Residential Prime Window Stock." Online, http://buildingsdatabook.eren.doe.gov/docs%5CDataBooks%5C2005_BEDB.pdf.)

6. US Department of Energy, *Energy Savers Booklet*. http://www1.eere.energy.gov/consumer/tips/pdfs/energy_savers.pdf

7. Greenhouse gases are defined by the U.S. Environmental Protection Agency as "gases that trap heat in the atmosphere." (http://www.epa.gov/climatechange/emissions/) These cases can be either the result of natural processes or exclusively the result of human activities. Carbon dioxide (CO2), Methane (CH4), Nitrous Oxide (N2O), and fluorinated Gases such as hydrofluorocarbons, and sulfur hexafluoride are the primary greenhouse gases produced by human activity. These are of concern as it is believed that they are accelerating the rate of climate change. Of these, carbon dioxide is central to this study as it is produced by burning fossil fuels—coal, oil, and natural gas. These fuels are the source of 74% of the U.S.'s heating and cooling energy either through direct burning or through the production of electricity. (U.S. Energy Information Administration) Thus, many consider reducing CO2 emissions to be critical to slowing climate change. This reduction in CO2 is typically measured as carbon savings, which is one of the variables in this study.

8. US Department of Energy, 2008 figures http://buildingsdatabook.eren.doe.gov/TableView.aspx?

9. Three studies of older, double-hung windows, Larson (1931), Lund (1952) and Center for Resource Conservation (2011) show air infiltration from leaky windows that is consistent with the values assumed in this report.

10. Heating Degree Day (HDD) and Cooling Degree Day (CDD) provide a rough estimate of seasonal heating and cooling requirements. HDD and CDD for each city are referenced here to show approximate climate variations between the cities selected for this study.

11. US Department of Energy, Energy Savers, Weather-stripping. Accessed April 2012. http://www.energysavers.gov/your_home/insulation_airsealing/index.cfm/mytopic=11280

12. *Measured Winter Performance of Storm Windows*. Joseph Klems. 2002.

13. International Living Future Institute, Living Building Challenge: https://ilbi.org/. The Red List contains materials and chemicals banned from use on Living Building projects: asbestos, cadmium, chlorinated polyethylene and chlorosulfonated polyethylene, chlorofluorocarbons (CFCs), chloroprene (Neoprene), formaldehyde (added), halogenated flame retardants, hydrochlorofluorocarbons (HCFCs), lead (added), mercury, petrochemical fertilizers and pesticides, phthalates, polyvinyl Chloride (PVC), wood treatments containing Creosote, arsenic or pentachlorophenol.

14. U.S. Department of Energy, Energy Savers. Passive Solar Window Design. Accessed August 2012. http://www.energysavers.gov/your_home/windows_doors_skylights/index.cfm/mytopic=13360

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X. APPENDIX

APPENDIX A: SIMULATION INPUTS AND ASSUMPTION

See Separate Excel Data File

APPENDIX B: SIMULATION DATA

See Separate Excel Data File

APPENDIX C: REGIONALLY ADJUSTED CONSTRUCTION COST ESTIMATES

See Separate Excel Data File

APPENDIX D: 11 STEPS TO HOME ENERGY SAVINGS

Simple, no-cost strategies for energy savings:

1. Make sure the furnace blower isn't on all the time. It should be set to "auto," not "on."
2. Lower heating thermostat setting by 2˚F, and turn off or set back thermostat 4 degrees F at night or when building is unoccupied. During summer months, set the air conditioner no lower than 76˚F and turn off or set back when building is unoccupied.
3. Remove second refrigerators and freezers.
4. Turn off all unused appliances including TVs, cable/satellite boxes, stereos and fans when not in use. Enable your computer's sleep feature versus leaving it on 24/7.
5. Set water heater temperature to 130˚F, if it is currently higher.

Most cost-effective investments in energy savings:

6. Insulate attics and walls if they are un-insulated; add to existing insulation only after completing air sealing work between the ceiling and the attic and mitigating all potential moisture accumulation in the wall cavity.
7. Hire an experienced contractor to perform blower-door-directed air sealing work, ideally with the help of an infrared camera.
8. Seal the seams of any ducts located outside of the conditioned space of the home, such as garages, attics and crawl spaces.
9. Replace old appliances, water heaters and HVAC with high-efficiency equipment.
10. Enhance lighting efficiency by adding motion detectors to outdoor lights and replacing incandescent bulbs with compact fluorescent bulbs wherever feasible.
11. Enhance the energy performance of existing windows with cost-effective energy retrofit measures, including do-it-yourself weather stripping and/or cellular shades (with or without side tracks) in cooler climates, do-it-yourself interior surface film in warmer climates, interior window panels, exterior storm windows, or any combination of these as time and budget allows.

APPENDIX E: PASSIVE SOLAR WINDOW DESIGN IN EXISTING HOMES

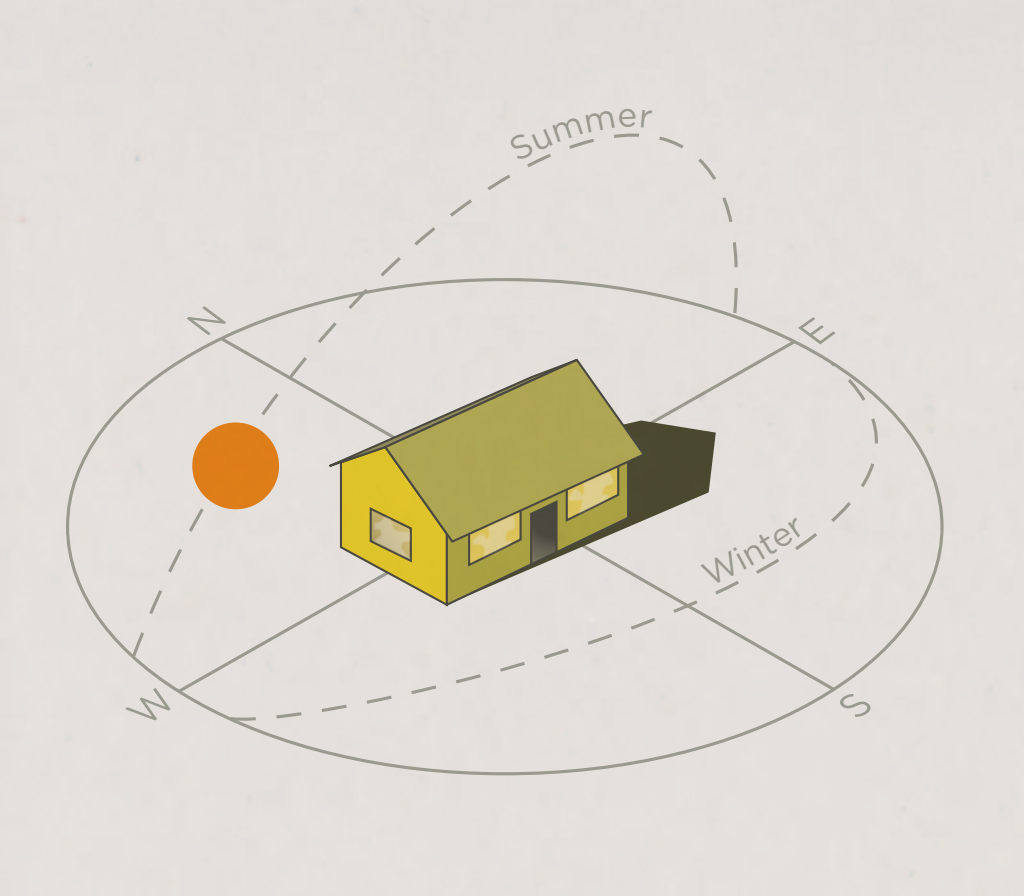
Adapted from the DOE Energy Savers Guide[14].

Properly designed, energy efficient windows represent a cost-effective way to use solar energy for heating. Windows are an important element in passive solar home designs, which can reduce heating, cooling, and lighting needs in a house.

Passive solar design strategies vary by building location and regional climate. The basic techniques involving windows remain the same—select, orient, and size glass to control solar heat gain along with different glazing usually selected for different sides of the house (exposures or orientations). For most U.S. climates, you want to maximize solar heat gain in winter and minimize it in summer.

HEATING-DOMINATED CLIMATES

In heating-dominated climates, major glazing areas should generally face south to collect solar heat during the winter when the sun is low in the sky. In the summer, when the sun is high overhead, overhangs or other shading devices (e.g., awnings) prevent excessive heat gain.



To be effective, south-facing windows usually must have a solar heat gain coefficient (SHGC) of greater than 0.6 to maximize solar heat gain during the winter, a U-factor of 0.35 or less to reduce conductive heat transfer, and a high visible transmittance (VT) for good visible light transfer.

East- and west-facing windows have difficulty in effectively control the heat and penetrating rays of the sun when it is low in the sky during the long morning and evening hours in heating-dominated climates. These windows should have a low SHGC and/or be shaded. North-facing windows collect little solar heat, and so a low-emissivity window treatment with a high SHGC, that maximizes both U-factor and VT, should be used.

COOLING-DOMINATED CLIMATES

In cooling climates, particularly effective strategies include preferential use of north-facing windows and generously shaded south-facing windows. Windows should choose low SHGCs on south-, east- and west- facing windows to effectively reduce cooling loads.