A Comparative Study of the Cumulative Energy Use of Historical Versus Contemporary Windows

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ABSTRACT

This study compares the life-cycle costs of two residential window systems in a pre-1940 house in Boston, Massachusetts. One is an original double-hung window with a new triple-track storm unit. The other is a new, vinyl, double-hung replacement window. Our results are obtained from an algorithm that yields the total present value of all costs associated with a window system over its entire life, including acquisition, installation, maintenance, and energy. Our study provided two notable findings: (1) the thermal performances of the two window systems are similar; and (2) taking all costs into account, it is more cost effective to add a storm window to an historical window, and it remains so at all times for the full 100-year life we considered.

INTRODUCTION

Americans are growing ever more conscious of their homes' energy use and are making investments they hope will improve efficiency and enhance sustainability. Federal and state governments and local utilities offer a myriad of incentives to homeowners to improve the energy efficiency of their homes. "Green" has penetrated the depths of our social consciousness. Americans want to ease the burden their houses place on our planet. They want to do the right thing. In response, businesses have filled the marketplace with products claiming energy and dollar savings. And homeowners are spending money, sometimes a lot of money, on these products.

One of the most costly changes is replacing original windows with new ones. Promises of dramatically lower fuel bills are compelling, and need to be if one is going to spend several hundred dollars per new window while tossing functioning units into the waste stream. After all, replacing a window will not improve one's enjoyment of a home, nor will it improve one's healthful living. It is usually simply replacing a view of the outside with a noticeably smaller view of the same outside.[1]

Is the more sustainable approach to replace the original windows with new? Will the homeowner see a financial return on an investment of several thousand dollars? Our study sought to answer these questions. We have developed an algorithm to calculate the life-cycle cost of any window system. We use it here to compare two window systems: an original, single-glazed double hung wood window with a new storm unit and a new double-glazed, double-hung vinyl window replacing the original sash. With a multitude of inputs, from U-factors and projected energy costs to the long-term viability of the materials and associated repair costs, the algorithm will quantify the cost of either system over any time period in discounted dollars of the current year. See **Figure 1** for discount factor explanation. In other words, we compute the present value of all

[1] Replacement window sash use larger wooden stiles and rails (the members that hold the glass) than those of historical windows. Because replacement units must fit within the existing opening, the glass area is decreased. An example comes from the home of one of this team's researchers. A replacement window vendor provided the researcher a proposal to replace the historical windows in his house. Per the submitted proposal, the daylight opening of each first floor window would decrease 2.5" in width and 4.5" in height.

expenditures associated with either system. This permits an informed, financially and environmentally sound decision.

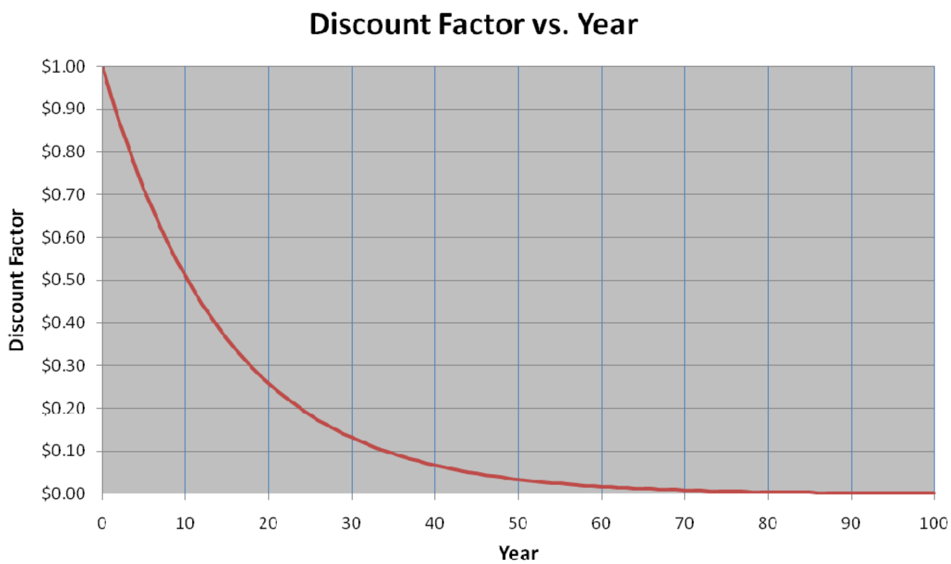

Figure 1: Discount factor $(1/1+i)^n$ vs. year

> The present value of a stream of money spent over 100 years is PV = SUM (n = 0 to 100) $C_n(1/1+i)^n$ where n = year, i = return on alternative secure investment corrected for inflation (in our case 0.07), and C_n = all costs incurred in year n expressed in dollars of the current year (2010). All initial costs occur at zero and are not discounted, because $(1/1+i)$ to the zeroth power equals 1. A dollar of the year 2010 (i.e., uninflated) spent in the 35th year is equivalent to a dime spent at the outset; it's present value is ten cents. A dollar of the current year spent in the 68th year is equivalent to a penny spent at the outset; its present value is one cent.

METHODOLOGY

Establishment of Parameters

For the historical window we chose a common 19th c sash: a wooden unit with double-hung sash and weight and chain operation. The overall frame is 36” x 60”. The sash are painted black,[2] each with six lites of clear glass, secured with putty. We assume the historical window is operational and in good condition.[3] It is covered by a new triple-track storm unit, the Harvey Tru-Channel with low-e glass and a black frame.

The replacement window is a Harvey Industries Vinyl Classic Double Hung Replacement unit with block and tackle operation. The frame is 36” x 60”, with black sash, insulating glass and the

[2] Dark colors were commonly used throughout the 19th c.

[3] Should one encounter a window that has not been maintained, the cost of refurbishment can be included in the algorithm alongside the cost of the new storm unit.

Federal Incentive package of six-over-six lites. Harvey is the selected manufacturer because of its national presence. The unit selected represents high-middling quality, within the financial reach of most homeowners while still providing good performance. Windows of less cost are available, and are often purchased as replacements, but their performance is unacceptable. Conversely, there are a few very high performing windows on the market, but these are deemed beyond the financial reach of most homeowners.

Historical windows can easily last two hundred years or more. For our study we assumed the window would not require replacement during the 100-year study period. The algorithm we assembled for this study can be adjusted for a shorter or longer life. Such adjustments are possible for all of the algorithm inputs.

With such varied inputs it was necessary to convert all into a common unit to run the algorithm. The unit chosen was the U.S. dollar of the current year. We use present-value accounting, assuming the annual rate of return on an alternative investment to be 7% after adjusting for inflation.[4]

Key data sources include the Lawrence Berkeley National Laboratory (LBNL). We used two LBNL programs: THERM and WINDOW. We used these programs together, referencing files between them, for modeling non-infiltrative heat transfer. We collected infiltrative heat transfer data from various field study reports. Other sources used include the U.S. Department of Energy, the U.S. Bureau of Labor Statistics, and performance data published by manufacturers and industry experts.

The final step, which also produced the algorithm, was determining the operating costs of the two window systems. Costs are considered in three parts: (1) the heating season of October through April, (2) the cooling season of June through August, and (3) the cyclical installation and maintenance costs of each window system over 100 years.[5] We calculate heating and cooling needs for Boston, Massachusetts (71.0°W, 42.4°N). A detailed review of the data and inputs for each of these categories follows.[6]

Operating Cost of Windows During the Heating and Cooling Seasons

To determine the annual cost of the energy lost through our windows we evaluated three terms: infiltrative thermal loss, non-infiltrative thermal loss, and solar heat gain.

We calculated the net heat loss through each window during the heating season. As infiltrative and non-infiltrative thermal loss are directly proportional to the temperature difference between

[4] We used the Standard and Poor's 500 return from 1925 to 1995.
[5] Expenses for the out years are heavily discounted for the time value of money.
[6] Values should be viewed as relative and used solely for comparison with other values derived in this study.

the interior and exterior, we needed the cumulative differential over a full heating season in Boston. An accepted measure is heating degree days (HDD). Our source for heating degree days is www.degreedays.com,[7] as they allow for flexibility in choosing a base temperature.[8] That site's data is collected from the Weather Underground.[9] We averaged the three most recent years (2007-2009) for our study. This three-year average is only 6% lower than NOAA's 129-year average, using 65 degrees as a base. For our study we assumed the base temperature to be 65°F for the heating season.

Similarly, for the cooling season of June through August, we used infiltrative and non-infiltrative heat loss, and solar heat gain. We used cooling degree days (CDD) from the same sources stated above and assumed a base temperature of 78°F for the cooling season.

The final step of this section was to convert into dollars the cumulative energy lost through each window system. Three elements were used to make the conversion: the cost of a unit of fuel, the energy content per unit of fuel, and the efficiency of the heating system in converting the energy of the fuel into heat delivered to the home.

1. Energy Transmission through a Window, Heating Season (Oct-Apr)
    a. *Infiltrative Thermal Loss.* This is the heat lost through the window via cracks/voids in and around the window components. We evaluated the two window systems separately as we saw different influences on each. Industry-standard air infiltration values are taken at 0.30 inches of H_2O (sustained 25 mph wind) for federal ASTM testing. Although this wind speed is higher than the average wind speed in Boston (12.4 mph)[10] we chose to use the federal standard as Harvey provides data for its windows at this wind speed. This will exaggerate the infiltration thermal loss, but as is explained below the initial infiltrative value for both windows is the same in our algorithm. Therefore neither window is biased by using the ASTM testing standard. Infiltration thermal loss can be adjusted in the algorithm for any wind speed by recognizing that the wind pressure is proportional to the wind speed squared. For the Infiltrative Thermal Loss portion of the Algorithm see **Table 1**. The equation in the algorithm for infiltrative heat loss per hour per degree ˚F is: L_{inf} [Btu/h˚F] = (Q [ft^3/mft^2]) (window area [ft^2]) (HCP_{air} [btu/ft^{3}°F]) (60 min/hr).

       - Infiltrative heat loss - L_{inf} [Btu/h˚F] (Btu per hour per degree Fahrenheit)
       - Infiltration rate - Q [ft^3m/ft^2] (Cubic feet per minute per square foot)
       - Window area - window area [ft^2] (Square feet)

[7] "Custom Degree Day Data." *degreedays.net* 2010
[8] The temperature at which you set your thermostat.
[9] wunderground.com 2010
[10] Forty-five year average for Boston, published by the National Weather Service.

- Heat Capacity of Air at Mean Sea Level[11] - HCP_{air} [btu/ft^{3}°F] (Btu per cubic foot per degree Fahrenheit)
- Minute to hour conversion – 60min/hr

Heating		
Infiltrative thermal loss per window - L_{inf}		
L_{inf} [btu/h * ˚F] = (Q [ft^{3}m/ft^{2}]) * (window area [ft^{2}]) * (HCP_{air} [btu/h * ˚F]) * (60 min) * (1/ft^{3})		
HCP_{air} [btu/h * ˚F] (Heat Capacity/Density of Air at Mean Sea level)	0.018	WAC 51-11-1008 - Section 1008 Air infiltration
Replacement infiltration value ([ft^{3}m/ft^{2})		
See Worksheet Ref - INF change replacement		
Q - new [ft^{3}m/ft^{2}] (tested infiltration @ ~ 0.3 inch H2O)	0.19	Harvey window specifications
Historical infiltration value ([ft^{3}m/ft^{2})		
See Worksheet Ref - INF change historical		
Q - restored [ft^{3}m/ft^{2}] (tested infiltration @ ~ 0.3 inch H2O)	0.19	Match to replacement

Table 1: Excerpt from the Infiltrative Thermal Loss portion of the algorithm. For the complete algorithm, see the end of the study.

i. Replacement Window.

1. The infiltrative value is represented by 'Q' in the algorithm. It is a measure of the rate of air movement for a given area for a given time (cubic feet of air per minute per square feet of window area). Published data by the manufacturer lists a Q of 0.19 for 0.30 inches of H_20 at 25 mph.[12]
2. New materials move and degrade, adversely affecting Q over time. We sought to account for the degradation of Q with time. But there is a lack of published data on the change of infiltration in replacement windows. With no other sources to guide the change of Q over time in a replacement window, we opted to replicate the slope generated for the historical window and storm (see section ii. Historical Window, part 2). We assumed that infiltration would degrade along this slope for the duration of the replacement window (35 years in this study before full replacement) to a Q of 0.407. When the window is replaced the Q is adjusted to the tighter value of 0.19, then degraded again over 35 years. This cycle repeats over the 100 year period, see **Figure 2**.

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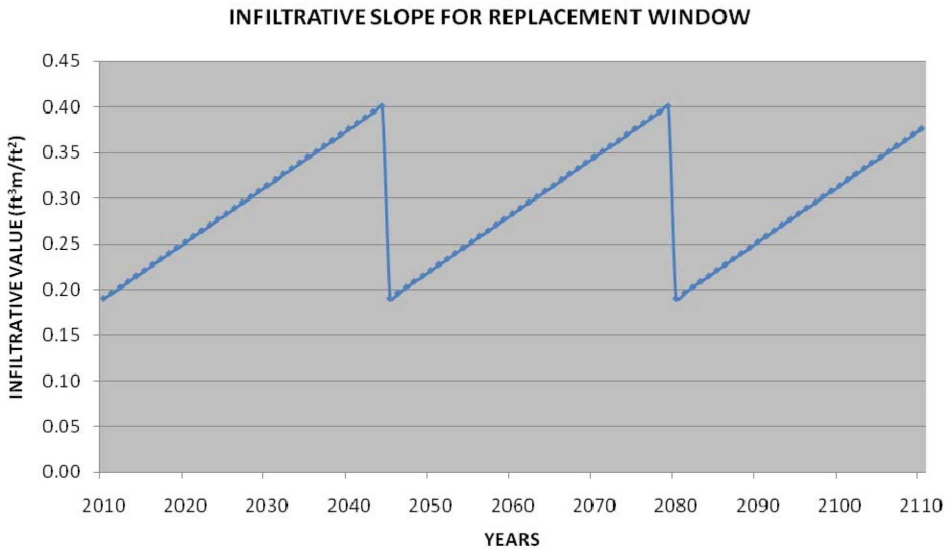
[11] The heat capacity of air at sea level will vary slightly with barometric pressure and temperature.

[12] "Structural Performance Data" Harvey Industries 2010.



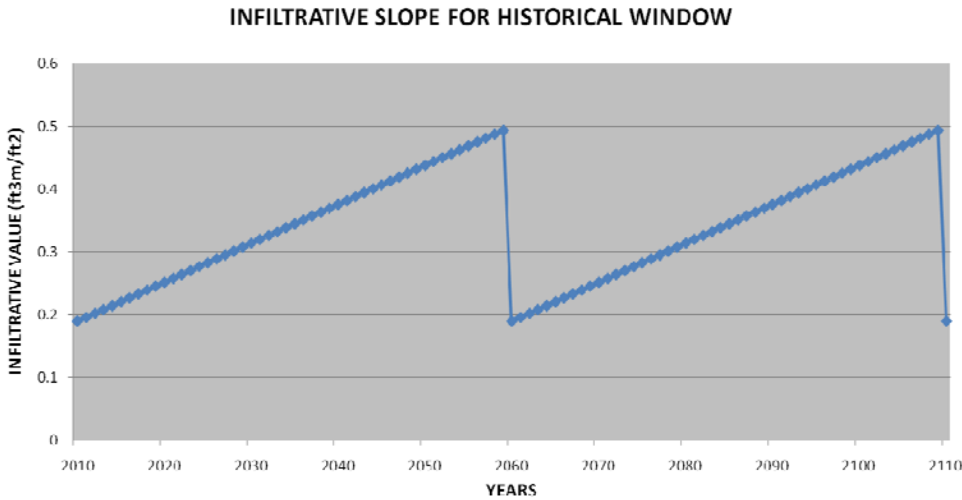
<u>Figure 2</u>: The infiltrative slope of the replacement window degrades over its 35 year life, then resumes the better value upon replacement.

ii. Historical Window

1. Harvey publishes a Q of 0.04 for its storm window. It is their tightest product. However, we are concerned that this low Q does not represent field installation conditions, particularly at the juncture between the storm unit's bottom flange and the window sill. This joint is rarely caulked and often there is a weep hole. Therefore, we raised the Q for the storm unit (increase its infiltrative loss). Without field tests to guide us, we chose to raise the Q to match that of the replacement window (0.19). The Q for the historical window/storm window combination was dictated by the new storm unit, which has a lower infiltration rate than published data on the Q of historical windows in good repair (Q = 0.27).[13]
2. As with the replacement window, we degrade Q over time for the historical window and storm unit. We assume that infiltration of the storm unit continues to define the overall infiltrative value for the system, even as the storm degrades. We did not find any studies on the change of Q over time for the Harvey storm unit. However, we did find that in the study, *Testing the Energy Performance of Wood Windows in Cold Climates,*[14] the measured Q of a historical window in good condition and one degraded in

[13] Brad James et al. 1996
[14] Brad James et al. 1996

fair condition. The Q degraded from 0.27 to 0.89 from one to the other. With no other data to use, and wanting to reflect declining infiltration resistance, we assume a comparable degradation in the storm unit, applied over a 50-year life (when the storm is replaced). The straight line slope yields a Q of 0.5 at the end of the cycle, see **Figure 3**.



<u>Figure 3</u>: The infiltrative slope of the historical window degrades over the 50 year life of storm, then resumes the better value upon replacement.

b. *Non-infiltrative Thermal Loss.* This is the energy lost through conduction and radiation. Conduction is energy lost through a material in contact with another material, and radiation is energy lost via electromagnetic waves. U-factor is the accepted coefficient. Again, we evaluate the two window systems separately as we saw different influences on each. For the Non-Infiltrative Thermal Loss portion of the Algorithm see **Table 2**. The equation assembled in the algorithm is L_u [btu/h˚F] = (U-value [btu/h ft^2 ˚F]) (window size [ft^2])

Non-infiltrative thermal loss per window - L_u		
L_u [btu/h * ˚F] = (u-value [btu/h * ft^2 * ˚F]) * (window size [ft^2])		
Area of window (ft^2) [36" x 60" window]	15	FSA
Replacement U-value (btu/h * ft^2 * ˚F)		
See Worksheet Ref - IGU decay		
U-value - new (btu/h * ft2 * ˚F)	0.3	Harvey window specifications
U-value - after IGU gas failure (btu/h * ft^2 * ˚F)	0.35	Harvey window specifications
Historical U-value (btu/h * ft2 * ˚F)		
U-value (btu/h * ft^2 * ˚F)	0.349	Average of Harvey window specifications & LBNL WINDOW software

<u>Table 2</u>: Excerpt from the Non-Infiltrative Thermal Loss portion of the algorithm. For the complete algorithm, see the end of the study.

i. Replacement Window

1. A U-factor of 0.30 (from Harvey) is used for the new unit at the time of installation.[15]
2. Insulating glass units degrade over time, affecting their U-factor. This is because the lower U-value IG units are inert gas-filled, with a seal to contain the gas (commonly argon). The gas has a lower U than air, but will slowly dissipate over time, being replaced by air. Because the seal will deteriorate over time, the exchange of low U gas for the higher U atmospheric air accelerates. We assume, however, the change of U is linear over 25 years, after which it is constant at 0.35 U. The degraded U of 0.35 was taken from Harvey's published U-factor for air-filled IG. This air is dry, providing a slightly better U than air containing humidity. Therefore the actual U of a degraded unit may be slightly worse than the U we used.[16] When the glass is replaced, U returns to the higher performing 0.30.

ii. Historical Window

1. We used a U-factor of 0.349 for the historical window and storm combination. Harvey published studies showing a U of 0.35. We sought to confirm this by modeling the scenario on the LBNL THERM program, see **Figure 4**, which yielded a U of 0.347. We used the average of the two for our algorithm.

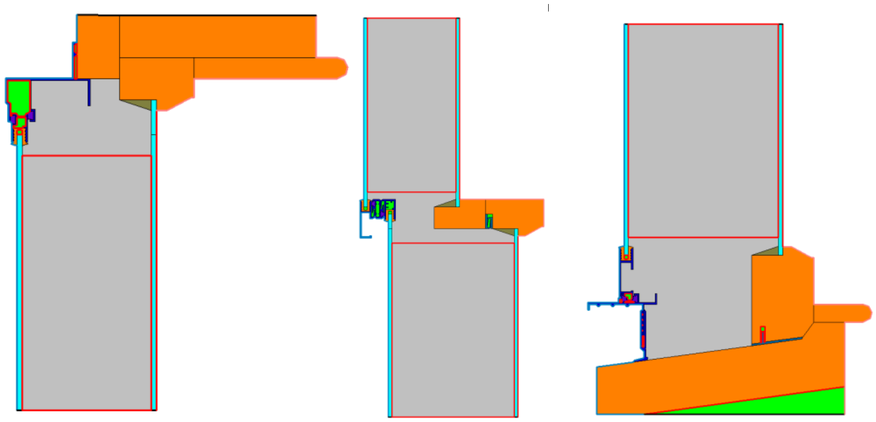


Figure 4: Head, Meeting Rail, and Sill models created in THERM

[15] "Thermal Performance Data" Harvey Industries 2010
[16] "Thermal Performance Data" Harvey Industries 2010

2. As there are no specialty gas or seals, we did not degrade the U over time for the historical window.

c. *Solar Heat Gain.* This section addresses the interior energy gain from solar radiation. Five components affect the net solar energy gain. Except for the SHGC, these components apply equally to both window systems. The net solar heat energy gain is subtracted from the heat loss values in the winter or added to the heat gain values in the summer. The components are:

   i. *Vertical Surface Gain.* This is the energy incident on the window glass (assuming the glass is perpendicular to the ground vertical orientation), and is measured as btu/ft^2/month. Sustainable by Design has an online calculator that uses monthly average climate data for Boston to produce a monthly total that depends on season.[17]

   ii. *Ground Reflectance.* This provides a coefficient for energy gained from light reflected off the ground. North-facing windows are most affected by this coefficient. Using the Sustainable by Design website we obtained a coefficient of 0.2 (the default, indicative of a site that is neither unusually reflective nor unusually absorptive). [18]

   iii. *Solar Heat Gain Coefficient (SHGC).* This coefficient is the fraction of solar energy incident on the window that passes through it. Many factors can affect SHGC, including glass-to-frame ratio, muntins, and the optical properties of the glass. Our two window systems have significantly different SHGC values. For the replacement window the SHGC is 0.21.[19] For the historical window with new low-e storm unit, Harvey has published field test results of 0.54. We also used the WINDOW modeling software as a comparison, which provided a value of 0.441. Because the Harvey data were from field tests we used this coefficient in the algorithm.

   iv. *Orientation.* Orientation has a dramatic effect on solar heat gain. We model a window oriented in each cardinal direction to demonstrate this.

   v. *Coefficient of Window Shading.* This value represents the degree to which the window is shaded and therefore has a commensurate reduction in solar heat gain. Sources of shading could be projecting eaves, porches, trees, or adjacent buildings. This coefficient is highly variable – truly site and building specific. We thought it is important to recognize that some shading will occur with nearly every building; therefore, we applied a coefficient of 0.75 to reflect 25% shading of all windows. We did not adjust this for seasonal changes in foliage or sun angle.

[17] "Window Heat Gain." *Sustainable by Design* 2009
[18] "Window Heat Gain." *Sustainable by Design* 2009
[19] "Thermal Performance Data" Harvey Industries 2010

2. Energy Transmission through a Window, Cooling Season (Jun-Aug). The algorithm reflects that mechanical cooling will run for all days in which CDD are recorded. However, in New England many owners will opt to open windows rather than run AC on days of moderate heat and lower humidity. This would reduce the energy loss of both windows at rates proportional to their performance. Infiltrative and non-infiltrative losses would be comparable between windows, but solar gain reductions would be more pronounced in the historical window because of its much higher SGHC. Therefore, we would expect a more pronounced reduction in cooling energy cost in the historical window due to periodically opened windows.
    a. *Infiltrative Thermal Loss.* The principles that apply to the exchange of infiltrative energy during the heating season also apply to the cooling season.
    b. *Non-infiltrative Thermal Loss.* The principles that apply to the exchange of non-infiltrative energy during the heating season also apply to the cooling season.
    c. *Solar Heat Gain.* The five factors considered in the heating section also apply to the cooling season..
3. Conversion of Cumulative Yearly Energy Loss into U.S. Dollars of the Current Year
    a. *The Energy Capacity Per Unit of Fuel.* We selected #2 grade home heating oil, whose energy content ranges between 137,000 BTUs and 141,800 BTUs per gallon.[20] For our calculations we assumed 138,600 BTUs/gal, a common value in published reports.
    b. *The Cost of Energy Per Unit Per Year.* We used the Department of Energy's *Annual Energy Outlook-2010* [21] for projections of future energy costs (oil for heating **Figure 5**, and electricity for cooling **Figure 6**). DOE's projection extends to the year 2035. Because we sought a 100-year cycle, we extrapolated the cost curve. The significance of errors made by extrapolation is greatly diminished by the discount factors for the out years.

[20] "Fuel Oil and Combustion Values." EngineeringToolBox.com
[21] "Annual Energy Outlook 2010 #:DOE/EIA-0383(2010) New England Sector." *Department of Energy U.S. Energy Information Administration* 2009

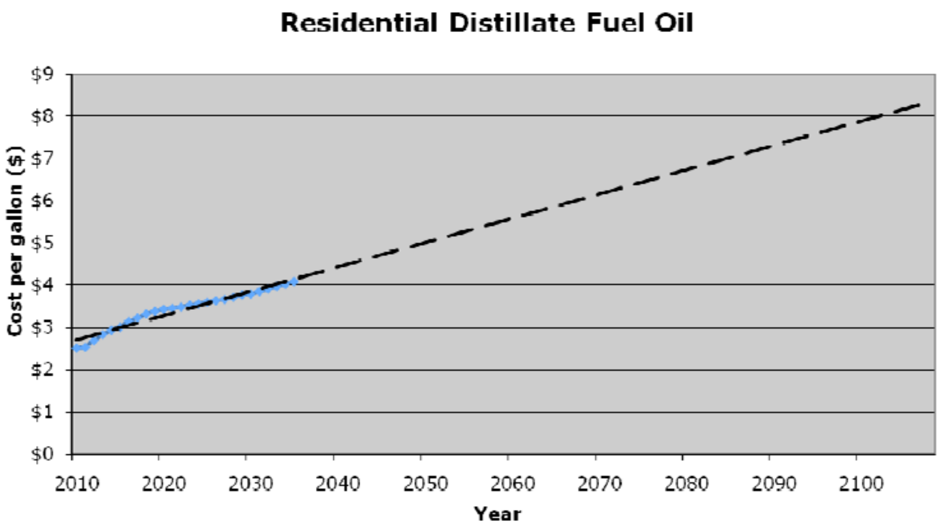


Figure 5: Fuel oil trendline (black dash) mapped over DOE projections (blue)

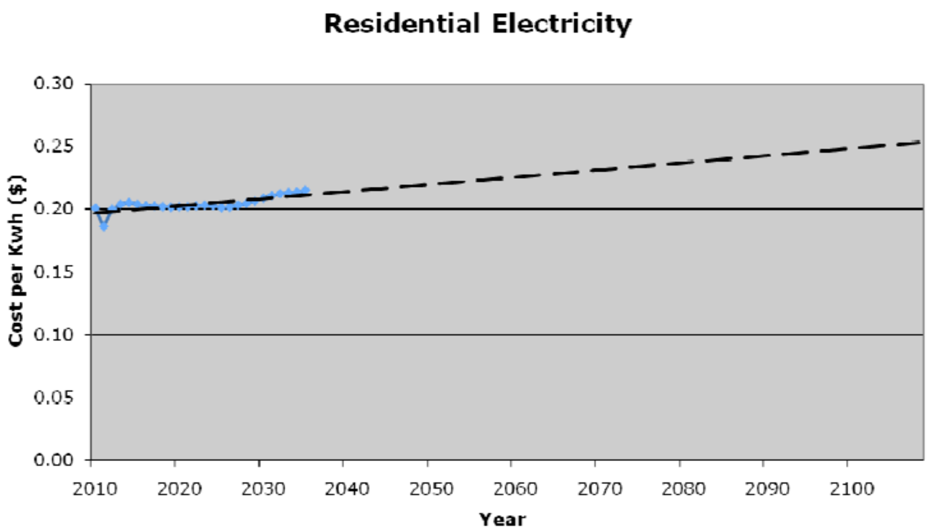


Figure 6: Electricity trendline (black dash) mapped over DOE projections (blue)

c. *Mechanical System Efficiency*.

i. For the heating system we model an atmospheric boiler with an annual fuel utilization efficiency (AFUE) of 78%. The AFUE represents the percentage of energy in the fuel delivered as heat to the house. An AFUE of 78% is the minimum allowed by the DOE for new units. There are many atmospheric boilers with higher efficiencies, and the more modern condensing boiler technology provides AFUEs in the mid-90s.[22] Although in our practice, we advocate these more efficient units, we decided that a lower cost boiler would represent a greater cross-section of the public. For the Heat Loss Conversion to Dollars portion of the Algorithm see **Table 3**. As with other inputs, the algorithm can easily be adjusted to reflect a higher efficiency boiler.

Annual heating loss per window - L_{yr}		
L_{yr} [btu/year] = ((L_{eff} [btu/h * ˚F]) * (heating degree-days fahrenheit [HDDF/year]) * (24hr/day))-(solar heat gain Gh_{season})		
Annual (1872:2001) average number of Heating Degree Days Fahrenheit for Boston MA [HDDF] Base temperature 65˚	5490.5	Degreedays.net
Annual heating cost per window - CH_{win}		
CH_{win} [$] = ((energy cost per unit [$/gal]) * ($L_{yr}$ [btu/year]))/ ((fuel heat capacity per unit [Btu/gal]) * (heating system efficiency))		
Energy cost per unit per year [$/gal] = (Best fit linear trendline for Distillate Fuel Oil in New England [0.0575*year + 2.657])	[0.0575*year + 2.657]	DOE Annual Energy Outlook 2010
Heat energy capacity per unit [Btu/gal] (No. 2 heating oil)	138600	Engineeringtoolbox.com - Fuel Oil and Combustion Values
heating system efficiency [atmospheric - 75%] [condensing - 95%]	93%	FSA

Table 3: Excerpt from the Heat Loss Conversion to Dollars portion of the algorithm. For the complete algorithm, see the end of the study.

ii. For the cooling system we assume central air conditioning rather than window units. The condenser has an Energy Efficiency Ratio (EER) of 12, a unit of middling efficiency. EER typically ranges between 9 and 22, with 9 an inefficient window unit. EER represents the ratio of BTU cooling output to electricity input. In conversations with a Carrier engineer,[23] we were advised to use EER rather than SEER (Seasonal Energy Efficiency Ratio) due its simpler structure, which made integrating it into the algorithm easier. For the Cooling Loss Conversion to Dollars portion of the Algorithm see **Table 4**.

[22] Condensing boiler technology cannot currently use heating oil as a fuel source.
[23] Bob Feduik, Carrier Corporation August 2010

Annual cooling loss per window - L_{yr}		
L_{yr} [btu/year] = ((L_{eff} [btu/h * ˚F]) * (cooling degree-days fahrenheit [CDDF/year]) * (24hr/day))+(solar heat gain GC_{season})		
Annual (1872:2001) average number of Cooling Degree Days Fahrenheit for Boston MA [CDDF] Base temperature 78˚	162.5	Degreedays.net
Annual cooling cost per window - CC_{win}		
CC_{win} [$] = ((energy cost per unit [$/kwh]) * ($L_{yr}$ [btu/year]))/ ((cooling energy capacity per unit [btu/kwh])		
Energy cost per unit per year [$/kwh] = (Best fit linear trendline for Kwh in New England [0.0575*year + 2.657])	[0.0005*year + .156]	DOE Annual Energy Outlook 2010
Cooling energy capacity per unit (btu/kwh) [12/EER = 12,000 btu per X kwh]	12000	Carrier Engineer
Cooling system efficiency (EER) [9 EER - 23 EER]	12	

Table 4: Excerpt from the Cooling Loss Conversion to Dollars portion of the algorithm. For the complete algorithm, see the end of the study.

Installation and Upkeep Costs of the Window Systems

The two window systems involve very different costs over the 100-year cycle. For the replacement window there is the immediate cost of purchase and installation. Maintenance is minimal, but we have accounted for anticipated, periodic component failure. Occasional accidental glass breakage is also accounted for in the algorithm. Because the materials and construction are designed for a limited life, we assume the replacement window is replaced every 35 years. Because of the discount factor for dollars of the 35th year (0.100), this affects the present value of this window system very little.

For the historical window there are no purchase or installation costs as the window exists. However, we add an aluminum, triple-track storm unit and so must account for its purchase and installation. Although we assume the historical window is in good working order,[24] it will require maintenance throughout its life. This upkeep is woven into the algorithm. As with the replacement window, we account for occasional glass breakage.

For both windows we assume professionals perform installation and maintenance. Their labor costs are included in the algorithm.[25] Sources for labor costs vary, but all are adjusted over the 100-year cycle. We use the U.S. Bureau of Labor Statistics for production workers' hourly earnings from the years 1972-2003. In present value dollars the actual hourly rate has dropped since 1972. Continuing this trend would eventually yield a rate of $0. Therefore our projections assume no change to the hourly rate, which produces a flat trendline, see **Figure 7**.

[24] A refurbishment cost can be added to the algorithm if refurbishment is required.

[25] It is possible that portions of the maintenance work could be executed by a well-equipped homeowner, saving on the associated labor costs. To allow for this, all labor costs have their own input in the algorithm; should the homeowner want to execute any maintenance item, the associated labor cost input can be removed.

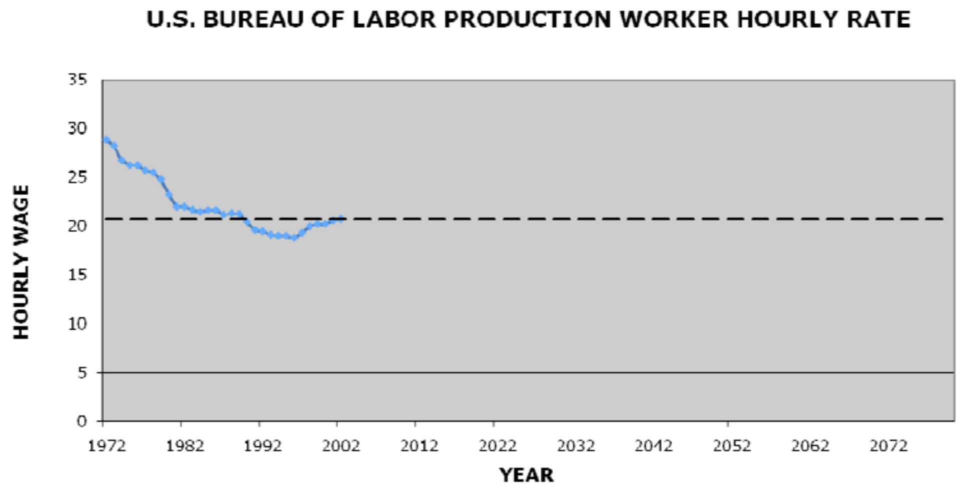


Figure 7: Worker hourly rate trendline (black dash) mapped over U.S. Bureau of Labor historical data (blue).

A detailed look at the costs associated with both windows follows.

1. Replacement Window Installation and Maintenance Costs
   For the Replacement Window Installation and Maintenance Costs portion of the Algorithm see **Table 5**.
   a. Installation
      i. The purchase price of $750 for the Harvey Industries Vinyl Classic Double Hung Replacement was provided to us from multiple dealers and installers.[26] The full unit is replaced at the end of its life, set at 35 years in our algorithm.
      ii. The labor cost of $150 to install the window was provided by the same dealers and installers who install the unit in the New England region. We assumed no complications with the installation, such as lead abatement, although new EPA laws will often add cost when removing materials from a house that predates 1978 (after which lead paint was banned from residential use).
   b. Maintenance
      i. *Labor cost to install insulating glass (IG) replacement due to seal failure.* Insulating glass can and does fail due to seal failure. This often causes 'fogging,' condensation that has a milky appearance, between the glass layers. Manufacturers have been improving the long-term quality of the seal and gas infill (including the use of desiccant to absorb some moisture that penetrates the seal). Today, an IG unit is often warranted for 20 years.

[26] Michaell Tighe, M T Boston Window, September 2010 and Stormtite Aluminum Products MFG, September 2010

We did not find definitive data on the expected failure rate of IG glass. For our algorithm we assume a 15% failure rate over the 35-year life cycle of the window. The labor cost to replace an IG unit is $85,[27] while the purchase cost is $200.[28] Failures will occur intermittently over the life of the window. Some will occur when the IG is under warranty, negating the purchase cost. For simplicity we incurred the cost once over 35 years, starting at year 35. To calculate the labor cost we assigned a total sash count of 40 (20 windows) of which 6 (15%) fail. We multiplied the labor cost with the failed sash count, then divided the product by the total windows to yield a labor cost per window of $25.50 for future replacement ($85*6÷20). We took a similar approach to address the purchase cost of the replacement IG, substituting the purchase cost for the labor cost in the equation, then discounting the purchase cost to only reflect failures after the twenty year warranty expires ([$200*6÷20]*[15÷35] = $25.71). Because both the labor and purchase cost are input as single point events starting at year 35, rather than as a uniform input across all years, the cost of IG failure is undervalued. We recognize this and chose this path for the simplification it provides in constructing the algorithm.

ii. *Purchase and labor costs to replace IG due to acts of God.* We used one researcher's home as the sample for the rate of glass breakage. Approximately 50% of the glass has been replaced in 118 years.[29] Adjusting for our 100-year cycle we use a 40% breakage rate. It should be noted that for the IG unit, which is a simulated divided lite, glass breakage requires the replacement of the full IG unit. This differs from the historical window, which has true-divided lite sash and therefore only the specific lite that was broken must be replaced. The cost to purchase and install a new IG unit matches that of the IG replacement due to failure, and is introduced in the algorithm in the same manner.

iii. *Labor to replace operating hardware.* The Harvey replacement window uses block-and-tackle hardware to operate the sash. This is a common choice for many replacement window manufacturers. This hardware will fatigue and can fail. Because lifetime warranties are offered by some suppliers, we carried only a labor cost ($50) for failure replacement. We did not find data on the expected rate of failure. For our algorithm we assumed 15% would fail over the 35-year life of the window.

[27] Michaell Tighe, M T Boston Window, September 2010 and Stormtite Aluminum Products MFG, September 2010
[28] Michaell Tighe, M T Boston Window, September 2010
[29] (the clarity of the glass being the test for original vs. replacement glass)

Event or Component	% of sashes effected at each cycle	Year duration of cycle	Averaged cost of each event or component	Cost of each event or component	Source of cost
Replacement Window					
Purchase of Harvey Replacement window, 6/6 SDL				$750.00	MT Boston Window
Removal & disposal of existing sash, installation of vinyl replacement [125-300 (upper range due to potential lead abatement issues)]				$150.00	Stormtite Aluminum Products MFG & MT Boston Window
Purchase of Replacement sash due to Insulated glass unit fogging (within 20 year warranty)				$0.00	Harvey Building Products
Purchase of Replacement sash due to Insulated glass unit fogging (outside 20 year warranty)	15%	35	$25.71	$200.00	MT Boston Window
Removal, disposal and installation of new sash - IGU Fogging - professional [0 if former client,85-100]	15%	35	$25.50	$85.00	Stormtite Aluminum Products MFG & MT Boston Window
Purchase of Replacement sash due to acts of god (glass breakage not covered under warranty)	10%	25	$40.00	$200.00	MT Boston Window
Removal, disposal and installation of new sash - Act of God - professional [0 if former client,85-100]	10%	25	$17.00	$85.00	Stormtite Aluminum Products MFG & MT Boston Window
Purchase of Replacement block and tackle (lifetime warranty)				$0.00	Harvey Building Products
Removal, disposal and installation of block and tackle - professional	15%	35	$15.00	$50.00	FSA

Table 5: Excerpt from the Replacement Window Installation, Maintenance & Repair Cost section of the algorithm. For the complete algorithm, see the end of the study.

2. Historical Window Installation and Maintenance Costs
   For the Historical Window Installation and Maintenance Costs portion of the Algorithm see **Table 6**.
   a. Installation
      i. The historical window exists therefore installation costs are not applicable.
      ii. The purchase price of $220 for the Harvey Industries Tru-Channel storm window unit with low-E is based on our experience and conversations with local installers.[30] The full unit is replaced at the end of its life, set at 50 years in our algorithm.
      iii. The labor cost of $75 to install the storm window is based on our experience and consultations with local installers.[31]This cost is incurred again at the end of its life, set at 50 years in our algorithm. As this unit is placed on top of the existing window casing, paint and trim is typically undisturbed. Consequently, EPA laws would not apply to the installation.
   b. Maintenance
      i. *Materials and labor to paint the historical window sash.* The cost of $130 is for a high performance paint (*Duration* by Sherwin-Williams) applied by a professional painter. The painting cycle is set at 12 years. Labor costs are based on consultation with local professionals.[32]

[30] Michaell Tighe, M T Boston Window, September 2010
[31] Michaell Tighe, M T Boston Window, September 2010
[32] Window Woman of NE & JFF Duddy, November 2010

ii. *Materials and labor to re-putty the glass.* The cycle for re-puttying is set at 60 years at a cost of $170. Re-puttying requires the sash be painted, and was addressed in the algorithm. We assume both are done professionally.

iii. *Purchase and labor costs to replace broken glass in historical window due to acts of God.* As noted in the Maintenance section of the replacement window, we carried a 40% breakage rate over 100 years. However, we assume that an accident would not break the glass of both the historical unit and the storm. Therefore, we assumed a 20% breakage rate for the historical window. Further, breakage replacement is limited to the specific lite broken because of the true-divided lite sash. The cost to purchase and install a new lite is $60.

iv. *Purchase and labor costs to replace broken glass in storm window due to acts of God.* As with the historical window we assumed a 20% breakage rate for the storm unit over 100 years. The cost to purchase and install a new storm panel is $50.

Historical Window					
Full refurbish of historical window - professional ($600-1000)				$600.00	Window Woman of NE
Purchase of Harvey triple-track aluminum storm window with low-e coating ($140-220)				$220.00	MT Boston Window & Window Woman of NE
Installation of storm window ($50-100)				$75.00	Window Woman of NE & MT Boston Window
Replacement of historical glass due to act of god breakage - professional ($60-85)	5%	25	$6.00	$60.00	Window Woman of NE
Purchase of storm window glass due to act of god breakage	5%	25	$5.00	$50.00	Window Woman of NE
Replacement of storm window glass due to act of god breakage - professional ($0-60)	5%	25	$6.00	$60.00	Window Woman of NE
Replacement of rope with chain in pulley - professional				$50.00	Window Woman of NE
Painting of window sash and frame - professional				$130.00	Window Woman of NE & JFF Duddy
Puttying & painting of window sash and frame - professional				$170.00	Window Woman of NE & JFF Duddy

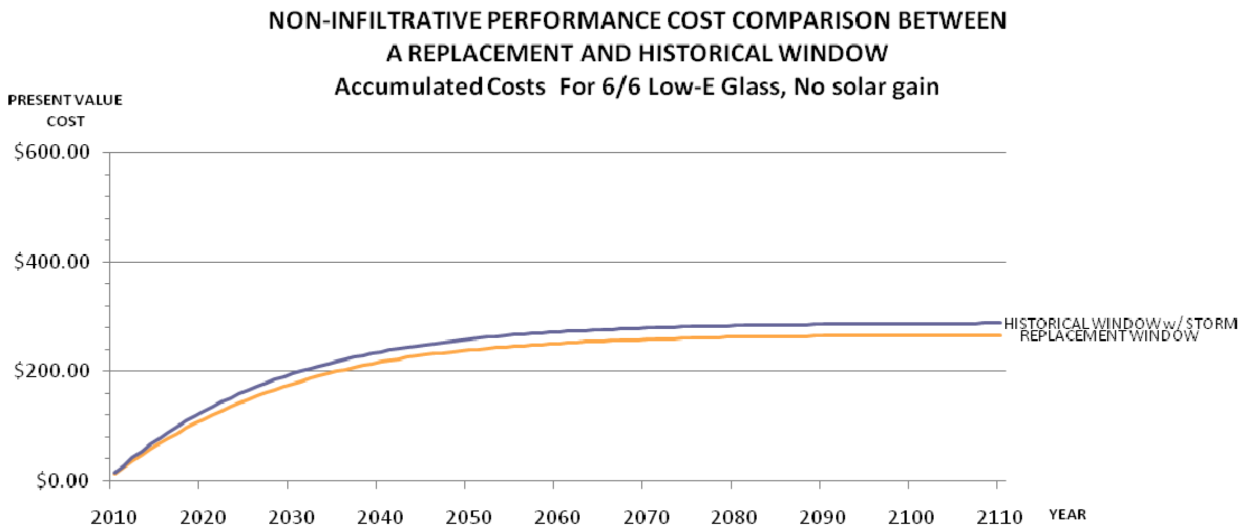
Table 6: Excerpt from the Historical Window Installation, Maintenance & Repair Cost section of the algorithm. For the complete algorithm, see the end of the study.

CONCLUSION

Our algorithm demonstrates that it is far more cost effective to add a storm window to a well-maintained historical window than to replace the window with a new IG unit. The thermal performance of the two window options is similar, see **Figure 8**. Therefore, the substantial upfront cost differential is never overcome. Let's look more closely at both the performance and the cost of the windows.

Performance

We chose Harvey Industries for both the replacement window and the storm window. We did so because both are of reasonable quality and are financially accessible to a broad audience. We feel this decision helps produce a balanced comparison of performance, because one company provided data on both products.



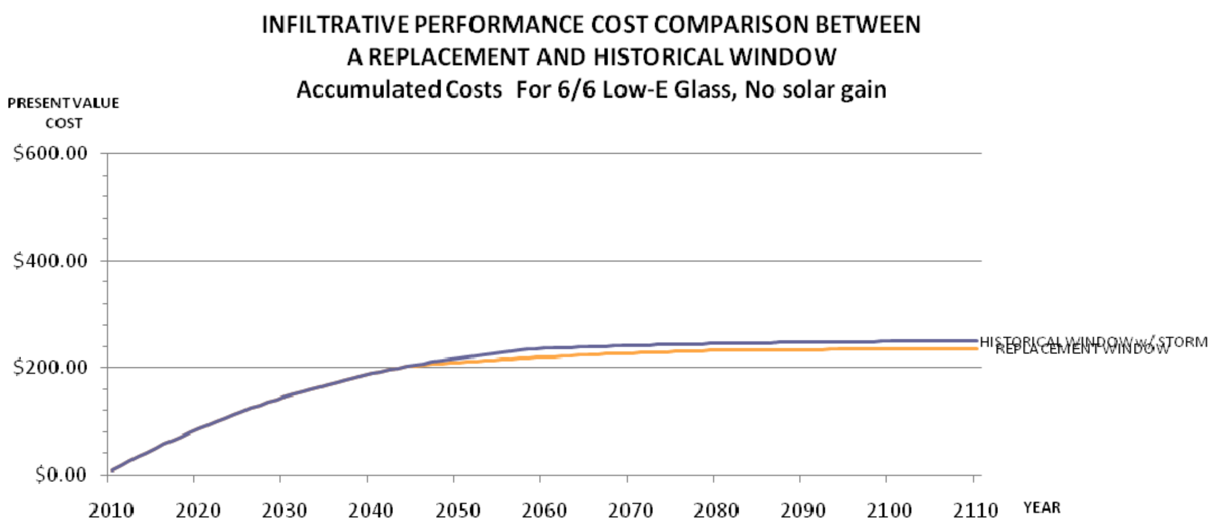


Figure 8:

- Harvey, Vinyl Classic Double Hung Replacement, 36" x 60", Black, 6 over 6 SDL, Federal Incentive Package, Low-e glass

- Historical window in situ, 36" x 60", 6 over 6 TDL with a Harvey, Tru-Channel Storm, 36" x 60", Black, Low-E glass

These graphs above show non-infiltrative and infiltrative costs respectively of the two window types.

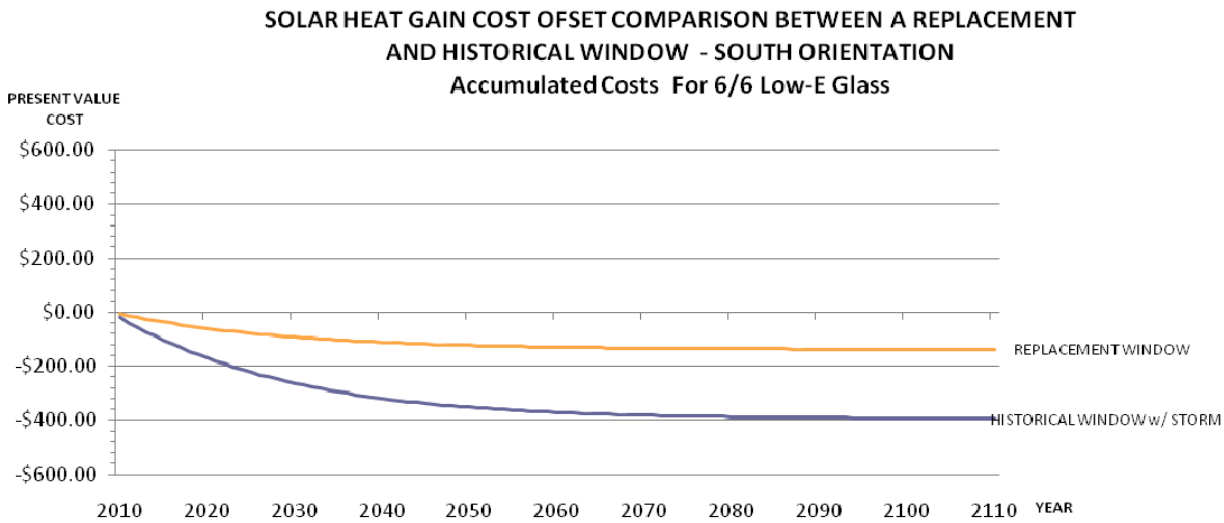
Perhaps surprising to some, the infiltrative performance was very similar between systems. In fact, Harvey states a better infiltrative value (Q = 0.04 at 25 mph) for its storm unit than for its replacement window (Q = 0.19 at 25 mph). In our algorithm we chose to increase Q (i.e. increase the rate of infiltration) for the storm unit above that published by Harvey to account for a weep hole for draining. We set the storm unit Q to match that of the published Q for the replacement window. It was also confirmed with Harvey that the storm was tested with sealed flanges on all sides. There is a lack of published data showing the rate of infiltrative performance decline over time, so we degraded the Q at the same rate for both windows. We believe the storm unit would not degrade more rapidly, and may degrade more slowly than the replacement window due to the storm unit's simpler construction, less variety of materials, and far less frequent operation.

The infiltrative performance of the two systems is the same for the first 35 years of the cycle. Then, the replacement window is again replaced and assumes the installation Q value (and the degradation slope restarts). The storm unit is replaced at year 50, so its Q continues to degrade for additional 15 years. At year 50, the storm assumes the installation Q value, and enjoys a slight performance advantage for 20 years. The two windows continue to leap frog in infiltrative performance for the remainder of the cycle.

Thus, for energy loss due to infiltration the two systems offered the same performance for the first 35 years of the cycle. Thereafter, each has periods of better performance, but never does the advantage prove meaningful in overall performance or cost, especially as these out years are heavily discounted.

Non-infiltrative performance was minimally better with the replacement window. This is due to the more sophisticated IG and its inert gas. Harvey states the replacement window has a U of 0.30 at installation (R value of 3.33), whereas the historical window and storm has an estimated U of 0.347 (R value of 2.88). However, the U of the replacement window degrades with time due to loss of the inert gas and seal leakage. The U-factor for Harvey's air filled IG units 0.35 was used to represent the degraded inert gas filled units. Harvey has no information on how quickly the U degrades, so we degraded its U over the 35 year cycle of the window. The historical window, however, does not experience non-infiltrative performance degradation because it does not rely on seals or inert gas for its U. Therefore, at the end of the replacement window's cycle its U is slightly worse than that of the historical window (net difference of 0.003). As with infiltrative performance, the two windows leap frog in U performance, although for the majority of the 100-year cycle the replacement window has better U performance.

Solar heat gain proved the most notable difference in performance between the two window systems. The solar heat gain coefficient (SHGC) was the single-most important factor. The replacement window has a SHGC of 0.21, per Harvey's data, while the historical window and storm have an estimated SHGC of 0.54, see **Figure 9 & 10**. The historical window's higher SHGC helps offset heat loss during the heating season, but it adds to the cooling load in the summer. However, Boston's heating loads are much greater than its cooling loads, therefore the solar heat gain of the historical window gave it a net performance advantage in this category.



<u>Figure 9</u>:

- Harvey, Vinyl Classic Double Hung Replacement, 36" x 60", Black, 6 over 6 SDL, Federal Incentive Package, Low-e glass

- Historical window in situ, 36" x 60", 6 over 6 TDL with a Harvey, Tru-Channel Storm, 36" x 60", Black, Low-E glass

The graph above shows only the solar heat gain cost offset comparison between the two windows for a southern exposure.

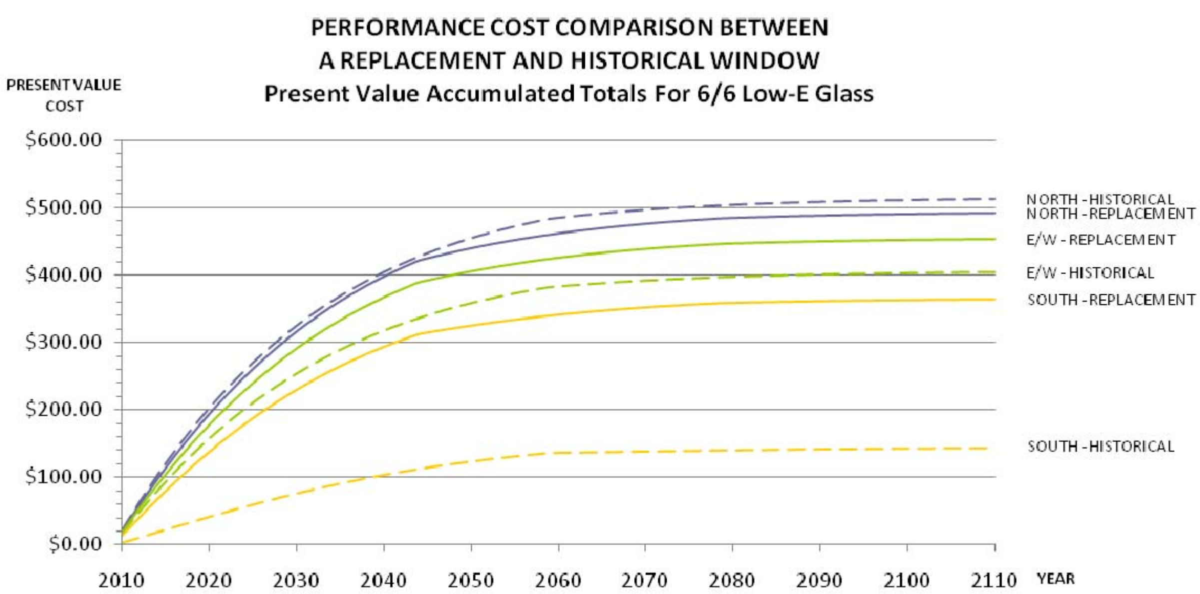


Figure 10:

- Harvey, Vinyl Classic Double Hung Replacement, 36" x 60", Black, 6 over 6 SDL, Federal Incentive Package, Low-e glass

- Historical window in situ, 36" x 60", 6 over 6 TDL with a Harvey, Tru-Channel Storm, 36" x 60", Black, Low-E glass

The graph above shows the performance cost (infiltrative, non-infiltrative loss for heating and cooling & solar gain) of the two window types. Because orientation has a significant effect on cost, we charted the window cost for three solar orientations (north, south and east/west).

A window's orientation greatly affects the net solar heat gain. A south-facing historical window receives so much additional heat from solar gain that its total energy use and cost was better than that of the replacement unit. Conversely, a north window receives little solar heat gain, and thus the replacement unit outperforms the historical window by the margins reflected in the **Figure 8** graphs.

In summary, the energy performance of the two window systems over the 100-year cycle is similar. Infiltrative performance is nearly identical, and the replacement window is better in non-infiltrative performance. But, the historical window admits far more solar energy, enough to offset its non-infiltrative underperformance on south facing windows, and to make its total energy loss commensurate with the replacement window on east/west and north facing facades.

Installation and Maintenance

Our algorithm reveals that replacement of an existing window with a new window is costly, so costly that a homeowner will not recover this cost. The Harvey IG replacement window costs $900 to purchase and install. The historical window exists, so has no initial cost. The Harvey storm window costs $295 to purchase and install. After these initial installation costs, routine maintenance, component failure, and damage from acts of God are the contributing future costs. Although the historical window has more routine maintenance, this is offset by the higher failure rate of the replacement window and its components and the life span of even a healthy window. The difference in the present value of costs actually increases over time, although after approximately 50 years (where the discount factor is 0.036) the present value of cost curves for both systems closely track one another and level off, see **Figure 11**.

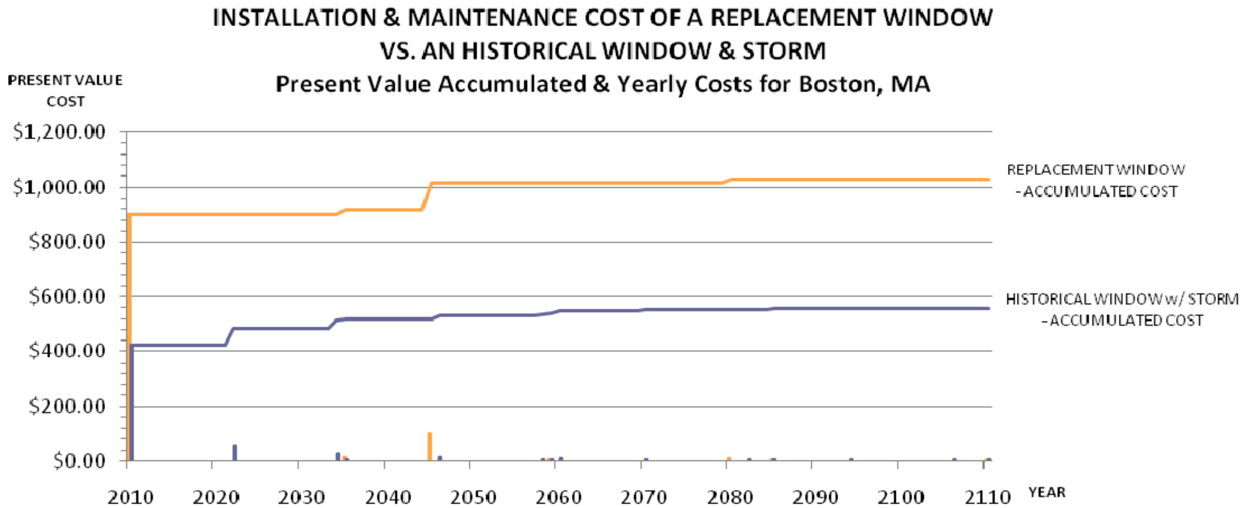


Figure 11:

- Harvey, Vinyl Classic Double Hung Replacement, 36" x 60", Black, 6 over 6 SDL, Federal Incentive Package, Low-e glass

- Historical window in situ, 36" x 60", 6 over 6 TDL with a Harvey, Tru-Channel Storm, 36" x 60", Black, Low-E glass

The graph above has two sections. The line graphs show the installation and maintenance cumulative cost (installation, maintenance and repair) of the two windows over a 100 year cycle. The bar graphs show expenses incurred over the cycle.

The replacement window is both more complex in its engineering and less well-built. IG is vulnerable to failure because of its reliance on a seal and captured inert gas. When it fails it must be replaced as the glass becomes milky. Buying IG glass is much more involved than conventional single pane glass – it must be purchased through the manufacturer or its agent. Installing IG glass is also more difficult. These affect the cost of replacing IG for failure and acts of God. Block-and-tackle operating hardware – the norm for many IG windows – does not have the durability of a historical window's rope or chain. Further, although there are several grades of block-and-tackle hardware available on the market, few window manufacturers use the higher grades due to cost. Therefore, the operating hardware of a replacement window is vulnerable to fatigue and failure. If the hardware fails it must be replaced. Further, block-and-tackle hardware is proprietary, typically manufactured by third parties. This hardware is subject to design changes. Obsolescence can complicate replacement because many window companies only stock obsolete parts for 10-15 years. Quantifying this risk is beyond the scope of our study and is not included in the algorithm.

Replacement windows – at least those within the financial reach of most homeowners – are built for a limited life. The wood used is commonly pine, harvested from tree farms. This wood is grown fast, as can be seen from the growth rings, more widely-spaced than those of the old-growth woods used in historical windows. Spring wood (lighter rings) is softer and less resistant to rot than summer wood (dark rings). In farmed pine the cross-section is skewed toward spring wood, making it weaker and less rot-resistant than the old-growth wood in historical windows. The wood frame and sill is clad in vinyl on the Harvey window, a common treatment among replacement windows. But vinyl will deteriorate from UV, has a high rate of thermal expansion and contraction, and can trap moisture in the wood substrate because vinyl does not breathe. Fabrication also contributes to the window's limited life. The health of the wood depends on the fit and finish of the cladding to keep water out. If the vinyl moves, separates or is not fitted tightly, rot will gain an early foothold. Wood lengths are finger-jointed, so glue plays a primary role in holding members together. All of these factors contribute to the limited life of the unit. In our experience, replacement windows 25-to-35 years old can suffer from rot, poor fit and difficult operation. For our study, we replaced the Harvey window every 35 years.

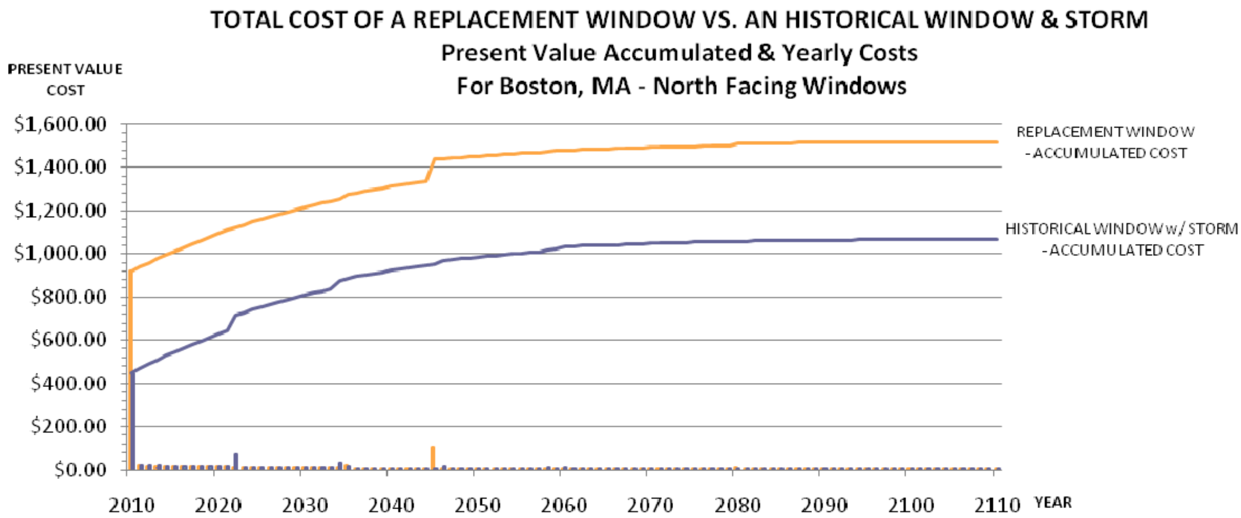
We assume in our study that the historical window is in good, operational condition. As alluded to earlier, historical windows are made with superior materials and workmanship. The wood is old-growth – hard and rot resistant. Wood members are solid, and joints between members rely on mechanical connections, via mortise-and-tenon joinery (and sometimes pegs, too), not glue. We paint the historical window every 12 years and re-putty them every 60 years. These intervals are more than sufficient to keep the window in good health.

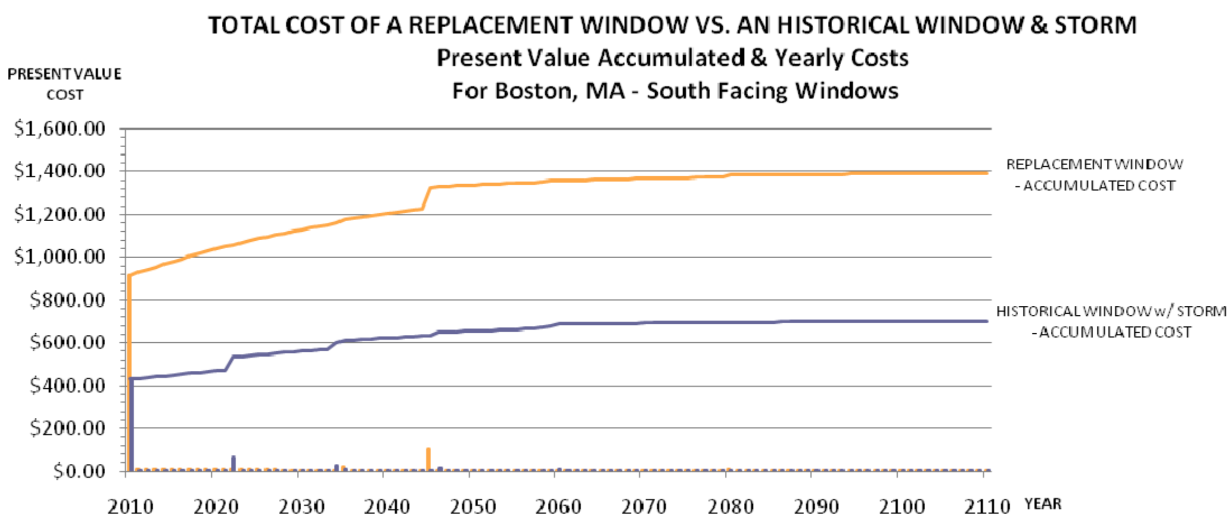
We assume the weight and chain operation is in working order. This simple but elegant system rarely needs attention. We did not carry a maintenance cost for the sash operation as the chain is not subject to failure. It is possible for the chain to become disconnected from the sash or the weight, although uncommon. We did not carry a cost to re-secure a chain. If a rope is used instead, it is possible that it is near or at the end of its life because ropes were typically a cotton weave. We did not carry a cost to replace an original rope, but this cost could be readily added to the upfront cost of the historical window.

The Harvey storm window is an aluminum frame, with factory-applied finish (black in our study). We assume that it will not require any maintenance, although we do replace the unit after 50 years.

Glass in both the historical window and storm is single pane therefore it is not subject to failure. Damage from acts of God are accounted for at the same interval as with the replacement window. We assume glass is professionally replaced, mainly due to the putty application required.

In summary, the replacement window requires a substantially higher upfront cost. Both windows incur maintenance and repair costs. Over our 100-year cycle these costs, too, are higher for the replacement window. The time value accounting dampens the long-term maintenance costs such that the present value cost of the replacement window widens to about $750 more than the historical window midway through the cycle. Thereafter the spread changes very little, see **Figure 12**.





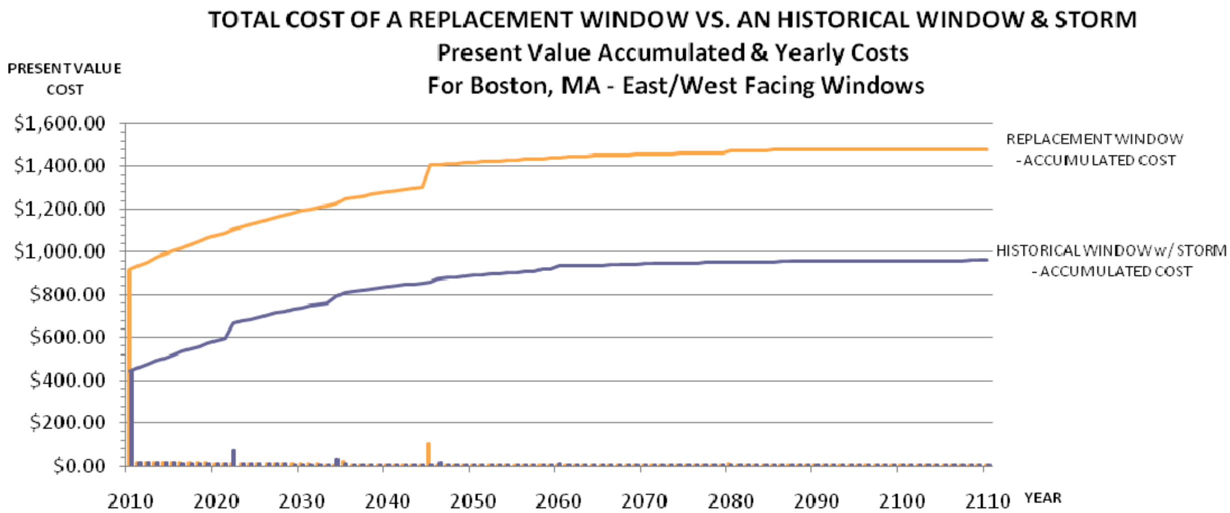


Figure 12:

- Harvey, Vinyl Classic Double Hung Replacement, 36" x 60", Black, 6 over 6 SDL, Federal Incentive Package, Low-e glass

- Historical window in situ, 36" x 60", 6 over 6 TDL with a Harvey, Tru-Channel Storm, 36" x 60", Black, Low-E glass

The graphs above have two sections. The line graphs show the total cumulative cost (energy loss, solar gain, installation, maintenance and repair) per orientation of the two windows over a 100 year cycle. The bar graphs at the base show expenses incurred over the cycle.

A replacement window does not offer the cost savings that would warrant replacing a historical window in operational condition. Instead, adding a much less expensive storm window to the historical window is more cost efficient. That the historical window is preserved also offers intangible priceless benefits, such as maintaining the more expansive daylight opening and maintaining the thin, elegant lines of the sash and muntins, neither of which is replicated in the replacement window. The storm unit is also a less invasive modification and can easily be reversed if desired. Finally, because the historical window with storm unit has a much lower life-cycle cost, it is the more energy efficient, sustainable solution. The price one pays for a product includes its embodied energy; otherwise someone is giving energy away, a most unsustainable practice.

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The Great Big Window Comparison

Comparative Study of the Cumulative Energy Use of Historical Vs. Contemporary Windows

Description of windows compared

Replacement Window

Harvey, Vinyl Classic Double Hung Replacement, 36" x 60", Black, 6/6 SDL, Federal Incentive Package

Historical Window

Wood Double Hung, 36" x 60", 6/6 TDL, chained pulleys, in maintained condition

Harvey, Tru-Channel Storm, 36" x 60", Black, Low-E glass

Present Value Variables

rate of return on potential investment	7.00%

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13
Window Performance Energy Costs														
Replacement Window	$14.23	$14.88	$15.55	$16.23	$16.93	$17.64	$18.37	$19.12	$19.88	$20.66	$21.45	$22.25	$23.08	$23.91
Historical Window	$3.78	$4.09	$4.41	$4.74	$5.09	$5.45	$5.82	$6.20	$6.59	$7.00	$7.41	$7.84	$8.28	$8.74
Replacement Window - Present Value Calculations	$14.23	$13.91	$13.58	$13.25	$12.92	$12.58	$12.24	$11.91	$11.57	$11.24	$10.90	$10.57	$10.25	$9.92
Historical Window - Present Value Calculations	$3.78	$3.82	$3.85	$3.87	$3.88	$3.88	$3.88	$3.86	$3.84	$3.81	$3.77	$3.73	$3.68	$3.62
Replacement Window - Present Value Accumulated Total	$14.23	$28.13	$41.71	$54.96	$67.88	$80.46	$92.70	$104.61	$116.18	$127.41	$138.32	$148.89	$159.14	$169.06
Historical Window - Present Value Accumulated Total	$3.78	$7.60	$11.45	$15.32	$19.20	$23.09	$26.96	$30.82	$34.66	$38.47	$42.23	$45.96	$49.64	$53.26
Installation & Maintenance & Repair Costs														
Replacement Window - Maintenance and Repair	$900.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Historical Window - Maintenance and Repair	$425.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$130.00	$0.00
Replacement Window - Present Value Calculations	$900.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Historical Window - Present Value Calculations	$425.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$57.72	$0.00
Replacement Window - Present Value Accumulated Total	$900.00	$900.00	$900.00	$900.00	$900.00	$900.00	$900.00	$900.00	$900.00	$900.00	$900.00	$900.00	$900.00	$900.00
Historical Window - Present Value Accumulated Total	$425.00	$425.00	$425.00	$425.00	$425.00	$425.00	$425.00	$425.00	$425.00	$425.00	$425.00	$425.00	$482.72	$482.72
Sum & Present Value														
Replacement Window - Sum of Costs	$914.23	$14.88	$15.55	$16.23	$16.93	$17.64	$18.37	$19.12	$19.88	$20.66	$21.45	$22.25	$23.08	$23.91
Historical Window - Sum of Costs	$428.78	$4.09	$4.41	$4.74	$5.09	$5.45	$5.82	$6.20	$6.59	$7.00	$7.41	$7.84	$138.28	$8.74
Replacement Window - Present Value Calculations	$914.23	$13.91	$13.58	$13.25	$12.92	$12.58	$12.24	$11.91	$11.57	$11.24	$10.90	$10.57	$10.25	$9.92
Historical Window - Present Value Calculations	$428.78	$3.82	$3.85	$3.87	$3.88	$3.88	$3.88	$3.86	$3.84	$3.81	$3.77	$3.73	$61.40	$3.62
Replacement Window - Present Value Accumulated Total	$914.23	$928.13	$941.71	$954.96	$967.88	$980.46	$992.70	$1,004.61	$1,016.18	$1,027.41	$1,038.32	$1,048.89	$1,059.14	$1,069.06
Historical Window - Present Value Accumulated Total	$428.78	$432.60	$436.45	$440.32	$444.20	$448.09	$451.96	$455.82	$459.66	$463.47	$467.23	$470.96	$532.36	$535.98

Replacement Window - Present Value over 10 years	$1,038.32
Historical Window - Present Value over 10 years	$467.23
Replacement Window - Present Value over 25 years	$1,175.36
Historical Window - Present Value over 25 years	$603.01
Replacement Window - Present Value over 50 years	$1,343.67
Historical Window - Present Value over 50 years	$675.68
Replacement Window - Present Value over 100 years	$1,375.36
Historical Window - Present Value over 100 years	$688.42

Window Performance Energy Costs

Component		Non Variable Values: Values	Non Variable Values: Value Source	Replacement Window: Values	Replacement Window: Value Source	Historical Window: Values	Historical Window: Value Source
Heating							
Infiltrative thermal loss per window - L_{inf}							
L_{inf} [Btu/h˚F] = (Q [ft³/mft²]) * (window area [ft²]) * (HCP$_{air}$ [btu/ft³˚F]) * (60 min/hr)							
HCP$_{air}$ [btu/h * ˚F] (Heat Capacity/Density of Air at Mean Sea level)		0.018	WAC 51-11-1008 - Section 1008 Air infiltration				
Replacement infiltration value ([ft³m/ft²)							
See Worksheet Ref - INF change replacement							
Q - new [ft³m/ft²] (tested infiltration @ ~ 0.3 inch H2O)				0.19	Harvey window specifications		
Historical infiltration value ([ft³m/ft²)							
See Worksheet Ref - INF change historical							
Q - restored [ft³m/ft²] (tested infiltration @ ~ 0.3 inch H2O)						0.19	Match to replacement
Non-infiltrative thermal loss per window - L_u							
L_u [btu/h * ˚F] = (u-value [btu/h * ft² * ˚F]) * (window size [ft²])							
Area of window (ft²) [36" x 60" window]		15	FSA				
Replacement U-value (btu/h * ft² * ˚F)							
See Worksheet Ref - IGU decay							
U-value - new (btu/h * ft2 * ˚F)				0.3	Harvey window specifications		
U-value - after IGU gas failure (btu/h * ft² * ˚F)				0.35	Harvey window specifications		
Historical U-value (btu/h * ft2 * ˚F)							
U-value (btu/h * ft² * ˚F)						0.349	Average of Harvey window specifications & LBNL WINDOW software
Effective thermal Loss per window - L_{eff}							
L_{eff} [btu/h * ˚F] = (L_{inf} [btu/h * ˚F] + (L_u [btu/h * ˚F])							
Annual solar heat gain effecting heating season (Oct-Apr) per window - GH$_{season}$							
GH$_{season}$ [Btu/year] = (heating season solar gain [Btu/ft2/year]) * (window glass area [ft2]) * (coefficient of solar gain contributing to heating) * (coefficient of window shading)				370,125		1,057,500	
Replacement window - Heating season solar gain [Btu/ft2/year] - North	0	3620	Sustainable by Design				
Replacement window - Heating season solar gain [Btu/ft2/year] - South	1	32900	Sustainable by Design				
Replacement window - Heating season solar gain [Btu/ft2/year] - East/West	0	14700	Sustainable by Design				
Historical window - Heating season solar gain [Btu/ft2/year] - North	0	10140	Sustainable by Design				
Historical window - Heating season solar gain [Btu/ft2/year] - South	1	94000	Sustainable by Design				
Historical window - Heating season solar gain [Btu/ft2/year] - East/West	0	41600	Sustainable by Design				
Coefficient of solar gain contributing to heating		1	FSA				
Coefficient of window shading		0.75	FSA				
Annual heating loss per window - L_{yr}							
L_{yr} [btu/year] = ((L_{eff} [btu/h * ˚F]) * (heating degree-days fahrenheit [HDDF/year]) * (24hr/day))-(solar heat gain Gh$_{season}$)							
Annual (1872:2001) average number of Heating Degree Days Fahrenheit for Boston MA [HDDF] Base temperature 65˚		5490.5	Degreedays.net				

Infiltrative thermal loss per window - L_{inf}:

Year	0	1	2	3	4
Replacement Window	3.078	3.17844	3.27888	3.37932	3.47976
Historical Window	3.078	3.17844	3.27888	3.37932	3.47976

Replacement infiltration value:

Year	0	1	2	3	4
Replacement Window	0.19	0.1962	0.2024	0.2086	0.2148

Historical infiltration value:

Year	0	1	2	3	4
Historical Window	0.19	0.1962	0.2024	0.2086	0.2148

Non-infiltrative thermal loss per window - L_u:

Year	0	1	2	3	4
Replacement Window	4.5	4.53	4.56	4.59	4.62
Historical Window	5.235	5.235	5.235	5.235	5.235

Replacement U-value:

Year	0	1	2	3	4
Replacement Window	0.3000	0.3020	0.3040	0.3060	0.3080

Effective thermal Loss per window - L_{eff}:

Year	0	1	2	3	4
Replacement Window	7.578	7.70844	7.83888	7.96932	8.09976
Historical Window	8.313	8.41344	8.51388	8.61432	8.71476

Annual heating loss per window - L_{yr}:

Year	0	1	2	3	4
Replacement Window	628443.216	645631.5557	662819.8954	680008.2	697196.5747
Historical Window	37920.636	51155.81568	64390.99536	77626.18	90861.35472

Installation & Maintenance & Repair Costs

Total # of double hung windows from which average expense is taken	20

Event or Component	% of sashes effected at each cycle	Year duration of cycle	Averaged cost of each event or component	Cost of each event or component	Source of cost	Year 0	1	2	3	4	5	6	7	8	9
Replacement Window															
Purchase of Harvey Replacement window, 6/6 SDL				$750.00	MT Boston Window	1									
Removal & disposal of existing sash, installation of vinyl replacement [125-300 (upper range due to potential lead abatement issues)]				$150.00	Stormtite Aluminum Products MFG & MT Boston Window	1									
Purchase of Replacement sash due to Insulated glass unit fogging (within 20 year warranty)				$0.00	Harvey Building Products										
Purchase of Replacement sash due to Insulated glass unit fogging (outside 20 year warranty)	15%	35	$25.71	$200.00	MT Boston Window										
Removal, disposal and installation of new sash - IGU Fogging - professional [0 if former client,85-100]	15%	35	$25.50	$85.00	Stormtite Aluminum Products MFG & MT Boston Window										
Purchase of Replacement sash due to acts of god (glass breakage not covered under warranty)	10%	25	$40.00	$200.00	MT Boston Window										
Removal, disposal and installation of new sash - Act of God - professional [0 if former client,85-100]	10%	25	$17.00	$85.00	Stormtite Aluminum Products MFG & MT Boston Window										
Purchase of Replacement block and tackle (lifetime warranty)				$0.00	Harvey Building Products										
Removal, disposal and installation of block and tackle - professional	15%	35	$15.00	$50.00	FSA										
						$900.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Historical Window															
Full refurbish of historical window - professional ($600-1000)				$600.00	Window Woman of NE										
Purchase of Harvey triple-track aluminum storm window with low-e coating ($140-220)				$220.00	MT Boston Window & Window Woman of NE	1									
Installation of storm window ($50-100)				$75.00	Window Woman of NE & MT Boston Window	1									
Replacement of historical glass due to act of god breakage - professional ($60-85)	5%	25	$6.00	$60.00	Window Woman of NE										
Purchase of storm window glass due to act of god breakage	5%	25	$5.00	$50.00	Window Woman of NE										
Replacement of storm window glass due to act of god breakage - professional ($0-60)	5%	25	$6.00	$60.00	Window Woman of NE										
Replacement of rope with chain in pulley - professional				$50.00	Window Woman of NE										
Painting of window sash and frame - professional				$130.00	Window Woman of NE & JFF Duddy	1									
Puttying & painting of window sash and frame - professional				$170.00	Window Woman of NE & JFF Duddy										
						$425.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00

Solar Heat Gain Data

Data from Sustainable by Design

Replacement Window SHGC Data

	North	South	East/West	
jan	330	4800	1400	
feb	440	4900	1900	Heating Season
mar	690	5000	2900	
apr	920	3600	3400	
may	1400	2800	4100	
jun	1800	2500	4400	
jul	1800	2900	4600	Cooling Season
aug	1300	3700	4200	
sep	870	4800	3400	
oct	610	5500	2500	
nov	340	4500	1400	Heating Season
dec	290	4600	1200	
Annual total	4900	9100	13200	
Annual total	3620	32900	14700	

city	Boston, MA
latitude	42.3
surface	default or unknown surface
ground reflectance	0.2
window SHGC	0.19 (From Harvey Literature)
units	Btu / ft2 / month

Historical Window SHGC Data

	North	South	East/West	
jan	940	14000	3900	
feb	1200	14000	5400	Heating Season
mar	1900	14000	8200	
apr	2600	10000	9600	
may	3900	8100	12000	
jun	5100	7200	13000	
jul	5000	8200	13000	Cooling Season
aug	3700	11000	12000	
sep	2500	14000	9600	
oct	1700	16000	7100	
nov	970	13000	4000	Heating Season
dec	830	13000	3400	
Annual total	13800	26400	38000	
Annual total	10140	94000	41600	

city	Boston, MA
latitude	42.3
surface	default or unknown surface
ground reflectance	0.2
window SHGC	0.54 (From Harvey Literature)
units	Btu / ft2 / month

Degree Day Data

Current Years Data

Current Year Data was used so that specific base temperatures could be calculated. The Historical Data found did not offer this flexibility.

Description: Farenheit-based heating degree days for a base temperature of **65F**
Source: www.degreedays.net (using temperature data from www.wunderground.com)
Station: Airport: Boston, MA, US (71.00W,42.36N)
Station ID: KBOS

Month starting	HDD
10/1/2007	220
11/1/2007	654
12/1/2007	1004
1/1/2008	972
2/1/2008	934
3/1/2008	822
4/1/2008	472
5/1/2008	259
6/1/2008	48
7/1/2008	3
8/1/2008	18
9/1/2008	91
10/1/2008	366
11/1/2008	643
12/1/2008	902
1/1/2009	1236
2/1/2009	894
3/1/2009	844
4/1/2009	460
5/1/2009	222
6/1/2009	102
7/1/2009	27
8/1/2009	15
9/1/2009	115
10/1/2009	407
11/1/2009	482
12/1/2009	982
1/1/2010	1091
2/1/2010	884
3/1/2010	653
4/1/2010	376
5/1/2010	167
6/1/2010	40
7/1/2010	4
8/1/2010	15
9/1/2010	54
07-08 Average	5497
08-09 Average	5826
09-10 Average	5155
	5490.5

Description: Farenheit-based heating degree days for a base temperature of **60F**
Source: www.degreedays.net (using temperature data from www.wunderground.com)
Station: Airport: Boston, MA, US (71.00W,42.36N)
Station ID: KBOS

Month starting	HDD
10/1/2007	120
11/1/2007	507
12/1/2007	849
1/1/2008	819
2/1/2008	790
3/1/2008	667
4/1/2008	335
5/1/2008	149
6/1/2008	13
7/1/2008	0
8/1/2008	2
9/1/2008	36
10/1/2008	240
11/1/2008	500
12/1/2008	750
1/1/2009	1081
2/1/2009	754
3/1/2009	690
4/1/2009	330
5/1/2009	121
6/1/2009	28
7/1/2009	3
8/1/2009	2
9/1/2009	42
10/1/2009	271
11/1/2009	338
12/1/2009	828
1/1/2010	936
2/1/2010	744
3/1/2010	504
4/1/2010	249
5/1/2010	90
6/1/2010	11
7/1/2010	0
8/1/2010	0
9/1/2010	14
07-08 Average	4287
08-09 Average	4541
09-10 Average	3985
	4263

Description: Farenheit-based cooling degree days for a base temperature of **80F**
Source: www.degreedays.net (using temperature data from www.wunderground.com)
Station: Airport: Boston, MA, US (71.00W,42.36N)
Station ID: KBOS

Month starting	CDD
10/1/2007	2
11/1/2007	0
12/1/2007	0
1/1/2008	0
2/1/2008	0
3/1/2008	0
4/1/2008	1
5/1/2008	1
6/1/2008	28
7/1/2008	36
8/1/2008	5
9/1/2008	6
10/1/2008	0
11/1/2008	0
12/1/2008	0
1/1/2009	0
2/1/2009	0
3/1/2009	0
4/1/2009	6
5/1/2009	6
6/1/2009	2
7/1/2009	13
8/1/2009	34
9/1/2009	0
10/1/2009	0
11/1/2009	0
12/1/2009	0
1/1/2010	0
2/1/2010	0
3/1/2010	0
4/1/2010	2
5/1/2010	10
6/1/2010	25
7/1/2010	64
8/1/2010	43
9/1/2010	22
07-08 Average	79
08-09 Average	61
09-10 Average	166
	113.5

Description: Farenheit-based cooling degree
Source: www.degreedays.net (using tem
Station: Airport: Boston, MA, US (71.00W
Station ID: KBOS

Month starting	CDD
10/1/2007	4
11/1/2007	0
12/1/2007	0
1/1/2008	0
2/1/2008	0
3/1/2008	0
4/1/2008	2
5/1/2008	2
6/1/2008	39
7/1/2008	52
8/1/2008	10
9/1/2008	10
10/1/2008	0
11/1/2008	0
12/1/2008	0
1/1/2009	0
2/1/2009	0
3/1/2009	0
4/1/2009	7
5/1/2009	8
6/1/2009	3
7/1/2009	23
8/1/2009	51
9/1/2009	2
10/1/2009	0
11/1/2009	0
12/1/2009	0
1/1/2010	0
2/1/2010	0
3/1/2010	0
4/1/2010	3
5/1/2010	14
6/1/2010	35
7/1/2010	90
8/1/2010	60
9/1/2010	29
07-08 Average	119
08-09 Average	94
09-10 Average	231
	162.5

days for a base temperature of **78F**
perature data from www.wunderground.com)
/,42.36N)

Description:	Farenheit-based cooling degree days for a base temperature of **76F**
Source:	www.degreedays.net (using temperature data from www.wunderground.com)
Station:	Airport: Boston, MA, US (71.00W,42.36N)
Station ID:	KBOS

Month starting	CDD
10/1/2007	7
11/1/2007	0
12/1/2007	0
1/1/2008	0
2/1/2008	0
3/1/2008	0
4/1/2008	2
5/1/2008	3
6/1/2008	53
7/1/2008	75
8/1/2008	18
9/1/2008	16
10/1/2008	0
11/1/2008	0
12/1/2008	0
1/1/2009	0
2/1/2009	0
3/1/2009	0
4/1/2009	9
5/1/2009	12
6/1/2009	5
7/1/2009	37
8/1/2009	72
9/1/2009	4
10/1/2009	0
11/1/2009	0
12/1/2009	0
1/1/2010	0
2/1/2010	0
3/1/2010	0
4/1/2010	4
5/1/2010	19
6/1/2010	48
7/1/2010	122
8/1/2010	80
9/1/2010	39
07-08 Average	174
08-09 Average	139
09-10 Average	312
	225.5

Description:	Farenheit-based cooling degree days for a base temperature of **74F**
Source:	www.degreedays.net (using temperature data from www.wunderground.com)
Station:	Airport: Boston, MA, US (71.00W,42.36N)
Station ID:	KBOS

Month starting	CDD
10/1/2007	10
11/1/2007	0
12/1/2007	0
1/1/2008	0
2/1/2008	0
3/1/2008	0
4/1/2008	2
5/1/2008	6
6/1/2008	70
7/1/2008	108
8/1/2008	30
9/1/2008	24
10/1/2008	0
11/1/2008	0
12/1/2008	0
1/1/2009	0
2/1/2009	0
3/1/2009	0
4/1/2009	11
5/1/2009	16
6/1/2009	8
7/1/2009	56
8/1/2009	98
9/1/2009	8
10/1/2009	0
11/1/2009	0
12/1/2009	0
1/1/2010	0
2/1/2010	0
3/1/2010	0
4/1/2010	6
5/1/2010	26
6/1/2010	67
7/1/2010	160
8/1/2010	105
9/1/2010	54
07-08 Average	250
08-09 Average	197
09-10 Average	418
	307.5

Historical Data

Monthly total heating degree days for Boston, MA

www.erh.noaa.gov
Monthly total heating degree days for BOSTON WSFO AP
The cumulative number of degrees in a month or year by which the mean temperature fa

Year	Jan	Feb	Mar	Apr	May	Jun	Jul
1872			1189	544	187	49	0
1873	1230	1073	955	594	297	51	15
1874	1062	1057	941	781	307	77	7
1875	1387	1189	1036	665	257	72	1
1876	1056	1082	971	624	339	54	10
1877	1240	855	926	615	335	43	4
1878	1142	961	780	499	264	88	7
1879	1259	1122	965	674	198	105	16
1880	934	955	978	549	150	64	2
1881	1328	1032	858	635	284	147	6
1882	1200	962	891	658	444	56	17
1883	1253	1007	1056	584	270	20	5
1884	1260	976	948	626	316	88	20
1885	1158	1235	1149	531	371	61	8
1886	1209	1065	975	485	265	85	1
1887	1231	1008	1030	618	200	68	0
1888	1386	1054	1010	666	365	39	26
1889	900	1084	824	510	190	20	14
1890	1008	880	924	555	243	88	18
1891	1044	919	964	506	287	100	8
1892	1128	1055	989	494	286	34	2
1893	1367	1061	962	611	292	93	3
1894	1073	1068	688	530	245	68	4
1895	1116	1126	938	566	226	49	11
1896	1235	1046	1019	532	188	68	16
1897	1124	948	863	477	221	128	17
1898	1118	897	680	629	289	75	17
1899	1106	1061	955	504	244	5	8
1900	1074	995	955	485	313	36	0
1901	1154	1132	886	638	336	51	7
1902	1176	1003	664	492	244	64	34
1903	1118	932	629	517	247	163	12
1904	1341	1224	937	602	166	117	9
1905	1229	1159	855	538	247	91	4
1906	899	982	1004	526	231	61	13
1907	1168	1208	832	642	387	120	0
1908	1046	1104	810	551	224	19	4
1909	1068	899	867	511	286	54	3
1910	1016	988	705	395	240	112	0
1911	1024	1059	909	565	143	57	4
1912	1343	1073	889	525	220	56	1
1913	789	1038	693	508	300	38	0
1914	1118	1133	869	590	200	43	39
1915	982	885	898	420	259	85	9
1916	980	1137	1059	577	198	108	5
1917	1073	1089	852	623	437	69	9
1918	1356	1057	869	508	102	86	16
1919	976	899	743	538	204	70	1
1920	1358	1077	790	588	319	100	4
1921	1015	901	577	391	262	34	6
1922	1163	914	774	480	139	32	3
1923	1171	1157	958	511	246	48	20
1924	1018	1107	847	526	266	64	5
1925	1165	748	673	456	234	19	2
1926	1046	1031	947	596	274	88	18
1927	1058	900	718	501	300	63	7