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DIVISION OF ENERGY RESOURCES

Window Retrofit Technologies

Increased Energy Efficiency without Replacement

Conservation Applied Research & Development (CARD)
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Abstract

This white paper explores the potential for energy savings with window retrofit technologies, specifically window panels and surface applied window films, in residential and commercial buildings across Minnesota. The retrofits are permanent products, unlike shrink-wrap plastic that is applied over a window frame for seasonal use. The report includes a literature review, the results of computer simulations of the products in commercial and residential buildings, information from product suppliers and building owners, and recommendations for increasing market adoption of the effective retrofits.

The total annual energy savings potential of window retrofits is 13 trillion, of which 80% is in houses. The commercial building sector uses a comparable amount of total energy per year (about 340 trillion Btu) to the residential sector (395 trillion Btu)[1], but windows represent only about 10% of the energy load in commercial buildings, compared to 30 to 35% in houses. The cost-effectiveness of window retrofits is also better in houses, both because of a large number of product suppliers and the cost savings offered by self-installed products. 3.4 trillion Btu, or about 26% of the total savings potential, can be achieved with retrofits that pay back in 15 years or less, based on energy cost savings.

This report considered five specific window retrofits:

1. Clear window panels;
2. Window panels with a low-e coating;
3. A moderate solar heat gain, low-e applied film;
4. A low solar heat gain, low-e applied film; and
5. A tinted window film.

The impact on heating and cooling energy based on the computer simulations is reported as kbtu/ft^2 of window area. The average savings, weighted by the window area of all building types in Minnesota were best for the low-e window panels, 39 kbtu/ft^2; followed closely by clear panels, 31 kbtu/ft^2; the low-e window films with moderate solar gain offered more modest savings of 13 kbtu/ft^2. In contrast, there was an energy penalty for both the low solar heat gain, Low–e film (7) kbtu/ft^2 and the tinted window film (13) kbtu/ft^2. The latter two retrofits are only suggested for special situations when justified by building-specific energy modeling.

Window retrofits cost between $3 and $7 per square foot (self-installed window panels) which is far less than the cost of window replacements ($30 to $90 per square foot) and in many cases produce the same energy savings. Current paybacks are long and modest utility rebate programs are suggested primarily to inform consumers that these products are effective.

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[1] Energy Policy and Conservation Quadrennial Report, 2012. Minnesota Department of Commerce, Division of Energy Resources.

Executive Summary

Most consumers are aware that better windows can save them energy, in part because of well publicized national studies stating that windows are the source of 34% of overall energy use in commercial buildings and about 30% in residential buildings (Apte and Arasteh, 2006). Existing buildings in Minnesota already have windows that perform substantially better than the national average, so there is less opportunity for savings than in other regions of the US. It is estimated that over 95% of the 300 million square feet of windows in the state are double glazed well above the national average of 60%. Window retrofits cost a fraction of the price of replacement windows and can be used on the great majority of windows in Minnesota, improving many to a level that meets current ENERGY STAR standards. The savings are comparable to those provided by triple pane windows.

The study includes five window retrofits: two types of window panels and three kinds of applied window films. These products were chosen because they are readily available commercially and do not require frequent human intervention to be effective (unlike window shades, blinds, curtains or awnings). Three of these window retrofit products are good candidates for utility Conservation Improvement Programs (CIP), primarily in residential homes, because they will save energy for many years following their installation. Two did not lead to energy savings in most situations and are not recommended for general use in Minnesota. The study excludes products that have not yet become widely available, such as electrochromic windows and refracting window films.

This report combines a literature review with climate specific energy modeling and presents results applicable to Minnesota (ASHRAE climate zones 6A and 7). Energy modeling was performed on a whole building level, using RESFEN for houses and EnergyPlus for commercial buildings. The impact of changing the u-factor and solar heat gain coefficient (SHGC) was determined and is reported by both building type and retrofit type.

Both types of window panels were the most effective at saving energy because they add an extra layer of air to the window assembly. The placement of the panels (inside or outside of the existing window) does not have an effect on the savings potential, nor does the choice of glazing (glass or plastic). Average savings were calculated based on a weighted average of windows in all building types, including houses. The best savings were provided by low-e coated glass window panels (the current coating process only works on glass), 39 kbtu/ft^2. (Energy savings are expressed as kbtu/ft^2 of window area. 100 kbtu = 1 therm = 29.3 kWh.) The low-e coating reduces heat transfer across the window surface. The reduced heat transfer effectively improves the u-factor of the panel. Clear window panels saved an average of 31 kbtu/ft^2. Both types of window panels save energy in all building types.

Applied window films produced variable results depending on the cardinal direction they face (they provide the most benefit on east or west sides of buildings) and the type of building. There are only a small number of commercially available films with low-e coating currently sold, and two were studied, a moderate SHGC film (0.46 vs. 0.60 for a clear window) and a low SHGC film (0.30). The film with moderate solar heat gain provided savings in most buildings, with a weighted average saving of 13 kbtu/ft^2. In contrast, the film with low SHGC led to an energy penalty in most cases, due to the reduction in passive solar heating during the winter months; the weighted average increase in energy use was 7 kbtu/ft^2 of building window area.

Tinted films, without a low-e coating, were also evaluated as they are often promoted as energy saving products. While they are effective in hot, sunny climates where solar heating causes increased cooling loads, in Minnesota the tinted films block solar heating in winter, leading to increased heating requirements. Overall, a building with tinted film applied to all the windows used 13 kbtu/ft^2 more than the same building with clear windows. They are not recommended as a window retrofit to save energy in Minnesota.

Window properties were modeled with WINDOW and THERM, which produce the values of u-factor and SHGC that are the inputs for the building simulations. Computer simulations were performed using RESFEN for houses and EnergyPlus for commercial buildings. The Department of Energy's sixteen reference buildings, which are representative of a majority of the building stock in the US, were used for specific building types. Over 4,000 simulations were performed in order to evaluate the general impact of variation of the u-factor, SHGC, climate zone and building type on total building energy. The results were constrained to changes in heating and cooling energy to match the project's assumption that no other building systems would be changed as part of a window retrofit project. In the case of a deep retrofit project, including window retrofits will allow other mechanical equipment to be downsized in some instances, leading to additional savings.

Using the results of national surveys (CBECS and RBECS), Minnesota characterization studies, a utility sponsored DSM potential study, and market research data on window sales, we estimated the number and characteristics of windows in Minnesota buildings. There are about 1.9 million buildings in the state, of which 1.8 million are residential and 100,000 are commercial. Buildings were grouped by function and/or structural characteristics. 80% of all windows (by area) are in houses, apartments have about 6%, one story buildings (small office buildings, stand-alone retail, strip malls, etc.) have 5%, schools and multistory offices about 3% each and the remainder are in hotels, healthcare and restaurant buildings. The replacement window market for residential buildings is about twice the size of commercial buildings, with about 55,000 houses having their windows replaced each year. This corresponds to an average window lifetime of about 35 years (which agrees with US Census data). When modeling buildings it was assumed that buildings between 10 and 25 years old would be the best candidates for window retrofits, and that they would be a good choice for building owners if they would pay for themselves with savings by the time the original windows were due for replacement, thus payback periods of up to 30 years would not be unreasonable. Using this criteria, up to 90% of the windows in Minnesota that are 10 to 25 years old are candidates for cost-effective window retrofits; and this could save nearly 12 trillion Btu a year across the state.

In houses, low-e window panels reduced heating and cooling energy use by an average of 14%; clear panels by 11% and the applied low-e film with moderate SHGC by 5%. Electric resistance heating is used by about 12% of Minnesota houses, and they can save up to $346 a year in Zone 7 by installing low-E window panels. In contrast for a house in zone 6 with natural gas heat (and 20% fewer heating degree days), the annual savings is only about $91, leading to a 16 year payback for self-installation or 26 years if the panels are professionally installed.

The magnitude of savings was highest with low-e window panels, between 30 and 40 kbtu/ft^2 of window area, in houses, office buildings, apartment buildings, schools, healthcare buildings and restaurants.[2] Smaller savings of 10 to 20 kbtu/ft^2 are seen in one-story buildings and hotels had savings under 10

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[2] Houses average 225 ft^2 of window area, apartments average 2,500 and multistory office buildings range from 7,000 to over 50,000 ft^2.

kbtu/ft^2. Overall, over 90% of the savings is due to reduced heating, regardless of building type. However, because cooling uses electricity, it tends to be about three times as expensive per unit of energy, leading to the occasional counterintuitive result that a product, like the low solar heat gain window film in medium office buildings, can save money and increase natural gas use at the same time. There is not a simple one-size fits-all solution: the retrofit that saves the most energy is not always the most cost-effective and the most effective retrofit (by either cost or energy savings) is different for different types of buildings.

The cost of window retrofits varies between \$3 and \$10 per square foot for self-installed products, with most between \$3 and \$7. Professionally installed applied window films cost between \$7 and \$20 per square foot, professionally installed window panels cost between \$10 and \$20 per square foot. These costs should be compared with replacement window costs that range from \$34/ft^2 for a double pane high gain, low-e window (that will perform slightly better than an existing single pane window with a storm window over it) to \$88/ft^2 for an ENERGY STAR triple pane window. Especially when self-installed, window retrofits will cost about 20% of the cost of replacement windows, and thus offer a good short term (10-20 years) option for homeowners wishing to save energy and improve comfort while deferring the cost and inconvenience of window replacement until the existing windows have reached their full useful life.

There are a number of non-energy benefits of window retrofits, including the reduction of ultraviolet radiation which is linked to skin cancers as deterioration of furniture and fabrics. Window panels also provide noise reduction, decrease drafts off of the existing windows, and reduce infiltration in some instances. There are several barriers that window retrofits face, beyond the general lack of awareness of their existence. Replacement windows are one of the most valued home improvements, and window retrofits may suffer in comparison; in addition some window panels may make it harder to open otherwise operable windows. Low-e window films are moderately reflective, which gives them a shiny appearance, and in certain situations where strong sun/shade lines occur on the window applied films can cause a large enough change in the surface temperature that the glass will break. (This is why professional installation is required for the low-e window films.)

Rebates are often recommended to increase product uptake; however because of the long paybacks they are not significant relative to the product cost. Rebatable window retrofit projects would include window panels (clear and low-e) for houses with electric heat: the rebate would be about \$130 for a whole house retrofit, or a little less than 10% of the total project cost, a fairly modest incentive. Incentives are still recommended for the reason that they serve as a validation by the utility of the energy saving potential of the products.

Approximately 3.4 trillion Btu annually can be saved with window retrofits that pay back in 15 years or less (the economic potential). If the payback period is extended to 25 years, which is a realistic lifetime for a window, then 90% of the technical potential savings can be achieved, or almost 12 trillion Btu per year, which is 1.6% of Minnesota's annual residential and commercial energy use.

Part I. The Impact of Windows on Building Energy Use

Most consumers are aware that better windows can save them energy, and studies show that windows are the source of 34% of overall energy use in commercial buildings and about 30% in residential buildings. (Apte and Arasteh, 2006). However, since existing buildings in Minnesota already have windows that perform substantially better than the national average, the opportunity for savings is smaller. Alternatively, window retrofits can effectively save energy and be used on the great majority of windows in Minnesota, improving most existing windows to a level that meets current ENERGY STAR standards. The savings are comparable to those provided by window replacements at a fraction of the cost, making window retrofits an attractive option. Unfortunately, most studies of window retrofits have looked at the impact of enhancing single pane glass windows, which are relatively rare in Minnesota, less than 4% of all windows (KEMA, 2013). This white paper therefore uses double pane, clear glass windows as the base case. The savings for windows that have single glazing are always larger.

The study includes three kinds of applied window films and two kinds of window panels. These products were chosen because they are readily available commercially and do not require frequent human intervention (unlike window shades, blinds, curtains or awnings). The study excludes products that have not yet become widely available, such as electrochromic windows and refracting window films. The selected retrofit products are good candidates for utility Conservation Improvement Programs (CIP) because they will save energy for many years following their installation.

Overview of building science as it relates to windows

The simplest view of a building is that it is a box made up of independent parts (wall, roof, foundation and windows), each with their own properties that taken together define the heating and cooling characteristics of the building. This is a fairly realistic way to treat residential houses as well as simple buildings such as warehouses. These buildings are described as being "building envelope driven." It is possible to predict the energy lost per square foot of window area for different window systems in these buildings. This method of analysis is commonly used by many contractors to determine the appropriate size of heating and cooling systems as defined in *Manual J*. (Rutkowski, H. 2011).

Table 1. Building Envelope Analysis of a Typical Minnesota Home Built Between 1960 and 1980

Building System	Area (square feet)	Percent of Area	R value	Percent of Heat Loss
Windows	255	6%	R-2*	32%
Walls	1,945	46%	R-9	48%
Roof	1,000	24%	R-20	12%
Foundation	1,000	24%	**	7%

*The window R value for Pre-1980 homes assumes that there are either storm windows or the windows have been replaced.
**The foundation value is taken from a published calculation that uses Minnesota soil temperatures with typical construction practices. (See Mechanical and Electrical Equipment for Buildings, 2011. Walter Grondzik, Alison Kwok, Benjamin Stein and John Reynolds, p 194-5).

Table 1 shows the results of the building envelope analysis of a typical Minnesota house built between 1960 and 1980. This type of analysis is often used in window sales materials. Each building component has an associated heat resistance (R) value which is used to determine the heat loss through it. The percentages represent the relative amount of heat lost through each of the building systems; windows have only 6% of the surface area but are responsible for 32% of the heat loss. Improving window energy performance is an obvious candidate for saving energy in houses and other buildings.

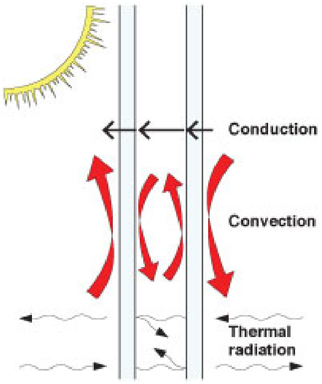
The simple envelope model does a poor job of predicting energy use in most commercial buildings because they are both structurally more complex and often include energy using and generating activities. Even in simple buildings this envelope model is only a first approximation of energy performance; the results are improved by accounting for the construction details of the windows (frame material, number of layers of glazing, glazing material), their placement on the building (north, east, south or west facing) and the degree of shading. While heat loss is the dominant factor in energy performance of window systems, solar heat gain also has a significant impact. In fact, current window research shows that with advanced designs (to capture solar energy), windows have the potential to be net energy sources for buildings (see Figure 5 and related discussion below).[3]

Above all, building science has shown that buildings need to be treated as systems of inter-related parts, so it is not possible to correctly predict the impact of a change in one component, such as the windows, without looking at the entire building. Factors that affect building energy use include: principal activity (office, retail store; warehouse; school, health care, etc.), window placement on the building (orientation), construction characteristics (wood, masonry, steel and glass), and the efficiency of the heating and cooling equipment. Computer modeling is now used to predict the energy use of buildings and the Department of Energy has created a group of standard buildings that can be used to simulate the effect of changing individual building systems. This is discussed in detail in Part 2.

Energy Performance of the Window System

The thermal performance of a window is dependent on conduction, radiation, and convection (Figure 1). Each of these modes of heat transfer is affected in different ways by the window frame, the glazing, the windows' immediate environment (orientation, solar angle, and degree of shading), and the connections between the building envelope, window frame and glazing.

Figure 1. Conduction, radiation and convection all are affected by adding an additional glazing layer to a window. [From commercial windows website.]



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[3] See Charlie Curcija; "Overview of Window research at Lawrence Berkeley National laboratory" in Ojczyk, C.; Carmody, J.; Haglund, K. (2013). Expert Meeting Report: Windows Options for New and Existing Homes. May 2013, NREL on behalf of U.S. D.O.E's. Building America Program.

Air infiltration is caused by imperfect seals between elements of the window and is generally caused by poor installation (the window does not properly fit into the wall opening) or deterioration of the window frame. Infiltration may be reduced by window retrofit products, but it is not their primary purpose. If the underlying cause of infiltration is not addressed by a retrofit the window system will remain substandard. A window panel may reduce infiltration from an operable window that does not seal well to its frame; on the other hand, if the window assembly fits poorly in the wall opening, unless the retrofit product is larger than the original opening, the problem will remain. Several field studies have anecdotally measured reductions in infiltration due to adding storm windows, but the results are highly variable, and completely dependent on the specific existing conditions (Klems 2002; Quanta Technologies 2013).

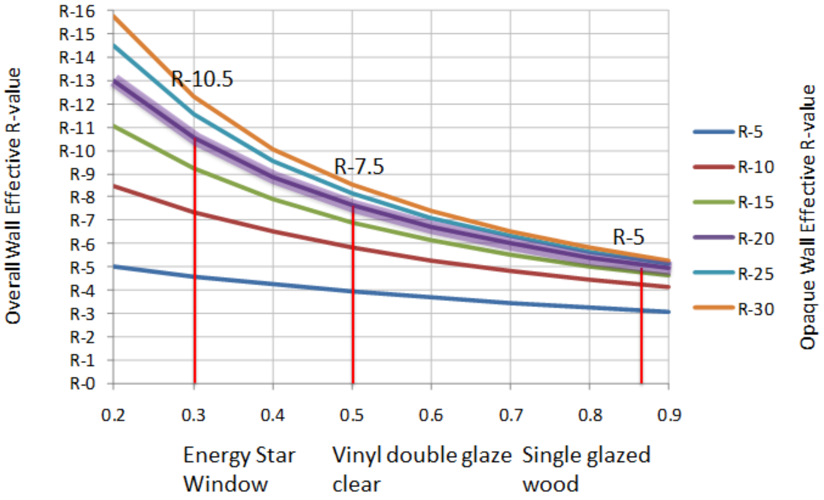
Windows can be described by their properties such as frame type, glass type, shape, and mechanism for operating. This report considers only those properties which have an impact on the energy performance of window retrofits: the rate of heat transmission (measured by the U-factor) and the amount of solar energy passing through the window (the solar heat gain coefficient, or SHGC). Since retrofits are added to existing windows, the subjects of window assembly or façade design are not relevant to this project although they are important considerations in new construction. The U-factor (insulation level), SHGC, overall emissivity of the window (the amount of radiation of all wavelengths including ultraviolet and infrared that is able to pass through the window), and visual transmittance of a window assembly will all be changed by any retrofit product and are discussed below in more detail.

Insulation level (U-factor)

Insulation level (U-factor) is the rate of thermal energy transmission across a window. The National Fenestration Rating Council (NFRC) reports the U-factor for most commercially manufactured windows. The lower the U-factor, the greater the insulation level of the window. In the US the U-factor is given in units of btu/ft^2/hr which are the inverse of the R values used for wall insulation (for example, a U-factor of 0.33 is the same as R-3). As points of reference, single pane glass has a U-factor of about 1.0, double pane glass has a U-factor of about 0.6; and an average insulated wall has a U-factor of 0.10 (R-10), much better than either window. U-factor times the window area times the temperature difference across the window gives the total heat loss for a window. In Minnesota where zone 6A (Minneapolis-St Paul) has about 8,400 heating degree days (HDD) and zone 7 (Duluth) has about 10,000 HDD the heat loss will be 19% larger in zone 7 than zone 6A because there are 19% more heating degree days in zone 7.

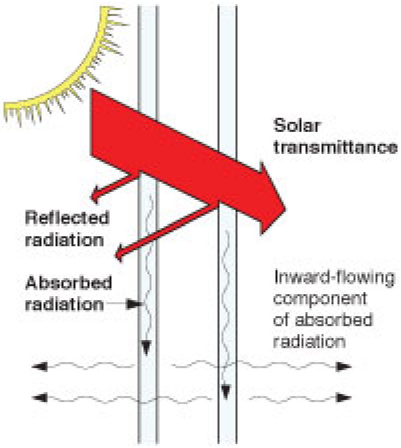
Figure 2 shows the benefit of improving the insulation value of windows compared to walls. The figure shows the overall R value of a wall assembly that includes an insulated outside wall (R values from 5 to 30 are shown) with three different window options (single glazed, double glazed and ENERGY STAR) Adding a window panel has the effect of making an existing window move to the next best category: a single window gets the insulation value of a double pane window; and a double pane window gets the insulation value of a triple pane (ENERGY STAR) window. The benefit of an additional layer of glazing is provided by the air layer next to the glass' surface, not the glass itself (Rubin, M, 1983). This is a primary reason that window panels are found to provide a greater insulating benefit than window films, which do not create a new air space.

Figure 2. Effect of window performance on the overall insulation level of a house wall. Figure courtesy of Building Science Corporation



Solar heat gain coefficient

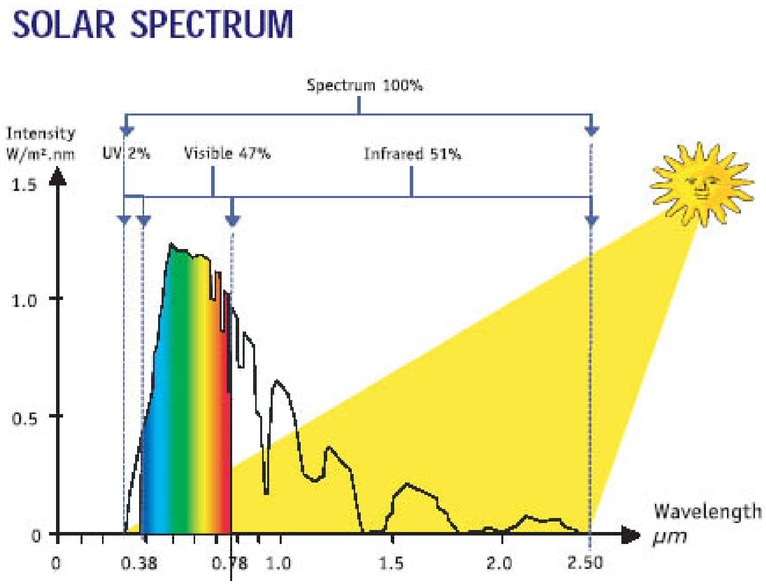
Figure 3. The interaction of solar energy with window surfaces. From commercial windows website



Solar heat gain coefficient (SHGC) is a measure of the amount of total solar energy that passes through the window assembly; it is measured in percent. Figure 3 illustrates that three things happen to incident solar radiation; it is reflected, transmitted or absorbed. Most of the energy that is absorbed by the glass is reradiated. The ratio of the total energy that passes through the window to the total incident energy is the solar heat gain coefficient. A solar heat gain coefficient of 1 means that all the solar energy incident on the window enters the building, a value of 0 means that the window blocks all of the solar radiation. Regular glass allows about 60% of the incident solar energy into the building; dark tinted glass may allow as little as 10% through.

Not all solar radiation is visible to the human eye. As a result, one strategy to reduce solar heat gain is to block the solar radiation that cannot be seen. Figure 4 shows visible light as part of the full spectrum of radiation. Forty-three percent of the sun's energy is in the visible part of the spectrum, 5% is in the ultraviolet region (shorter wavelength than visible), and 52% is in the infrared region (longer wavelength). Blocking ultraviolet radiation (uv) also has a health benefit as exposure to uv is known to cause skin cancer.

Figure 4. The visible spectrum From theglassblog website



Innovative window products, referred to as “spectrally selective,” are designed to block the radiation outside the visible range while allowing visible light to pass. If the glazing blocks any radiation, visible or invisible, by reflection, then it will also have the property of reflecting interior heat back into the building, effectively increasing the insulation value of the window. Some window films have this property and their energy saving potential is discussed in more detail in this report.

Emissivity

Emissivity refers to the amount of absorbed thermal energy that a material emits as radiation. An object with low-emissivity (low-e) absorbs heat re-radiating only some of it. One benefit of reduced heat transfer is that the insulation value (U-factor) of the overall window is improved. Spectrally selective coatings (Figure 4 above) that allow visible light to pass, but reflect infrared radiation back have low emissivity.

Regular glass has an emissivity of about 90%. While only some of the light that hits glass is absorbed (most of it is either reflected or transmitted), the emissivity rating means that 90% of any light absorbed by the glass (and turned into heat) is re-emitted as thermal radiation. Only 10% of any absorbed energy stays in the glass, raising its temperature. Window films and coatings with emissivity below 30% are generally labeled “low-e.” They allow much less thermal energy to pass across the window surface: the rest is either reflected or absorbed by the film as heat. One undesirable consequence is that the glass can expand, deforming or even cracking, because of the added heat. Many companies that sell Low-E window films require professional installation to avoid situations where this is a high risk.

Metal oxide coatings are used to lower the emissivity of glass. Two fabrication techniques are used: pyrolytic coating of fluorinated tin oxides, in which a thin film is sprayed onto the semi-molten glass during the float glass manufacturing process (at temperatures above 1000° C); and magnetron sputtering of silver and other metal oxides (zinc, tin and titanium) in a high vacuum, a process that is similar to the manufacture of computer chips. The second process is only used in the manufacture of integrated glass units (IGUs). These are multilayer assemblies where the coating in on an inside surface of a sealed unit. Pyrolytic coatings require a sealed environment because the silver oxide on the surface will tarnish (blacken) if exposed to airborne sulfur dioxide pollutants.

Coatings that reduce emissivity can also be enclosed between two layers of plastic in a window film, although these use completely different chemical materials to achieve the desired spectral selectivity (see Figure 10). These films all have a shiny appearance because they reflect some light in all regions of the spectrum, including the visible range. The film manufacturer's challenge is to create a material that blocks thermal radiation, but not visible light. There are very few of these products commercially available at the present (less than five with NFRC certified values in 2013). Many tinted and reflective films reduce solar heat gain, but do not change the insulating value of the window, so they do not reduce heat loss by transmission.

Visual transmittance

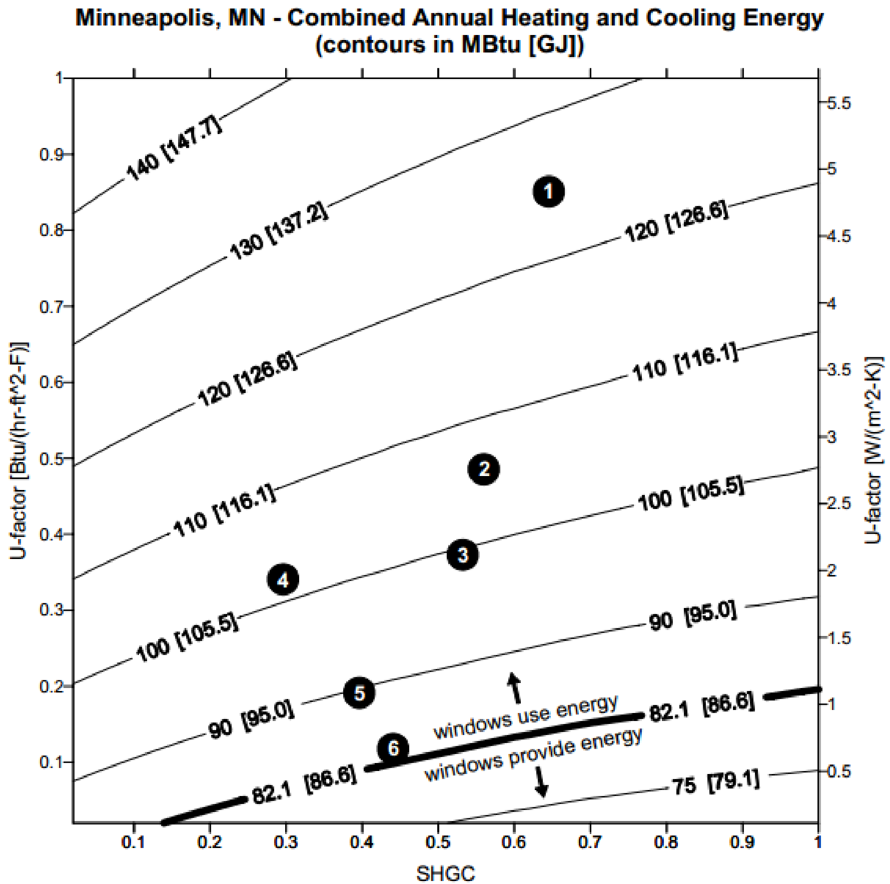
Visual transmittance (VT) is the measure of the amount of visible light that passes through a window, generally expressed as a percentage. Traditional clear glass has a VT of 0.76, which means that 76% of the visible light hitting the window actually passes through to the inside, the other 24% is either reflected back outside (typically 7%) or absorbed by the glass itself (the remaining 17%). Tinted windows lower the amount of visible light transmitted, which also reduces solar heat gain. On its own, VT does not have a direct impact on heating and cooling energy used. One consequence of reduced VT is an increased need for artificial lighting even when there is daylight available; this secondary impact is not in the scope of the current study.

The Combined Effect of Changing U-factor and Solar Heat Gain Coefficient

The energy impacts of changes to the U-factor and SHGC are not independent of one another. In climate zones 6A and 7 (including all of Minnesota) the effect of changing the U-factor is generally much larger than changing the SHGC. The impact of changing both U-factor and SHGC are non-linear: doubling the relative U-factor change does not necessarily double the savings, for example.

Researchers at Lawrence Berkeley Laboratories have looked at the interaction of U-factor and SHGC in a variety of climates, as part of a project to design advanced windows that can contribute to a net zero energy home. The contour plot below (Figure 5) shows how the U-factor and SHGC mutually determine window energy performance in Minneapolis. The simulation for this study assumed that each face of the house has an equal window area; varying the distribution and actual orientation of the windows on the house leads to slightly different results. The lines in Figure 5 are contours of total energy required to heat and cool house in Minnesota, as a function of U-factor and SHGC. The heavy line near the bottom is the total energy required for heating and cooling when the heat transfer across the windows is arbitrarily set to zero; thus the area below the line represent the characteristics of windows that can provide net energy to the house.

Figure 5. Contour plot of lines of constant energy for residential windows in Minneapolis St. Paul. from Arasteh, D. K. et al. 2006.



ID	U value Btu/ ft^2/hr ^{o}F	SHGC	Window Description	Comparable Retrofit Window In This Report
1	0.84	0.64	Single clear, wood/vinyl	Single pane
2	0.49	0.56	Double clear, air, wood/vinyl	Base Window (Double Clear or with a Tinted Film applied)
3	0.37	0.53	Double, moderate gain low-e, Ar fill, wood/vinyl	Base Window Plus Clear Panel (Glass or plastic)
4	0.34	0.30	Double, low gain low-e, Ar fill, wood/vinyl Current ENERGY STAR (to 2013)	Base Window Plus Glass Panel with a low-e coating
5	0.18	0.40	Triple, moderate gain low-e, Kr fill New ENERGY STAR (2014)	
6	0.12	0.44	Improved triple, low-e, Kr fill Best Available Technology	

In Minnesota improving the U-factor always reduces energy loss through the window, while decreasing the SHGC increases whole house energy requirements by rejecting "free solar heating." In Figure 5 windows #5 and #6 represent the best commercially available windows today (triple pane). Plots for other climate zones are very different; for example in Phoenix the contour lines run fairly steeply from the upper left towards the lower right; in the hot sunny climate, decreasing SHGC dramatically decreases cooling energy, which is the majority of the total energy use (in Phoenix).

Window Retrofit Products

Window Panels

Window panels are familiar to most Minnesotans as exterior mounted glass storm windows with frames made of wood or metal (Figure 6). These products were installed to improve that performance of single pane windows and to protect the existing window from weather, hence the name “storm” window. In many cases when single pane windows are replaced with double pane windows the storm window assembly is removed on the presumption that it is no longer needed. In fact, this often means that the replacement double pane window has the same insulation value as the single pane/storm window combination, and there is no energy savings. When a window panel is added as a retrofit, the additional pane (mounted on the inside or outside) with an air tight seal, is always beneficial. A panel placed over a double pane window provides the same insulation value as a triple glazed window at a lower cost. A double pane, clear glass window (of the type commonly installed in many homes between 1980 and 2000) has a U-factor of about 0.5, adding an additional panel increases this to about 0.33, reducing heat loss by about 1/3. Current Minnesota building code requires new windows to have a U-factor 0f 0.35 or better.

Figure 6. Traditional exterior storm window (screen only on the right). from betterhouseinc website

This report considers two recent product innovations as storm windows have become “window panels”: interior mounting and low-e coating. Interior mounting can offer greater convenience and reduced installation and maintenance costs, especially in multistory buildings, and low-e coatings enhance the insulating value of the window surface. Interior mounted window panels can also be made slightly “tighter” than exterior storm windows because they are less likely to be a site of condensation and do not require weep holes (a source of air infiltration). Field studies have verified that adding a storm window to an existing single pane window had the same energy benefit as a double pane replacement window. (Klems, J. 2003)

Glass Panels (Interior or Exterior)

Glass window panel retrofits are available for either exterior or interior window installation. They are made by a variety of manufacturers. Most interior panels are made by manufacturers who also make exterior storm windows (such as Larson and Quanta)[4]. Both products are distributed at home improvement centers (such as Menards, Home Depot, and Lowe's) as well as directly from small manufacturers and a small number of contractors. Most independent replacement window companies are unfamiliar with the product and do not offer it even when specifically requested.

Figure 7. Interior Window Panel. from cmsilver1 website

Some glass panels simply fit in place covering the existing window, as shown in Figure 7, while others are operable, with the same type of construction as exterior storm windows as shown in Figure 8.

Figure 8. Operable interior window panel. Building Green photo**.**

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[4] A partial list of window retrofit manufacturers is in Appendix A

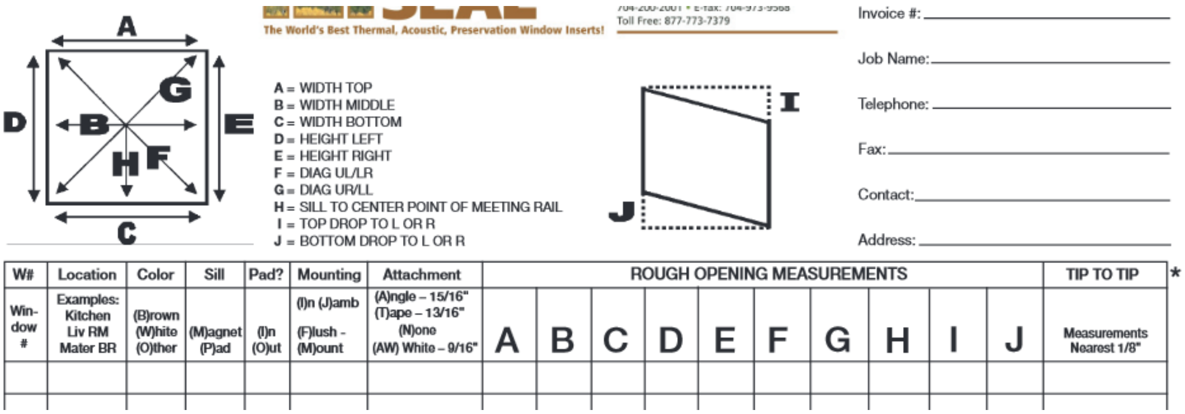
One advantage of glass window retrofit panels is that they are available with low-emissivity (low-e) coatings. The coating is usually applied to the inner surface of the glass to avoid scratching; the coating has the same lifetime as the glass itself, that is, at least 20 years.

Plastic Panels

Interior panels can also be made with clear plastic glazing. The advantage of plastic panels is that they are lighter and more flexible than those made with glass. The most common plastics are acrylic (Plexiglas®) and polycarbonate (Lexan®). Polycarbonate is stronger than acrylic, but is softer and therefore easier to scratch; it also will yellow with time. The panels come in thicknesses that are similar to glass (1/8" (3mm) for residential use and 1/4 "(6mm) for commercial use). At least one manufacturer uses a rigid vinyl film stretched on a frame. Plastics are more difficult to clean than glass and can be scratched when using traditional window cleaning methods.

There are many different mounting styles for the plastic panels. Because they are lightweight most are fit into place by light pressure using a simple "frame" installed just inside of the existing window (see Figure 7) or with a magnetic strip that contacts a metal frame piece installed on the permanent window casing. At present interior plastic panels are primarily products for a "do it yourself" installation, and most are sold directly by small manufacturing companies. An example of an order form is shown in Figure 9: it displays the measurements required for these custom made products. Most of the products we found had a ten year warranty; the major limitation on the lifetime is discoloration of the plastic glazing.

Figure 9. Measurement instructions for custom made interior window panels. from Climate Seal



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A = WIDTH TOP
B = WIDTH MIDDLE
C = WIDTH BOTTOM
D = HEIGHT LEFT
E = HEIGHT RIGHT
F = DIAG UL/LR
G = DIAG UR/LL
H = SILL TO CENTER POINT OF MEETING RAIL
I = TOP DROP TO L OR R
J = BOTTOM DROP TO L OR R

W#	Location	Color	Sill	Pad?	Mounting	Attachment	ROUGH OPENING MEASUREMENTS										TIP TO TIP *
Win-dow #	Examples: Kitchen Liv RM Mater BR	(B)rown (W)hite (O)ther	(M)agnet (P)ad	(I)n (O)ut	(I)n (J)amb (F)lush - (M)ount	(A)ngle – 15/16" (T)ape – 13/16" (N)one (AW) White – 9/16"	A	B	C	D	E	F	G	H	I	J	Measurements Nearest 1/8"

Surface Applied Window Films

Window films can be applied to the surface of the glass on the inside or outside of a window in order to change its optical properties.[5] This project considered only interior applied films because interior application is required to save heating energy. External films may be used to reflect sunlight (which will

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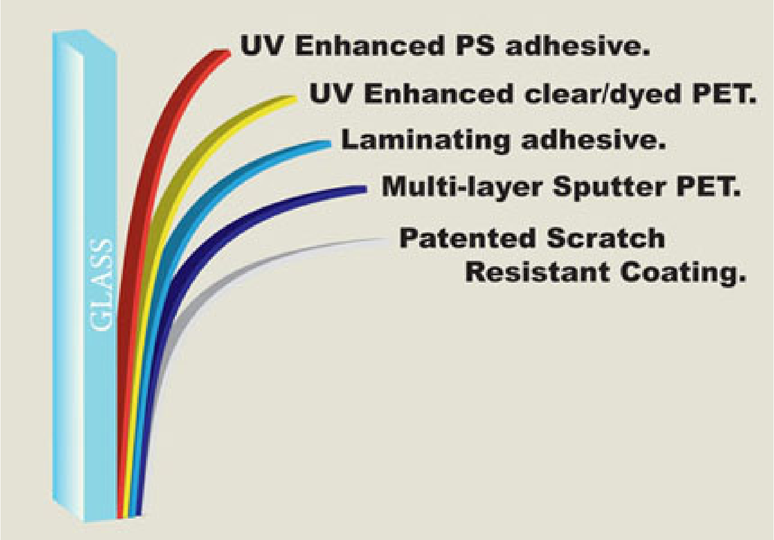
[5] These films should not be confused with the seasonal shrink wrap type plastic sheeting such as the "3M Indoor Window Insulator Kit" that are sold in many hardware stores and home improvement centers with a cost of $3 to $5 per window. These kits are a temporary version of the window panels discussed in this report.

save energy in climates where cooling is more important than heating) or for security reasons. In many southern climates it is desirable to reduce the amount of heat or glare entering buildings through windows, and films can do this. However, in Minnesota windows with a high SHGC are desirable, so a product that blocks LESS heat in the summer will have better winter performance from internal heat retention and passive solar heating (Wulfinghoff 1999). Tinted films that keep out the light do not save energy in most Minnesota buildings; films must be carefully chosen to receive an energy benefit. (See the Efficient Windows Collaborative's web site (www.efficientwindows.org/lowe.php) for extensive information on low-e window films and other specific products.) The lifetime of window films is between ten and twenty years, about half the lifetime of glass window panels and approximately the same as plastic window panels.

Window films are made of multiple layers of plastic materials, each of which can add a particular property to the product, as shown in Figure 10. Window films are a rapidly evolving family of products and a great deal of research continues to be done developing new polymers with novel properties. An example of this is a film that can reduce internal lighting needs by bringing daylight farther into a building by refracting it at the window (3M Daylight Redirecting Film). Continued advances in window films may lead to products with improved insulation value which will be beneficial in Minnesota.

Figure 10. Window film showing the layers making up a typical product. from ice-films website



Part II. Methodology

Literature Review

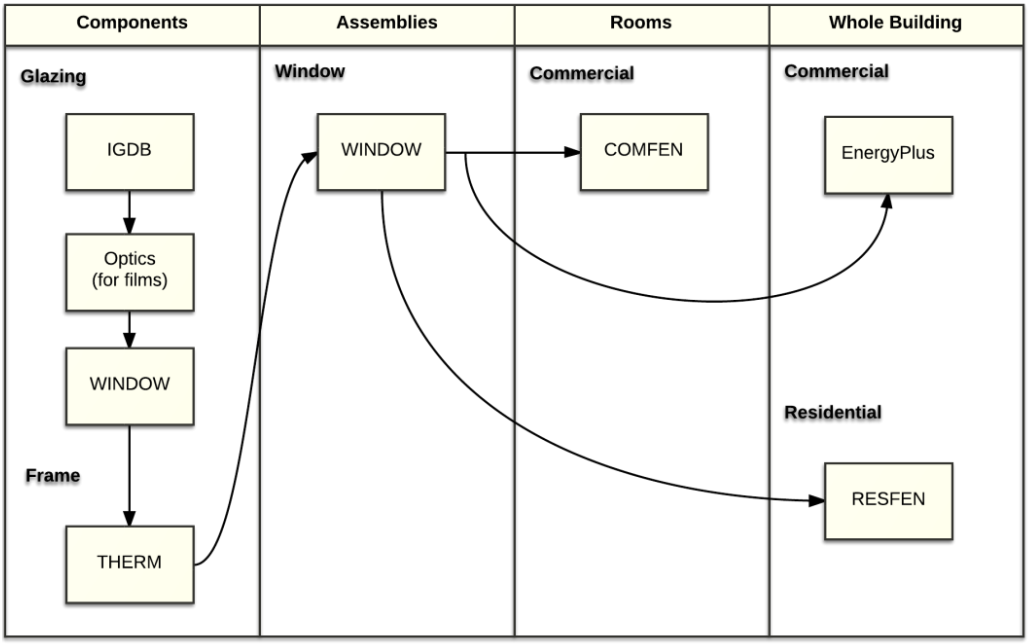
A wide variety of literature source was used in this project. They included books; journals; research reports; databases of governments, non-profits and private companies; websites of manufacturers, suppliers, distributors and installers; and interviews with manufacturers, suppliers, installers, customers and scientific experts in the field. The results of the literature review are integrated into the report as the information applies throughout.

Computer Modeling

Overview

Modeling is useful for designers when comparing different building components that might be used in a particular building. There is specialized software for analyzing the impact of windows in both residential homes (RESFEN, "Residential Fenestration") and commercial buildings (COMFEN, "Commercial Fenestration"). In this section residential energy use modeling is discussed first, followed by commercial building modeling, which is much more complex. Computer modeling of buildings and building components has become an increasingly important tool for energy analysis in the past twenty years. The US Department of Energy is a major driver in the development of building energy modeling software and first introduced DOE-2 in 1979. Building modeling software and supporting applications have undergone continual improvement since that time.

Figure 11. Software programs used for energy modeling



Seven different software programs were used to create the building models and simulate the total annual energy use. Most parameters were fixed at values taken from current building codes while the window attributes were varied to represent the retrofits. Figure 11 illustrates the programs used and their relationship to one another. The attributes of the window components are first modeled (using IGDB, Optics, WINDOW and THERM) then these results are combined in a window assembly (using WINDOW). The outputs of WINDOW are then used directly in RESFEN or COMFEN to determine whole building energy use. As an alternative, the impact of a window on part of a commercial building (a single wall area or façade, for example) can be modeled in COMFEN without needing to know the attributes of the rest of the building. It was found that window retrofits vary greatly in different commercial building types. Additional information on the software can be found in the resources in Appendix B.

To model the window assembly it is first broken into individual components (frame, parts, glazing, gas fill, etc.) which are combined in THERM, a program that uses the laws of thermodynamics to describe heat transfer through each component. These parts are then put back together as an assembly that is analyzed based on its designed configuration in WINDOW.

WINDOW produces the following outputs: U-factor, SHGC and VT for each specific window assembly. These values are used as inputs to RESFEN or EnergyPlus, making it possible to compare the relative performance of a controlled group of window assemblies in a variety of buildings. In all cases, the same set of window retrofits was compared to the base case of double pane windows made with clear glass. Because the materials used to make residential window frames are quite different than commercial window frames (metal for commercial vs. wood or vinyl for residential) the base case U-factors for the residential window factor of 0.51 btu/ ft^2/hr ^{0}F are lower than commercial ones (0.60 btu/ ft^2/hr ^{0}F); this means that residential windows are better insulators than commercial windows because of their frames don't conduct as much heat as the metal commercial frames.

Residential Building Energy Modeling

Modeling energy use in a residential house with RESFEN is straightforward. The house size, number of floors, window area, roof and wall insulation levels are all inputs as are the heating and cooling system efficiencies. We used the current building codes for typical values and made minor modifications so as to match published averages of heating and cooling energy use in Minnesota homes (680 Therms and 840 kWh in Minneapolis; 870 Therms and 260 kWh in Duluth, from U.S. Department of Energy (2012) 2011 Buildings Energy Data Book). Results are provided in MMBtu's for heating and kWh for cooling.

Commercial Building Energy Modeling

Modeling of commercial buildings requires many more steps. The WINDOW and THERM results were first used with COMFEN, also developed by the Lawrence Berkeley National Laboratory. COMFEN looks specifically at the behavior of windows in commercial buildings where the effect of the windows is limited to the perimeter zone (approximately 30 feet or less from the exterior walls). COMFEN takes into account basic thermal attributes as well as building orientation and environmental conditions, such as shading. While COMFEN is useful in describing the relative impact of a window selection on a space within a building, it does not produce whole building energy use results[6]. In order to obtain whole building results, the Department of Energy's Reference Buildings were used for the simulations (see

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[6] More detail can be found at their website and in their publications. (Carmody, J.; Selkowitz, S.; Arasteh, D.; Heschong, L. 2007. Carmody, J.; Selkowitz, S.; Lee, S.H.; Arasteh, D.; Willmert, T. 2004).

below). Finally the behavior of each building over a typical meteorological year was generated by EnergyPLUS again for both climate zones.

Approximately 4,000 EnergyPLUS simulations were initially performed; the variations are described in Table 2 below. These simulations covered the entire possible range of values for each variable in order to understand the impact of each variable on building heating and cooling energy, as well as possible interaction effects. Results were normalized to heating and cooling energy per square foot of window area so buildings of all sizes and types could be easily compared. It was found, for example, that visible transmittance had no impact on heating and cooling energy, so VT was kept as a constant in subsequent simulations[7]. Similarly, once there was a general understanding of the impact of climate zone and date of construction, there was no need to simulate all possible combinations of these parameters in subsequent runs. On the other hand, the variation by building type was much greater than expected, so the study was expanded to include all sixteen of the reference buildings. The simulations required approximately 500 hours of computer time.

Table 2. Parameters used in building energy simulations for initial analysis

Variable	**# of variations**	**Variable values**
U-factor (btu/ ft^2/hr ^oF)	7	0.28, 0.42, 0.56, 0.70, 0.85, 0.99 and 1.13
Solar heat gain coefficient	7	0.10, 0.25, 0.30, 0.50, 0.70 and 0.90
Visible transmittance	3	0.1, 0.5, 0.9
Building types	6	Large office, small office, strip mall, primary school, secondary school and mid-rise multifamily housing
Date of construction	3	Prior to 1980 1980-2004 (ASHRAE 90.1, 1989) New (ASHRAE 90.1 2004)
Climate Zone	2	Zone 6A (Minneapolis) Zone 7 (Duluth)

Because a large variation in energy loss per square foot of window area by building type (as opposed to by window type) additional simulations were performed on the remaining ten commercial building types. For these simulations the specific values of U-factor and SHGC for the five commercially available retrofits were used; their properties are shown in Table 3. These simulations were limited to climate zone 6A with the period of construction from 1980 to 2004.

The EnergyPLUS models of the reference buildings were further constrained to simulate actual retrofit practices. When not constrained, the model downsizes the internal building systems if the energy load on the building decreases. This makes sense for designers of new buildings, since smaller systems use less energy; but for an existing building retrofit it is assumed that this equipment would not be replaced.

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[7] Visible transmittance of the glass can affect building energy use if lighting controls are present; however the present study is limited to the thermal benefits of window retrofits, which are independent of VT.

Table 3. Parameters used for the commercial building window retrofits

Window Description	U-factor (btu/ ft^2/hr ^{o}F)	Solar Heat Gain Coefficient
Double Clear (Base Case)	0.60	0.60
Low-e Panel added to Double Clear	0.33	0.45
Clear Panel added to Double Clear	0.40	0.59
Moderate Gain, Low-e Film (Film A)	0.47	0.46
Low Solar Gain, Low-e Film (Film B)	0.52	0.30
Tinted Film	0.60	0.40

The characteristics of these support systems were held constant and the potential energy savings were not included when calculating the total energy saved at the building level. For example all lighting was modeled using the 1989 ASHRAE standard. Additional energy savings or losses due to the impact of window retrofits on daylighting were not included in the calculations, although the use of daylighting can be a source of considerable energy savings when integrated into the building design process (for example, see the Architecture 2030 website (http://architecture2030.org/).

In order to quantify the potential benefits of window retrofits it is necessary to define the buildings used for the energy simulations. In this case, we used the reference buildings defined by the DOE (Deru, M. et al., 2011). These reference buildings were specifically designed for computer simulations of whole building energy use. The building types were determined by consensus between DOE, the National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL) and Lawrence Berkeley National Laboratory (LBNL).

There are sixteen reference buildings based on the most common building types found in the Commercial Building Energy Consumption Survey (CBECS). The reference buildings reflect standard construction practices and realistic building designs; it is estimated that they characterize over 60% of the commercial building stock in the U.S. These reference buildings have been extensively studied and are the basis for a great deal of building design work. They offer the best publicly available models for research projects such as this one. Each reference building has three versions which reflect the evolution of building energy codes and construction practices over the past 40 years: pre-1980, post-1980 (based on ASHRAE Standard 90.1 1989), and new construction (based on ASHRAE 90.1 2004). The report focused on the post 1980 buildings as they are representative of the construction practices most likely to be found in 10 to 30 year old buildings that are the primary candidates for window retrofits.

The reference buildings are operated according to defined schedules and conditions typical of the building activity. The impact of changing a specific building element, such as the window systems, can be determined easily by changing only that parameter. At the same time, because these are not real buildings, the specific results will not match the absolute energy use in a particular building, but the relative results provide a good guideline of the changes that can be expected by altering a building feature. Each simulation computes the total annual energy used in the building made up by fourteen different end uses. These studies considered the variation of three energy end uses: gas energy for heating, electric energy for heating and electric energy for cooling. The inputs, which can be varied in the models, are divided into 4 categories: building program (the total building floor area, location and basic use of the building), building form (number of floors and shape), building fabric (wall, roof and window materials) and building equipment (internal equipment including office equipment, kitchen equipment and mechanical equipment). A complete list is provided in Appendix D. There are standard default values which were used for everything except the fenestration.

Simulations of the five window retrofits in climate zone 6A were run for all sixteen reference buildings. In a selected subset (large and small office buildings, strip malls, mid-rise apartments and schools) climate zone 7 and all three periods of construction were also studied. The general characteristics of the reference buildings, including their site Energy Use Intensity in Climate Zone 6A (EUI, measured in kBtu/ft^2) are summarized in Table 4.

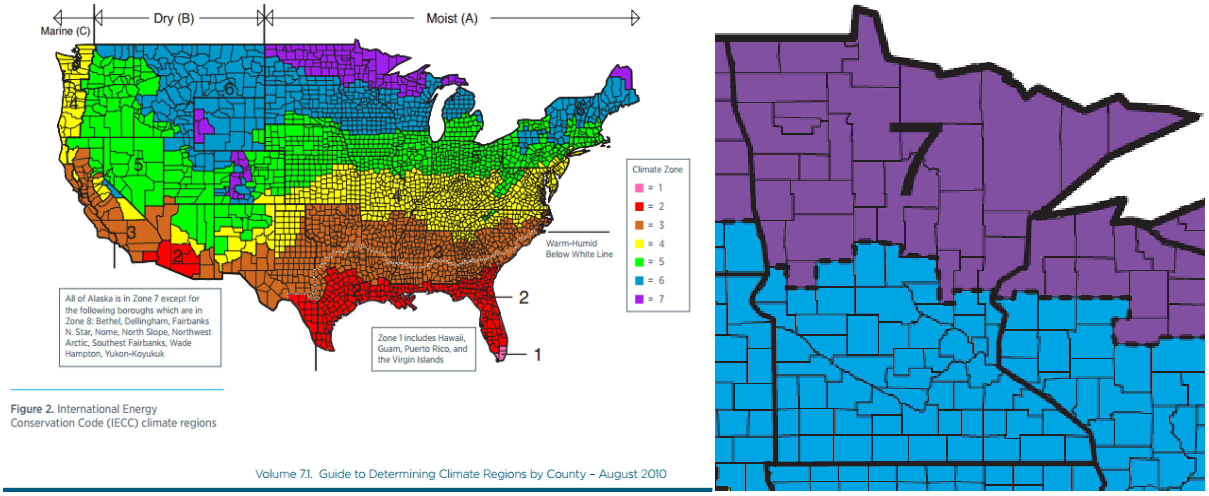
Table 4. Characteristics of DOE Reference Buildings in climate zone 6, construction date 1980-2004

Building Type	**Floor Area (ft^2)**	**Window Area (ft^2)**	**Window Area (% of wall)**	**Floors**	**EUI kBtu/ft^2**
Medium Office	53,628	7,025	33%	3	72
Large Office	498,588	53,441	38%	12	64
Mid Rise Apartment (32 units)	33,740	2,490	15%	4	90
Quick Service Restaurant	2,500	280	14.0%	1	731
Full Service Restaurant	5,500	504	17.0%	1	780
Small Office	5,500	642	21%	1	78
Stand Alone Retail	24,962	892	7.0%	1	145
Strip Mall	22,500	1,339	10.5%	1	164
Supermarket	45,000	1,905	11.0%	1	261
Warehouse	52,045	165	0.6%	1	74
Small Hotel	43,200	2,006	11.0%	4	89
Large Hotel	122,120	12,901	27.0%	6	261
Primary School (650 students)	73,960	9,463	35%	1	88
Secondary School (1200 students)	210,887	21,009	33%	2	101
Hospital	241,351	9,307	15.0%	5	195
Outpatient Healthcare	40,946	2,687	19.0%	3	233

The HVAC equipment in these buildings is defined for each building type. The heating system is either a standard furnace (small office and strip mall buildings) or boilers (large office, schools and the mid-rise apartment building). The furnace efficiency is 80% and boiler efficiency is 73-76%. Cooling is provided by packaged units (small office, strip mall, primary school and mid-rise apartment building) or chillers (with multizone VAV systems in large offices and secondary schools). The HVAC equipment is sized 20% above what is needed for design conditions and standard code based equipment efficiencies are used. The equipment lives range from 15 years (furnace, AC) to 23 (chillers) to 30 (boilers).

Minnesota contains two climate zones, designated 6A and 7, as shown in Figure 12 below, with Minneapolis and Duluth as the largest cities in each of these zones, respectively. Simulations were performed for the selected retrofits on a variety of building types in both climate zones. Approximately 4.5 million people live in Zone 6A and 830,000 live in Zone 7. The statewide savings estimates are weighted accordingly in the discussion below.

Figure 12. ASHRAE Climate Zones



All of Alaska is in Zone 7 except for the following boroughs which are in Zone 8: Bethel, Dellingham, Fairbanks N. Star, Nome, North Slope, Northwest Arctic, Southeast Fairbanks, Wade Hampton, Yukon-Koyukuk

Zone 1 includes Hawaii, Guam, Puerto Rico, and the Virgin Islands

Figure 2. International Energy Conservation Code (IECC) climate regions

Volume 7.1. Guide to Determining Climate Regions by County – August 2010

Most national window studies and marketing materials are based on the window performance in climates zones 2, 3, 4 and 5 as they account for about 90% of the U.S. population. Minnesota averages about twice the heating degree days (7,000 to 10,000) and half the cooling degree days (500) of these climate zones and this has an impact on retrofit recommendations.

Part III. Results and Discussion

Characteristics of Minnesota's Existing Buildings

Before looking at the impact of windows on buildings in Minnesota, it is necessary to discuss the general characteristics of buildings as it will structure the analysis of the window retrofits. As construction practices have evolved, aided by new materials and building codes, buildings envelopes have become more energy efficient. It is also the case that construction practices differ to some degree by the type of building (where building type is generally determined by its purpose). In addition to climate zone, discussed above, the characteristics considered below include type and age of buildings.

Residential Buildings (Houses)

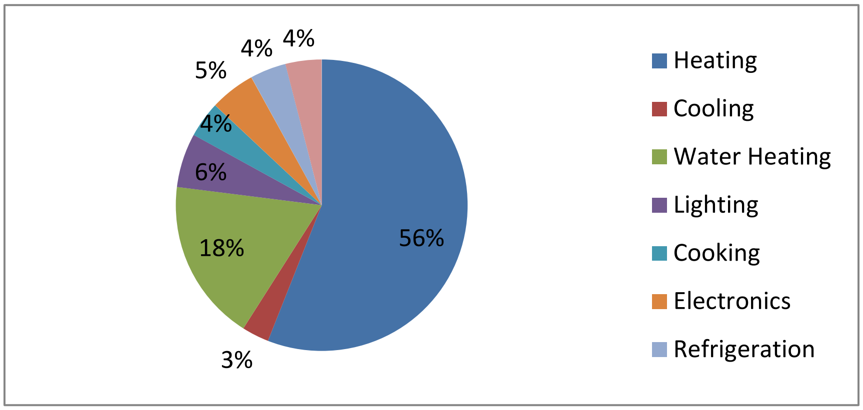
Residential buildings make up over 90% of the buildings, by count, in Minnesota. There are currently (in 2013) approximately 1.8 million residential houses and 100,000 commercial buildings in the state. Details are given in Table 5 below and are based on the 2010 US Census data.

Table 5. Characteristics of housing in Minnesota. From 2010 Census

Housing Type	Number of housing units	Percent
Single family, detached	1,582,374	67.4
Single family, attached	172,942	7.4
Multifamily, 2 to 4 units	104,870	4.5
Multifamily, 5 units and up	402,777	17.0
Mobile Home	84,317	3.6
Other	648	0.1

New home construction has averaged about 20,000 per year, so that the current number of single family homes (attached and detached) is estimated at 1.8 million. According to the 2011 Building Energy Data Book (2011 Building Data Book) and the EIA's 2009 Residential End Use Consumption Survey (RECS) approximately 56% of residential energy use in Minnesota is for heating and 2-3% is for cooling. Figure 13 below shows these values, along with values for other minor end uses of household energy.

Figure 13. Residential site energy by end use. Energy Information Administration 2009



The average Minnesota home was built in the 1970's and has 1,934 square feet of floor space and 222 square feet of windows (11.5% window to floor ratio)[8]. US Census data provide information on the age distribution of Minnesota homes and show the average age to be about 40 years. Twenty percent of homes are estimated to have inadequate ceiling insulation and 9% to have inadequate wall insulation. It is likely that many of these homes also have windows that could be improved with retrofits. Sixty-eight percent of Minnesota homes are heated with natural gas, 12% with electricity, 10% with propane, 6% with fuel oil and 2% with all other fuels. The average home in zone 6 uses about 70 MMBtu of heating energy annually. (2010 Census)

Commercial Buildings

Commercial buildings vary widely in size, primary use, construction standards and the ratio of window to floor area. Building modeling was used to determine the impact of installing the five window retrofits to assess which of these variables affected the energy performance of window retrofits. The impact of retrofits in commercial buildings was found to be very different from residential houses in a fundamental way: the building use had a major impact on the energy lost through a standard window area. Expressed differently, it is not possible to prescribe a simple energy savings value per square foot of window area for commercial buildings.

The results of the simulations show that the sixteen reference building types can be combined into seven groups (shown in Table 6) each of which has similar relative impacts of the five retrofits.

Table 6. Buildings grouped by similar window retrofit potential

Building Group	Group Members	Comment
Office	Large Office Medium Office	Good savings found
Multifamily	Mid-Rise Apartments	Good savings found
Restaurants	Quick Service Restaurant Full Service Restaurant	Fair savings found
Single Story	Small Office Stand Alone Retail Strip Mall Supermarket Warehouse	Low savings found
Hotels	Large Hotel Small Hotel	Low savings found
Schools	Primary School Secondary School	Good savings for clear panels. EnergyPlus model shows unexpected behavior when changing SHGC
Healthcare	Hospital Outpatient Healthcare	Good savings for clear panels. EnergyPlus model shows unexpected behavior when changing SHGC

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[8] U.S. Department of Energy. (2012) *Buildings Energy Data Book.* Page 2-13.

The behavior of most of the groups can be rationalized based on their usage (occupancy and schedules), window area and construction characteristics. However, the schools and healthcare buildings showed energy use changes when SHGC was varied that did not have a good physical explanation. These building models did behave reasonably with changing U-factors, so those results are included in the report. Because we could not form a reasonable physical explanation for the SHGC results, they are excluded from our final results and recommendations.

Table 7 is based on data gathered in the 2003 CBECS survey in conjunction with information from the Minnesota Benchmarking and Beyond (B3) database (https://mn.b3benchmarking.com/), property tax data from several of Minnesota's large cities, and the ENERGY STAR Portfolio manager database.

Table 7. Commercial buildings by size in Minnesota. CBECS 2003

Building Size (ft^2)	# of Buildings	% of Buildings	Total Area (sq.ft.)	% of Buildings by Area	Typical Building Uses
5,001 to 10,000	17,090	20%	126,785,374	10%	Small Office, Restaurant
10,001 to 25,000	14,602	17%	228,206,463	18%	Strip Mall, Standalone Retail, Mid-rise Apartment
25,001 to 50,000	4,705	5%	169,131,293	13%	Small Hotel, Outpatient Healthcare, Supermarket
50,001 to 100,000	2,650	3%	185,518,027	14%	Medium Office, Primary and Secondary School, Warehouse
100,001 to 200,000	1,334	2%	184,184,014	14%	
200,001 to 500,000	469	1%	135,095,918	10%	Large Office, Hospital, High Rise Apartment
Over 500,000	144	0%	138,088,435	11%	

Figure 14 shows that, like the distribution of total residential energy use, in commercial buildings just under half the total energy is for space conditioning (heating, ventilation and air conditioning – HVAC) (U.S. Department of Energy, 2012). The majority of the remaining energy is used for lighting (25%) and plugged in equipment (25%).

The energy simulations of the reference buildings in climate zone 6 were used to determine the ratio of heating and cooling energy to total building energy for each of the sixteen building types, shown in Figure 15. The fraction of total building energy required for heating and cooling is dependent on the building's primary use, from 28% in a small hotel to 78% in a warehouse. The average value of 41% is a good match for the heating and cooling energy from CBECS shown in Figure 14. Warehouses have very little energy consuming activity other than heating and cooling, while hotels have many other energy consuming activities. The greatest potential for total energy savings with window retrofits will be buildings that use a large fraction of total energy for heating and cooling energy, and have a large window area. While warehouses use most of their energy for heating and cooling, they also have few windows, so as a class of buildings they are unlikely to benefit greatly from window retrofits. On the other hand, standalone retail buildings use over half their energy for heatng and cooling and represent

12.2% of the commercial building window area, so appear to be good candidates for window retrofit programs.

Figure 14. Minnesota commercial building site energy use. CBECS 2003

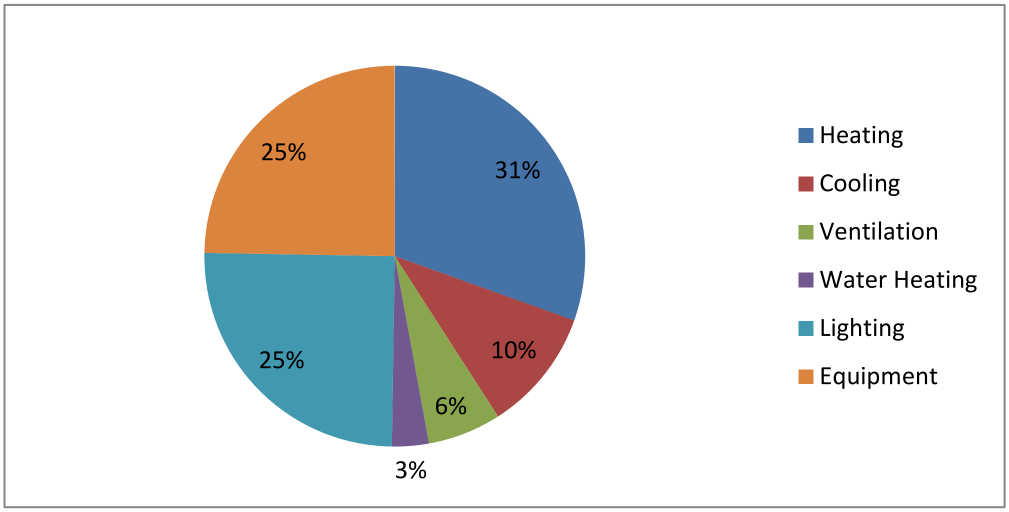


Figure 15. Percentage of building total energy that is used for heating and cooling. The average for all commercial buildings is about 41%, with a broad range from 28% to 78%.

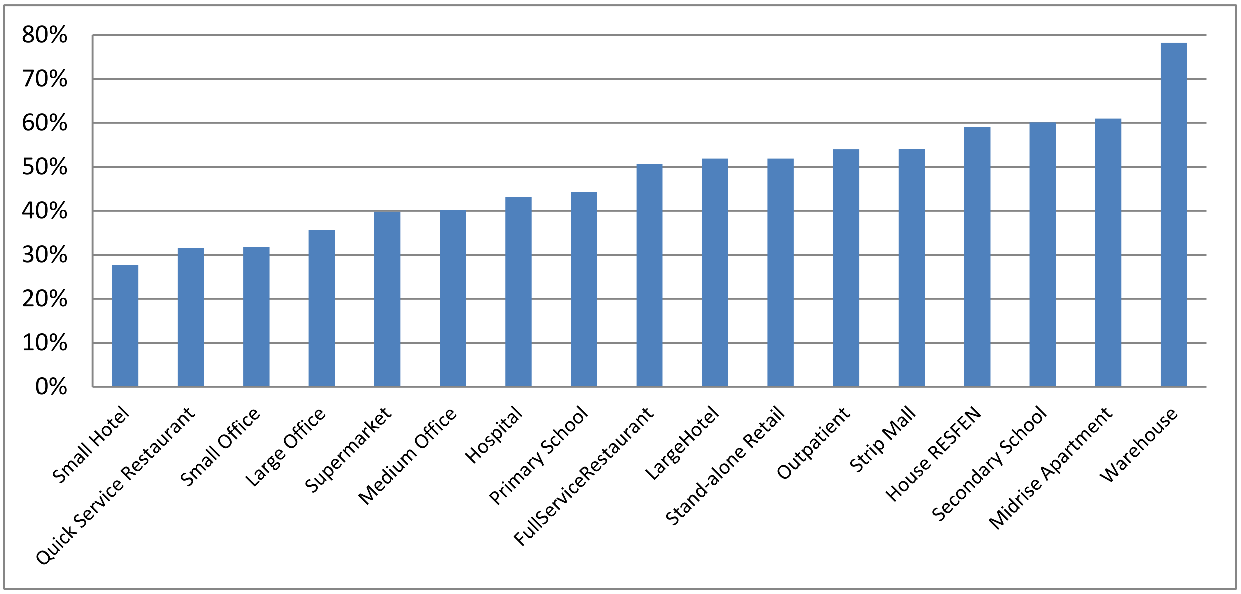
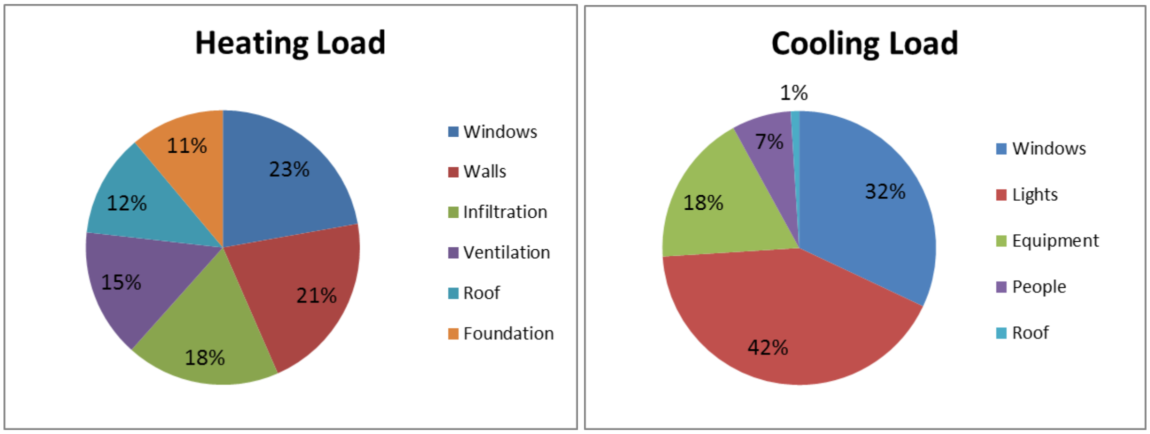


Figure 16 shows the source of heating and cooling loads in an average commercial building. On average window are responsible for about a quarter of the heat loss in commercial buildings and one third of the excess heat that requires cooling. The physical basis of these window loads is very different. The heating load is caused by heat loss through the window (inside to outside) measured by the U-factor, and the cooling load is driven by the radiant solar energy that enters the building through the window (outside to inside) measured by the SHGC. The impact of heat transfer is more or less the same for any window in the building, while the solar heat gain is totally dependent on the amount of incident solar radiation, including hours of solar exposure each day, solar angle and degree of shading.

Figure 16. Heating and cooling loads in commercial buildings. Building Data Book (Table 3.1.12)



Characteristics of Windows in Minnesota's Existing Buildings

One of the main reasons for undertaking this project is the fact that most window retrofit studies have assumed that existing buildings have single pane clear glass windows. While this is true in much of the US it is not the case in Minnesota. The base case used in this report is based on a variety of sources that characterize the windows of existing Minnesota buildings. The characterization covers not only the windows, but the entire building envelope, as this determines the relative impact of window retrofits on total energy performance.

Windows in Existing Residential Buildings

The typical house has 15 windows, averaging 15 sq. ft. each, that are double paned, and have a life span of 35 to 45 years (2011 Building Data Book). This window life is consistent with the Ducker survey of window sales (Ducker Research Corp., 2012) which estimates 55,000 existing homes in Minnesota had their windows replaced in 2009 (assuming 15 windows per home), also giving an average window lifetime of 36 years (dividing the total number of existing windows in houses by the number of windows replaced in one year). The KEMA study (KEMA 2013) reports that 86% of Minnesota single family homes have double pane windows, which have been standard in new home construction since the 1980's. The study also reports that about 30% of low income housing still has single pane windows. However, single pane windows with exterior storm windows may be classified as single pane in this survey; even though from an insulation perspective this combination performs as a double pane window. Taking the impact of storm windows into effect, it appears that 95% (or more) of Minnesota houses have double pane windows.

Table 8 shows the impact of building codes on the insulation and heat loss of a typical house using a simple building envelope model. Two scenarios are shown, the first for an existing house built between 1960 and 1980 and the second for a home built according to the building code introduced in the 1980's. As wall and roof insulation has improved the total energy use of the house has gone down by about 20% and while the amount of energy lost through the windows has not changed, the share of heat loss through the windows has increased from 32% to 40%. Thus a retrofit that can reduce the heat loss through windows will address the area of greatest potential in a home's envelope.

Table 8. Insulation and heat loss characteristics of a typical Minnesota house

Building System	Area (square feet)	Typical Pre 1980	Post 1980
Windows	255	32% (R-2)*	40% (R-2)
Walls	1,945	48% (R-9)	43% (R-14)
Roof	1,000	12% (R-20)	8% (R-40)
Foundation	1,000	7% (**)	9% (**)
Total Improvement due to Building Codes			20%

*The window R value for Pre-1980 homes assumes that there are either storm windows or that the windows have been replaced with double pane windows, following the average 30-40 year replacement cycle. R-value, which is commonly used to describe most building materials, such as insulation, is equal to the inverse of the U-factor (R-2 is the same as a U-factor of 0.50; R-3 is the same as a U-factor of 0.33).
**The foundation value is taken from a published calculation that uses Minnesota soil temperatures with typical construction practices. (See Mechanical and Electrical Equipment for Buildings, 2011. Walter Grondzik, Alison Kwok, Benjamin Stein and John Reynolds, p 194-5).

Table 9. Energy and cost impact of changing to double pane windows on a typical Minnesota house (Heating and Cooling). RESFEN Simulation Results

Window Type	U-factor	MMBtu/Year Heating and Cooling	% Change from Single Pane	$/Year Natural Gas Heat	$/Year Electric Heat
Single Pane, Clear	0.88	30.8	0	$272	$ 772
Double Pane, Clear	0.51	16.2	-45%	$163	$ 418

The fact that most existing windows in Minnesota houses are double pane already greatly reduces the financial benefit of window retrofits compared to what is found in many other areas of the country where single pane windows are common. This is illustrated in Table 9, which shows the heating and cooling energy (in MMBtu per year) as well as the cost for the energy that is lost through the windows of a typical home in Zone 6A (the southern half of Minnesota). This is not total energy used, just the energy required for the windows. Double pane, clear glass windows reduce the energy loss through the windows by 45% compared to single pane windows in the same house. However, only about 3% of homes in the state have single pane windows.

Windows in Existing Commercial Buildings

Sales of windows for commercial buildings are reported by window area, not by the number of windows (window sizes in commercial buildings are highly variable). According to the survey data of the American Architectural Manufacturers Association and the Window and Door Manufacturers Association for the West North Central region (MN, ND, SD, IA, MO, NE, KS) approximately 6 million square feet of windows were installed in Minnesota in 2009 (Ducker Research Inc., 2012). The breakdown is shown in the Table 10 below. The majority of commercial window purchases are for use in new construction (64%), nearly the opposite of residential windows where the majority of current window sales are for use in existing houses. This suggests that commercial buildings may have windows that would benefit from retrofits.

Table 10. Commercial window installations in Minnesota. From Ducker (2012)

Window Type	New Construction	Remodeling and Replacement	% New Construction
Site Fabricated	1,300,000 ft^2	460,000 ft^2	74%
Shop Fabricated	440,000 ft^2	1,100,000 ft^2	28%
Curtain wall	1,200,000 ft^2	230,000 ft^2	84%
Store Front	1,150,000 ft^2	500,000 ft^2	70%
Total	4,090,000 ft^2	2,290,000 ft^2	64%

Colleges were singled out in the KEMA study as containing a large fraction (up to 90%) of windows with single pane glass (KEMA, Inc. 2013). This does not match our observations. We surveyed 35 campuses of the Minnesota State College and University system (MNSCU) as part of the Public Building Enhanced Energy Efficiency Program (PBEEEP) from 2009-2013 and did not observe any significant installations of single pane glass. Insulated glass units are standard for these buildings and older single pane windows have largely been replaced. As part of the current project, a survey of the campus of the University of Minnesota in the Twin Cities was done, inspecting 42 buildings constructed between 1900 and 1980 and not recently renovated. Of these, only 14 (33%) had single pane windows, while the majority were double pane glass. In addition, 36% of the campus buildings were constructed after 1980 and all appear to have double pane windows. While there are a considerable number of single pane windows on college campuses, 25% appears to be a better estimate than 90%.

The same study also reported that about 30% of multifamily housing still has only single pane windows, although it is not clear whether a single pane window with an exterior storm window was considered to be single pane or double pane (KEMA, 2013). The 2013 Minnesota Multifamily Rental Characterization Study (Pigg et al., 2013) looked specifically at this issue and found that that while 25% of multifamily buildings did have single pane windows, most of these (88% or 22% of all the buildings) also had storm windows, making them double glazed from a U-factor perspective. This report found that only 3% of the multifamily buildings had true single pane windows.

Because double pane, clear glass windows are predominant in Minnesota buildings of all types, they are used as the base case in this report. In those cases where the existing windows have only a single glazing layer, the savings will be larger as is shown in Figure 46 and Table 9.

Table 11 combines data from CBECS, the U.S. Census, and the Minnesota Multifamily Characterization Study (Pigg et al. 2013) for the estimated number of each type of building in Minnesota along with the average window area per building. This is then used to estimate the relative fraction of the total area of commercial windows, by building group and building type. This information can be used by utilities for their Conservation Improvement Programs to target building types with the greatest total potential for energy savings based on window area.

Table 11. Percentage of window area in commercial buildings by building group and type

Building Group	Building Type	Number of Buildings in Minnesota	% of Commercial Window Area	Building Group % of Total Window Area
Office	Large Office	64	4%	14%
	Medium Office	1,557	10%	
Apartment	Midrise Apartment	12,500	29%	29%
Restaurant	Full Service Restaurant	1,594	1%	1%
	Quick Service Restaurant	2,953	1%	
One Story	Small Office	10,543	7%	23%
	Stand-alone Retail	10,694	9%	
	Strip Mall	1,632	2%	
	Supermarket	2,450	4%	
	Warehouse	2,449	0.3%	
Hotel	Large Hotel	561	7%	8%
	Small Hotel	763	1%	
School	Primary School	547	6%	17%
	Secondary School	474	12%	
Healthcare	Hospital	269	2%	8%
	Outpatient Clinic	2,353	6%	

The Five Window Retrofits

The key attributes of the five window retrofits are provided in Table 12, along with the characteristics of a typical replacement window for comparison. Examples of the retrofits were given in Part 1 of this report. Window panels add a layer of glazing to the existing window, while applied films do not change the number of layers of glazing; that is their fundamental difference.

Table 12. The window retrofit parameters

Retrofit Type	Description	Commercial Buildings (1)		Residential Buildings (2)	
		U-factor	SHGC	U-factor	SHGC
None	Standard Window	0.60	0.60	0.51	0.57
Panel	Clear Panel	0.40	0.59	0.32	0.51
Panel	Low-e Panel	0.30	0.45	0.26	0.47
Film	Moderate gain Low-e Film	0.47	0.46	0.39	0.46
Film	Low gain Low-e Film	0.52	0.30	0.435	0.30
Film	Tinted Film	0.60	0.40	0.51	0.40
Replacement Window (Reference)	Commercial: "spectral selective" that meets Residential ENERGY STAR	0.46	0.34	0.32	>0.40

1. The commercial building values are taken from Commercial Windows, the National Fenestration Research Council and manufacturers' data.
2. The residential building values are taken from Culp and Cort and manufacturers data.

The U-factors for the commercial windows are all higher than the residential ones because the standard commercial window frame is metal, which has a higher thermal conductivity than the wood/vinyl frames found in most residential window assemblies; the metal frame increases the U-factor. Some commercial buildings use "residential" windows and the energy performance of their windows will be better; however, the impact of the different retrofits will still be similar to those presented here for the specific building types.

Results of Residential House Modeling

Houses were modeled using RESFEN, which provides details on energy loss through the windows on each of the four walls by facing direction (north, south, east or west; the house is lined up with the directions of the compass). The building geometry is a simple rectangular box and the choices of insulation levels and foundation type were selected to achieve the best fit to actual reported energy use in Minneapolis, between 70 and 75 MMBtu annually (U.S. Energy Information Administration, 2009). This resulted in a 2 story frame house with a gas furnace, central air conditioning, and slab on grade foundation. The foundation choice is not as strange as it initially seems: basements in the RESFEN model are unheated, so a two story slab on grade house is equivalent to a single level rambler with a heated basement, a common style of house in Minnesota. Finally the total square footage used was 1,500.[9] The base case results are shown in Table 13.

Table 13. Annual heating and cooling energy use for a typical Minnesota house. RESFEN results

Location and heating source	Annual natural gas usage (therms)	Annual electric usage (kWh)	Total energy use (MMBtu)	Annual energy cost*
Zone 6, natural gas	683	842 kWh	77.0	$674
Zone 6, electric resistance		16,449	77.0	$1,826
Zone 7, natural gas	868	261	89.5	$767
Zone 7, electric resistance		20,095	89.5	$2,231

*Costs from EIA's March 2014 forecast; $0.85/therm and $0.111/kWh

The houses used in the RESFEN simulations have 225 square feet of window area, evenly distributed on all four sides. The largest energy savings is on the north facing windows due to the improved insulating value of the retrofits. The smallest net annual energy savings is on the south facing windows because the effect of SHGC. Figure 17 shows the total change in energy intensity for windows on different sides of the house with the four energy saving retrofits (the tinted film did not save energy on any window). Film B, which has only moderate solar heat gain, does not save energy overall, but does offer small savings on the north facing windows. On the other windows it increases the heating energy needs of the house.

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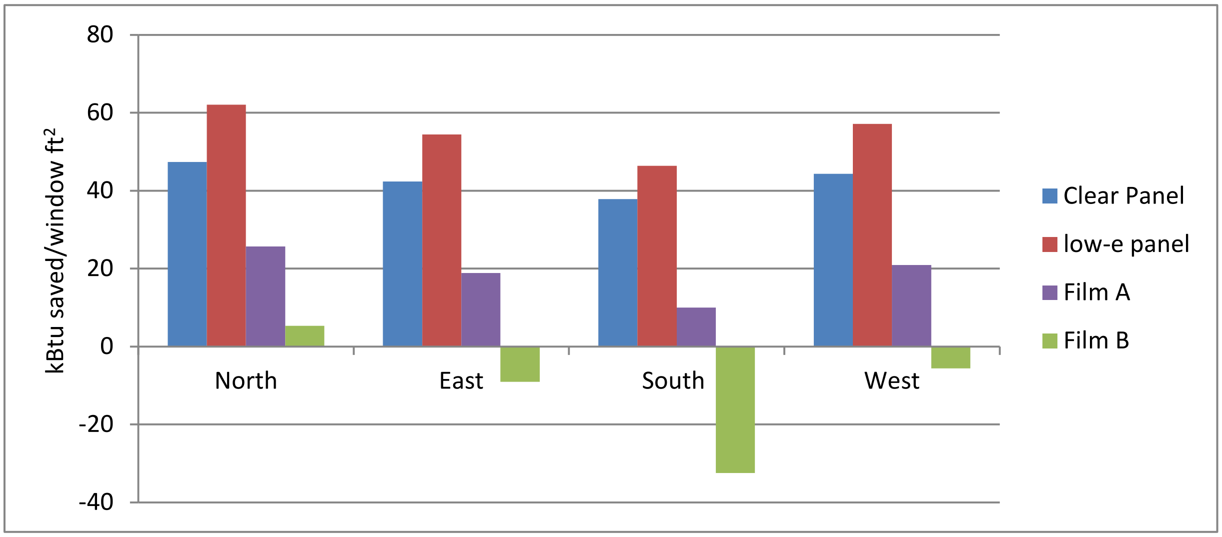
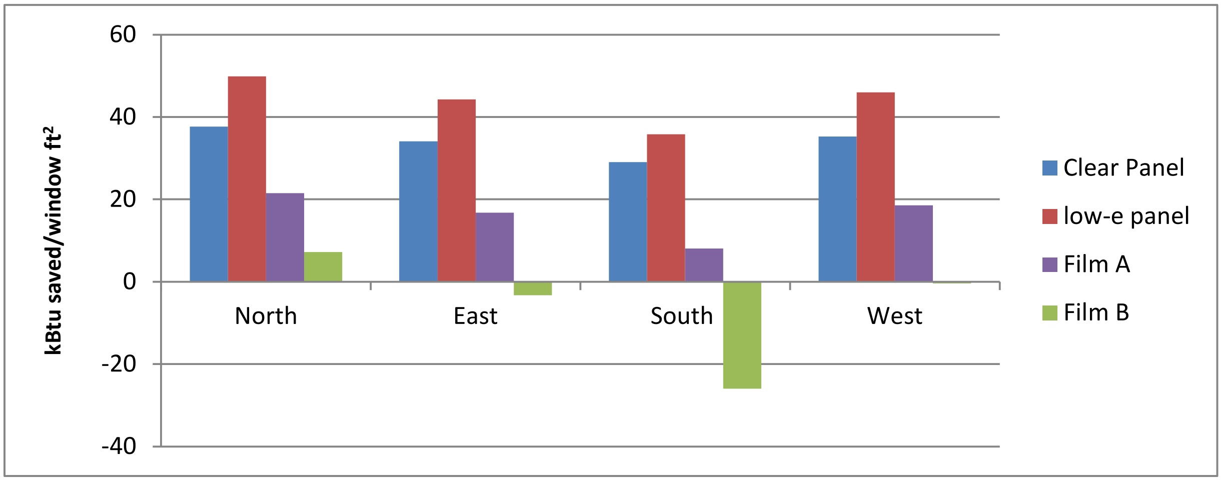
[9] The complete RESFEN simulation results are available on request from cplum@mncee.org.

Figure 17. Energy saved by window retrofits on a house in Duluth, based on the orientation of the window.



The energy savings for houses in Duluth and Minneapolis-St Paul show the same general behavior in terms of the relative savings for each window retrofit on each face of the house except that the savings for the house in Minneapolis is about 20% lower than in Duluth as shown in Figure 18. The tinted film did not save energy on any window and is omitted from the figures for clarity.

Figure 18. Energy saved by window retrofits on a house in Minneapolis-St. Paul, based on the orientation of the window.



The energy calculations are independent of the heating fuel, but the energy costs are dependent on the choice and price of fuel. The energy and financial savings amounts from RESFEN are shown in Table 14. The heating savings account for 90% or more of the total energy savings for all of the retrofits. The fraction of savings from heating is highest in Zone 7, with over 99% of the energy savings from a clear window panel retrofit due to heating. These results are very different from what is seen in some internet sites, where the search results for "energy saving window products" often show only cooling savings (some calculators say the products save energy, but show $0 for the savings).[10]

Table 14. Window retrofit savings in Minnesota homes from RESFEN.

	Zone 6A (Minneapolis-St. Paul)				Zone 7 (Duluth)			
Window Retrofit	**Total Energy Saved %**	**Total Energy kbtu/ft^2**	**Annual $ Savings (gas heat)**	**Annual $ Savings (Electric)**	**Total Energy Saved %**	**Total Energy kbtu/ft^2**	**Annual $ Savings (gas heat)**	**Annual $ Savings (Electric)**
Panel, clear	10.5%	34	$ 69	$210	11.1%	43	$ 88	$271
Panel, Low-e	13.8%	44	$ 91	$268	14.3%	55	$108	$346
Moderate SHGC, Low-e Film	5.5%	16	$ 38	$83	4.9%	18	$ 39	$111
Low SHGC, Low-e Film	0.1%	(5)	$ 7	-$86	-2.6%	(13)	-$17	-$97
Tinted Film	-2.7%	(13)	-$13	-$116	-4.8%	(21)	-$35	-$144

The percentage savings in the table is for heating and cooling energy, not whole house energy (Figure 13 shows that heating and cooling are 59% of the total energy use of an average house.) The low-e window panel provided the largest total energy savings, reducing energy lost through the windows by about 14% (whole house energy savings is about 8%). The cost for a whole house retrofit ranges from $1,200 for self-installed clear window panels to as high as $2,500 for professionally installed low-e window panels (about $11 per ft^2 of windows). The paybacks for these window panels then range from 11 years to over 24 years with natural gas heat, but are as low as 4 years for houses with electric resistance heating (or delivered fuels). While these payback times appear long, it should be noted that these retrofits produce energy savings that are comparable to those achieved with ENERGY STAR replacement windows at a fraction of the cost (typically between three and ten times the cost of the window panel retrofits).

Results of Commercial Building Energy Modeling

The results of the energy simulations of the sixteen commercial buildings are presented by building group. The buildings in each group have similar savings for the various retrofits. Some groups are based on construction characteristics (one-story buildings, for example) others are based on function (offices, restaurants and hotels). Those based on function have similarities of construction, activity and ventilation requirements. Low-e window panels are the retrofit product producing the largest total savings in each building group. Most buildings will save energy with one or more of the retrofits; however, at current energy prices the payback for most is 20 years or more. Contrary to some literature claims, we did not find any examples where the simple payback was three years or less.

Each section includes graphs of the energy saving potential of each retrofit. Results are normalized (energy change per square foot) by window area and the same scale is used in all the graphs, with a maximum of 50 kBtu/ft^2 per year. As noted in the methodology section, the results are based solely on heating and cooling energy; secondary energy benefits due to changes in the load on other equipment,

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[10] See website examples in the Appendix C: Some list only cooling savings.

particularly fans and pumps are not included as they would require additional equipment retrofits. Unless otherwise noted, the results are for the DOE Reference Buildings with a construction date of 1980 to 2004 and weather data for Minneapolis -St. Paul (zone 6A). We chose this construction period and climate zone because it includes the largest number of likely candidates for window retrofits (i.e. buildings between 10 and 30 years old and the climate zone with 84% of the state's population). The Energy Plus models for schools and health care buildings included humidification requirements which were not able to be held constant across simulations. These changed when the SHGC was varied. Because the results included anomalous behavior, they were excluded from the report.

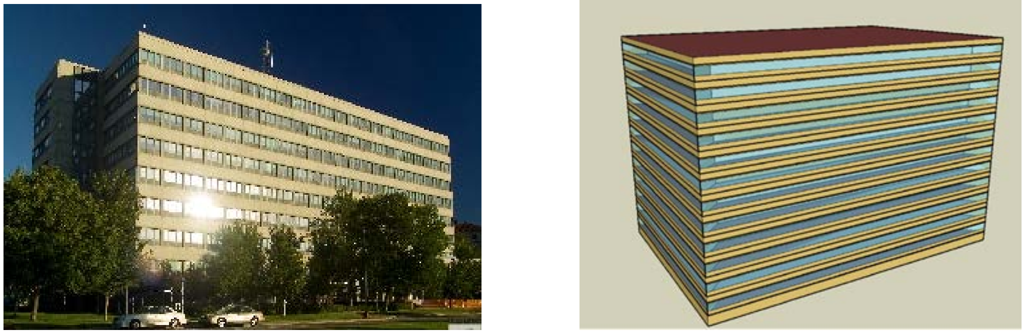
The simulations are intended to provide a starting point for more detailed analysis of actual buildings, which will differ from these results because of their specific attributes. The simulations here quantify the general magnitude of energy savings that window retrofits can provide in many commercial buildings. Because the retrofits are relatively expensive to install for large projects (i.e. buildings with over 5,000 square feet of window area) custom modeling is recommended in those cases to determine the best product and expected energy savings.

The table in each section lists the energy savings of the building (both the total for the building and as a fraction of the heating and cooling energy alone); the heating and cooling energy savings per square foot of window area (allowing comparisons across buildings and retrofits), the electric and gas savings, and the payback for the retrofit. Where appropriate, separate payback amounts are shown for self-installed and professionally installed scenarios. The self-installed cases are based on the cost of materials only; the professional installation includes both materials and installation. In some of the reference buildings there is electric heating in the VAV boxes, which generally improves the payback.

Multi-story Office Buildings

Multi-story office buildings include medium and large office buildings. These are buildings of three or more stories with large window areas and relatively high internal loads. A typical large office building is shown in Figure 19 with the DOE large office reference building used in the simulations. The reference medium office building is 53,628 square feet and 3 stories; the large office building is 13 stories and 498,588 square feet. Both have windows on about 1/3 of their exterior wall area.

Figure 19. Large office building (Minnesota Department of Transportation, St Paul, MN) and DOE Reference Building for comparison. Photo from www.citiesarchitechture.com



All the retrofits except for the tinted film save energy in these buildings in all areas of Minnesota. Figure 20 shows results for each retrofit for heating and cooling. The values are weighted by the window area in the population of each building type (74% medium offices, see Table 11). Low-e coatings are the most effective at reducing SHGC and reducing heat loss. Overall the energy saving is dominated by reducing thermal energy transfer across the windows, making the panels the most effective retrofits because they provide the increased insulation value of an additional glazing layer. The tinted films cause an increase in heating energy because they reduce passive solar heating. Figure 21 shows the total energy savings by retrofit and by size of office building.

Figure 20. Multistory office building heating and cooling savings

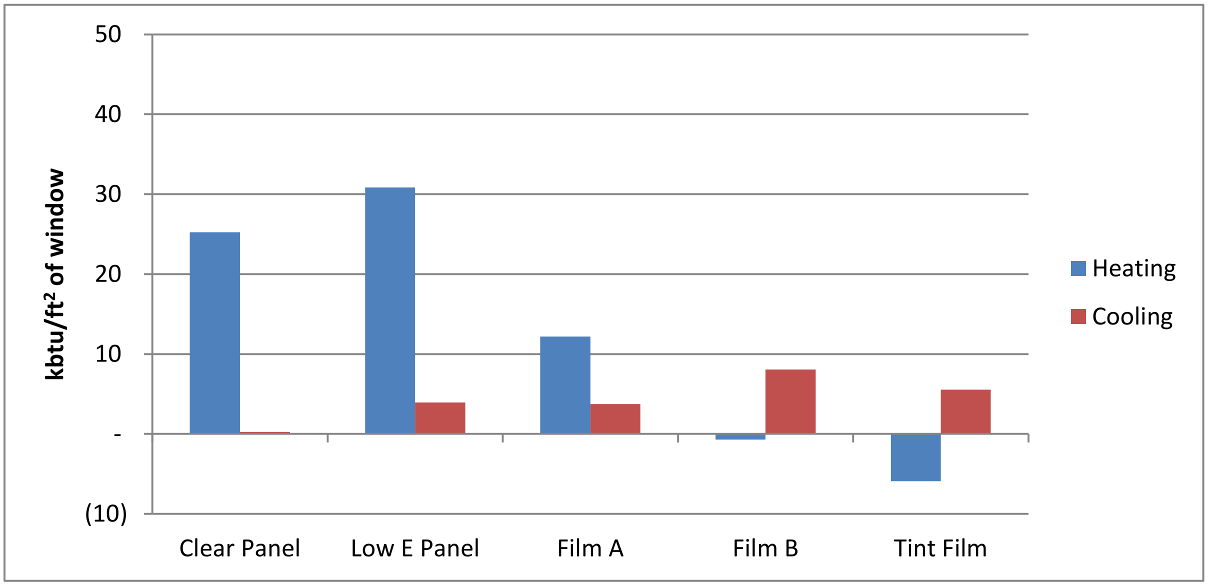
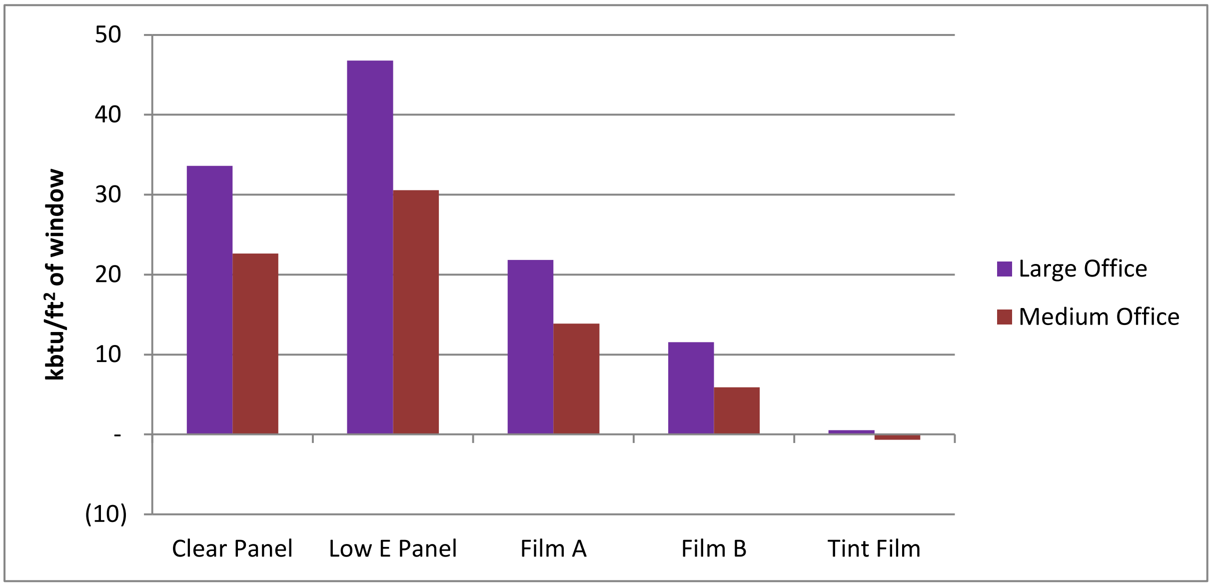


Figure 21. Total Energy Savings by retrofit for large and medium office buildings



Large office buildings use approximately 35% of their total energy for heating and cooling. Large offices have the highest space cooling energy use of any building type in Minnesota at 18% of the total heating and cooling energy. This is due to their high internal loads and the fact that office buildings have a low ratio of surface area to volume, which makes the building core less dependent on the envelope. As a rule of thumb, the windows only affect the zone of the building within thirty feet of the outside walls (Carmody et al. 2004). The magnitude of the savings in medium office buildings is about 2/3 that found in large office buildings for each of the retrofits. The estimated paybacks for the different retrofits are shown in Table 15. However, paybacks in medium office buildings are shorter because it is assumed that they use electric resistance reheating in the VAV boxes, increasing their cost (and savings) per btu.

Table 15. Energy savings and paybacks for window retrofits in multistory office buildings.

Multistory Office Buildings		**Energy Saved (%)**		**Energy saved by end use kBtu/ft^2**		**Energy saved by fuel source kBtu/ft^2**		**Payback: Professional Install (Years)**
	Retrofit	**Total**	**Heating & Cooling**	**Heating**	**Cooling**	**Gas**	**Electric**	**(Medium offices might do self-installs)**
Large Office	Clear Panel	5.7%	16%	34	(0)	34	(0)	147
Large Office	Low-e Panel	8.3%	22%	45	2	45	2	102
Large Office	Film A	4.1%	10%	20	2	20	2	25
Large Office	Film B	2.9%	5%	7	5	7	5	56
Large Office	Tint Film	0.8%	0%	(3)	3	(3)	3	95
Medium Office	Clear Panel	4.2%	10%	22	0	0	23	12
Medium Office	Low-e Panel	5.9%	14%	26	5	(6)	36	10
Medium Office	Film A	2.8%	6%	10	4	(6)	20	22
Medium Office	Film B	1.6%	3%	(3)	9	(13)	19	18
Medium Office	Tint Film	0.2%	0%	(7)	6	(9)	8	37

Apartments

Mid-rise apartments have savings that are similar to residential houses, indicating similarities in both usage and construction (see comparison in Figure 23). Window panels in mid-rise apartments can save about 4% a year on heating and cooling costs, which, while significant, still does not lead to a very attractive payback if the building is heated with natural gas (20 years if self-installed, 33 if professional).

Figure 22 shows that both types of window panels, with and without a low-e coating, produce the largest and most consistent energy savings potential. Of the applied window films, only the high solar heat gain window film (Film A) provided an energy saving benefit in these buildings, although all the films reduced the cooling required in summer. The reduction in winter solar heat gain also lowers the energy saved by the low-e panel compared to the clear window panel, one of the few cases for which this was seen. Figure 23 shows that the energy savings from window retrofits in the mid-rise apartment building are comparable to those in residential homes, another indicator that building space use is an important determinant of the magnitude of savings from window retrofits.

Figure 24 shows a typical mid-rise apartment building. These buildings have moderate window areas and relatively low internal loads, like single family houses. It is likely that the window retrofit savings will be similar in low-rise apartments, although these were not modeled for this report.

Figure 22. Window retrofit savings in mid-rise apartment buildings

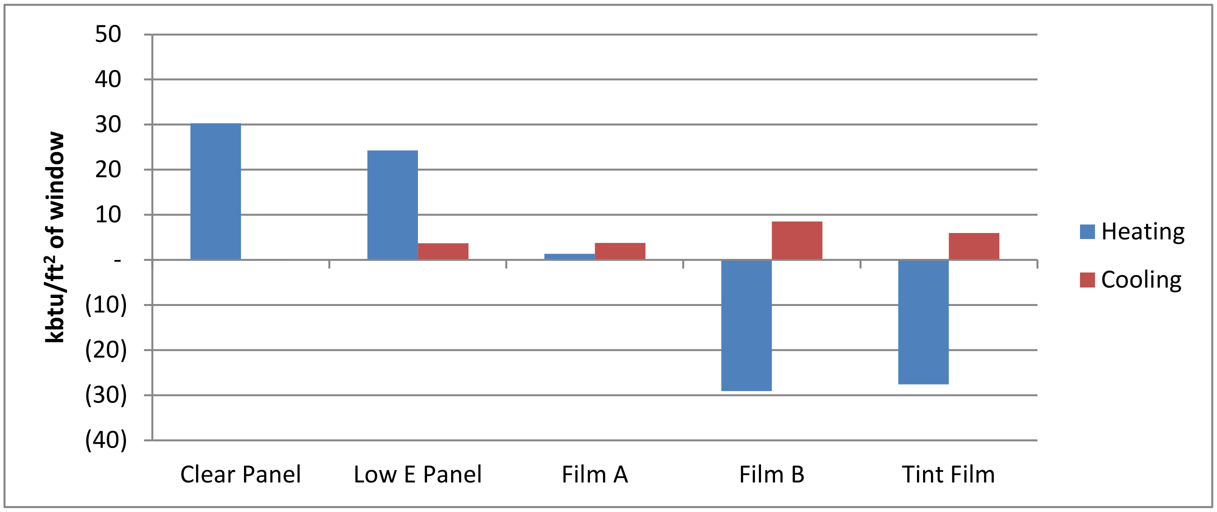


Figure 23. Heating and cooling energy savings by window retrofit type in residential buildings

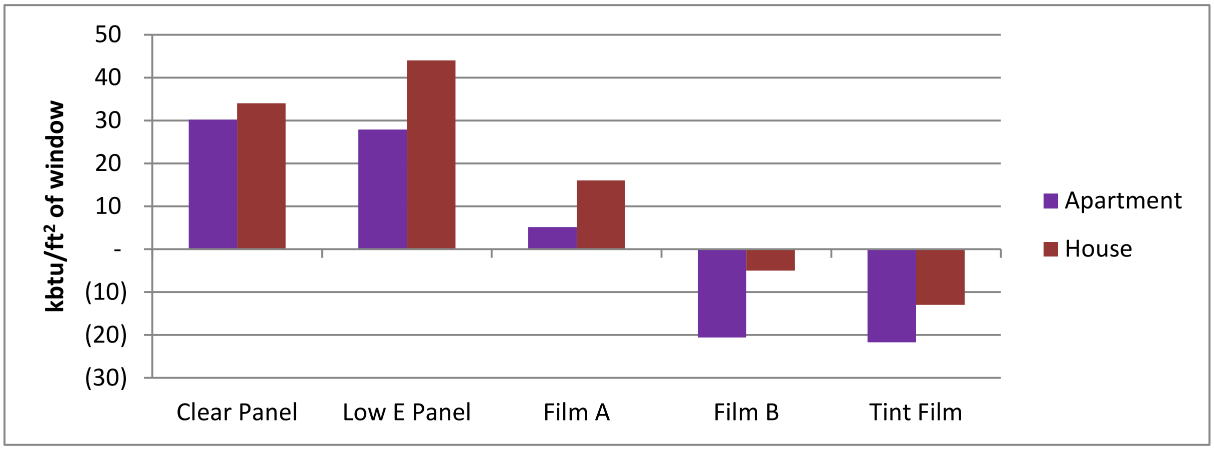
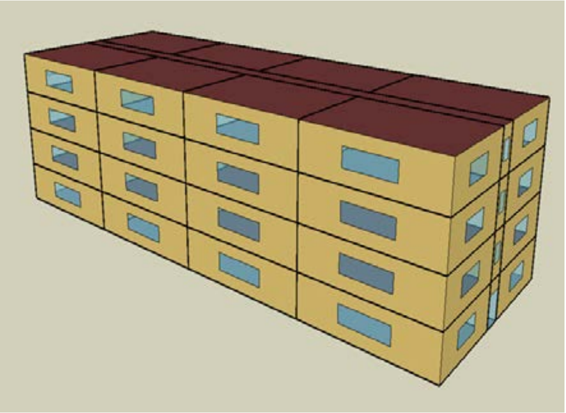


Figure 24. Mid Rise Apartment Building (Maple Grove, MN) and Reference Building. Photo www.apartmenthomeliving.com



Mid-rise apartment buildings use between 55 and 60% of their total energy for heating and cooling, with over 90% of that for heating. Building code changes in the past thirty years have led to significant improvements in their overall energy efficiency. Window retrofits offer a way to further improve existing apartment buildings. While they have a long payback period it is still comparable to their expected useful life which is 30 years (or more) and the cost is much lower than replacement windows (Table 16). There are also benefits of improved comfort that are not captured in the utility cost savings (Sailor, 2013).

Table 16. Energy savings and paybacks for window retrofits in residential buildings

Apartment		**Energy Saved (%)**		**Energy saved by end use ($kBtu/ft^2$)**		**Energy saved by fuel source ($kBtu/ft^2$)**		**Installation Payback (Years)**	
	Retrofit	**Total**	**Heating & Cooling**	**Heating**	**Cooling**	**Gas**	**Electric**	**Self**	**Pro**
Midrise Apartment	Clear Panel	2.6%	4%	30	0	30	(0)	21	35
Midrise Apartment	Low-e Panel	2.5%	4%	24	4	24	4	20	33
Midrise Apartment	Film A	0.5%	1%	1	4	1	4	-	96
Midrise Apartment	Film B	-1.7%	-3%	(29)	8	(29)	8	122	367
Midrise Apartment	Tint Film	-1.8%	-3%	(27)	6	(28)	6	(66)	(154)

Restaurants

Both full serve and quick serve restaurants can benefit from window retrofits. Restaurants have very high process loads due to the food preparation, so while the savings per window area are comparable to those of other commercial buildings, the impact on total energy use in these buildings is small. Table 4 shows that the average restaurant uses ten times the energy per square foot as a small office building. The savings per window are attractive (Figure 25) but are only about 0.5% of total energy used for restaurants. Figure 26 shows that the savings for both types of window panels are approximately 17% larger for quick serve restaurants than full serve.

Figure 25. Heating and cooling savings for window retrofits in restaurant buildings

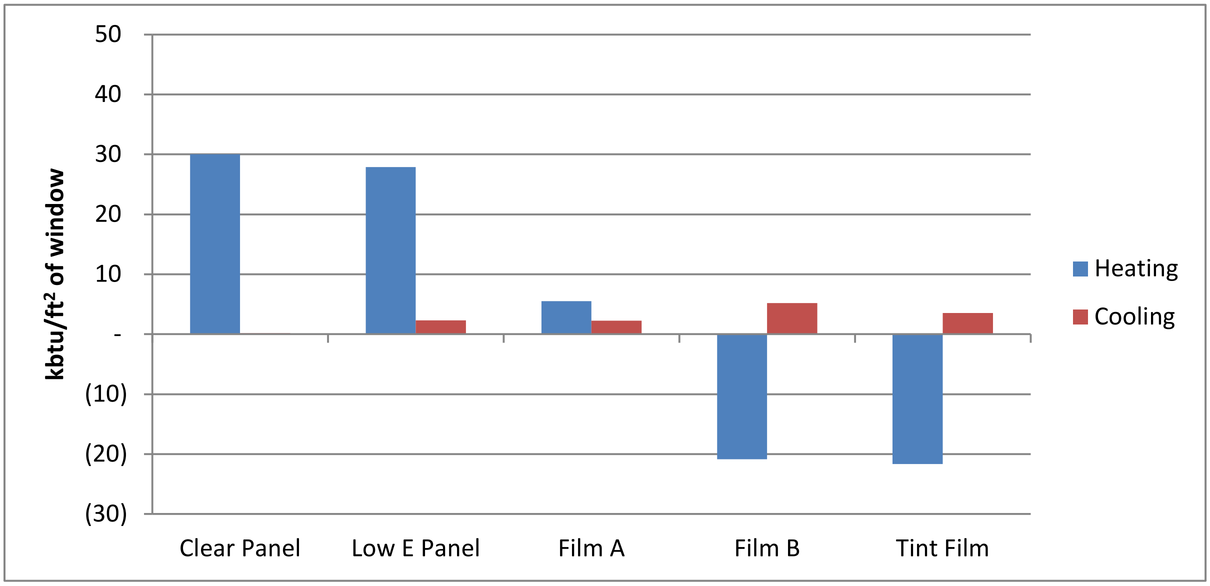


Figure 26. Window retrofit energy saved per square foot of window area for restaurants in zone 6A

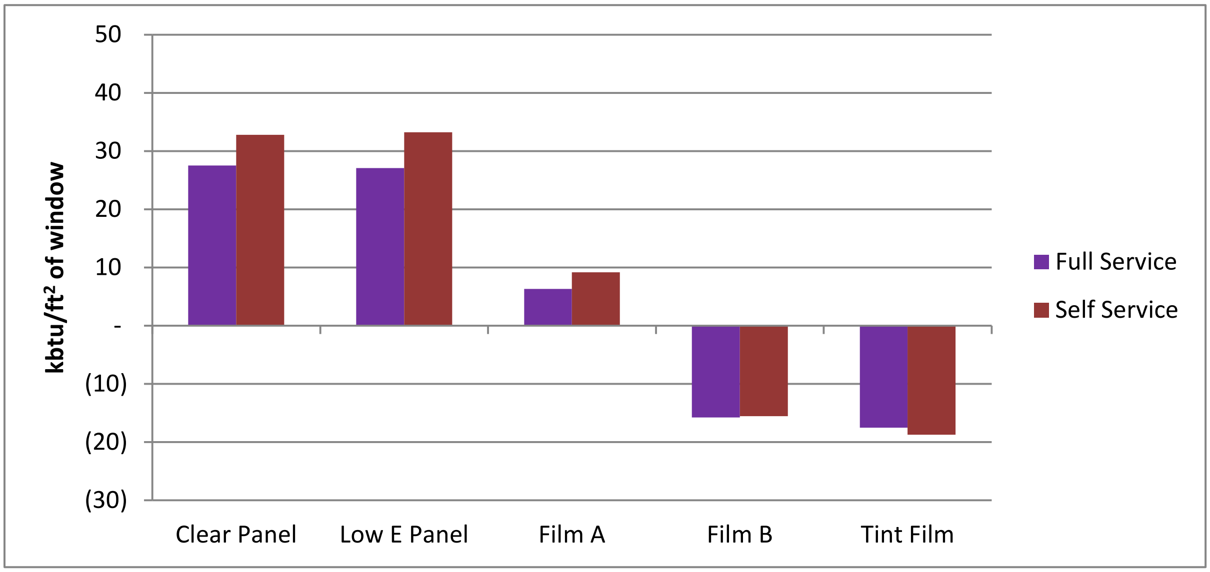


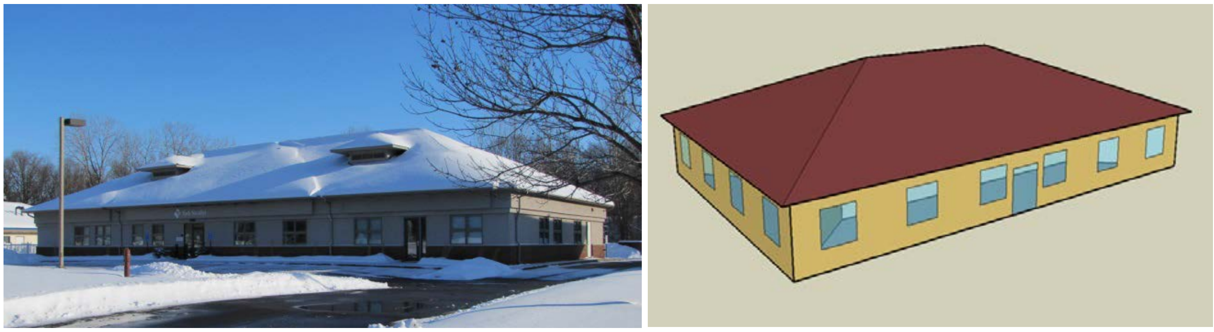
Table 17. Energy savings and paybacks for window retrofits in restaurant buildings

Restaurants		Energy Saved (%)		Energy saved by end use and fuel source (kBtu/ft^2)		Installation Payback (Years)	
	Retrofit	Total	Heating & Cooling	Heating/ Gas	Cooling/ Electric	Self	Pro
Full Service	Clear Panel	0.4%	1.2%	27	0	23	38
Full Service	Low-e Panel	0.5%	1.2%	25	2	23	39
Full Service	Film A	0.2%	0.3%	4	2	NA	126
Full Service	Film B	-0.2%	-0.7%	(21)	5	NA	NA
Full Service	Tint Film	-0.2%	-0.8%	(21)	3	NA	NA
Quick Serve	Clear Panel	0.5%	1.6%	33	0	19	32
Quick Serve	Low-e Panel	0.5%	1.6%	31	3	19	32
Quick Serve	Film A	0.2%	0.4%	7	2	NA	96
Quick Serve	Film B	-0.2%	-0.8%	(21)	6	7,800	NA
Quick Serve	Tint Film	-0.3%	-0.9%	(22)	4	NA	NA

Table 17 shows the total energy savings and paybacks for the both types of restaurants. The clear panel offers the best energy savings and lowest product cost. NA indicates a negative payback. The low-e panel offers slightly higher cost savings that make the paybacks essentially the same as the clear panel. None of the films offers a payback that is shorter than the expected product life. These simple buildings are assumed to get all their heating from a furnace (or boiler), with the result that gas savings and heating savings are the same; cooling savings and electrical savings are the same. Restaurants that use delivered fuels will see faster paybacks. While the magnitude of the window panel savings are comparable to those in apartments and office buildings (about 30 kbtu/ft^2) the impact on heating and cooling energy, as well as total energy, is quite a bit smaller in restaurants which have energy use that is largely determined by the ventilation needs of these high occupancy buildings with a need to maintain indoor air quality, and remove excess heat from cooking.

One-Story Commercial Buildings

Figure 27. Small Office Building (Excelsior, MN) and DOE Reference Building. CEE photo



This building group includes small offices, stand-alone retail stores, strip malls, supermarkets and warehouses. These buildings range from 2,500 to 52,000 square feet, are one story tall, and are built with slab on grade construction. The impact of the various window retrofits is similar in all of these buildings, but the savings as a group are small when compared to most other building groups. Windows make up a very small fraction of the surface area of these buildings and thus generally will not have a large impact on total building energy use. Only the window panels offer consistent heating and cooling savings; the films generally lead to increased energy use. The variations among the individual building types are shown in Figure 27 and Table 18.

Figure 28. Window retrofit savings in single story commercial buildings

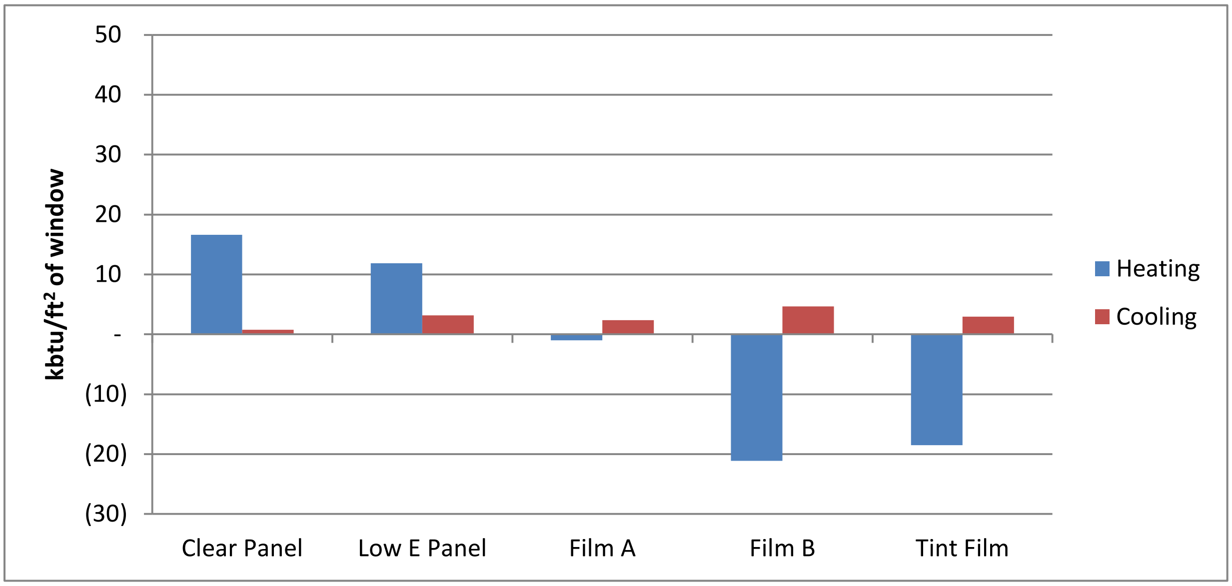
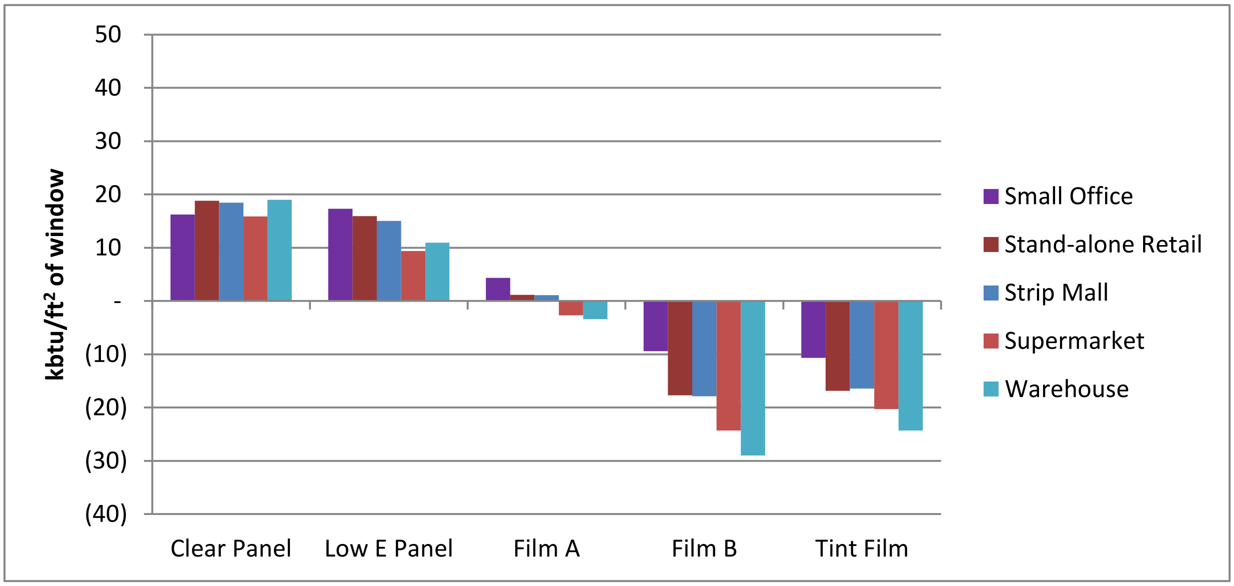


Figure 29. Total window retrofit energy savings by single story commercial building type



The best savings are provided by clear panels that increase the insulation value of the windows and allow the most passive solar heating. In all areas of Minnesota adding either a tinted film or Film B will increase the building's heating energy requirements, causing a net energy loss. Film A provides small energy savings due to reduced cooling energy in some, but not all, of these buildings, as is seen in Figure 29. None of the retrofits has a payback of less than 15 years. The buildings in this group have widely varying internal loads (from 20% in a warehouse to 60% of the total building energy use in supermarkets and small offices), but this has a minimal impact on the energy savings per square foot of window area.

Table 18. Energy savings and paybacks for window retrofits in single story buildings

Single Story Buildings		Energy Saved (%)		Energy saved by end use and fuel source (kBtu/ft^2)		Installation Payback (Years)	
	Retrofit	Total	Heating & Cooling	Heating/ Gas	Cooling/ Electric	Self	Pro
Small Office	Clear Panel	2.9%	8%	16	0	39	64
Small Office	Low-e Panel	3.9%	8%	14	3	28	48
Small Office	Film A	1.6%	2%	1	3	NA	111
Small Office	Film B	0.1%	-4%	(16)	7	35	105
Small Office	Tint Film	-0.7%	-5%	(15)	5	120	280
Stand-alone Retail	Clear Panel	0.5%	1%	18	0	28	46
Stand-alone Retail	Low-e Panel	0.5%	1%	13	3	28	48
Stand-alone Retail	Film A	0.1%	0%	(1)	2	-	203
Stand-alone Retail	Film B	-0.4%	-1%	(23)	5	NA	NA
Stand-alone Retail	Tint Film	-0.4%	-1%	(20)	3	NA	NA
Strip Mall	Clear Panel	0.8%	1%	18	1	32	52
Strip Mall	Low-e Panel	0.7%	1%	12	3	34	57
Strip Mall	Film A	0.1%	0%	(1)	2	-	198
Strip Mall	Film B	-0.6%	-1%	(22)	5	NA	NA
Strip Mall	Tint Film	-0.6%	-1%	(20)	3	NA	NA
Supermarket	Clear Panel	0.3%	1%	15	0	38	62
Supermarket	Low-e Panel	0.3%	0%	8	1	57	97
Supermarket	Film A	0.0%	0%	(4)	1	NA	NA
Supermarket	Film B	-0.4%	-1%	(26)	2	NA	NA
Supermarket	Tint Film	-0.3%	-1%	(22)	1	NA	NA
Warehouse	Clear Panel	0.1%	0.1%	19	0	32	53
Warehouse	Low-e Panel	0.0%	0.1%	10	1	53	90
Warehouse	Film A	0.0%	0.0%	(4)	1	NA	NA
Warehouse	Film B	-0.1%	-0.2%	(31)	2	NA	NA
Warehouse	Tint Film	-0.1%	-0.1%	(26)	1	NA	NA

Table 18 shows the total energy savings and paybacks for the different single story buildings. The savings as a percentage of total building energy also varies significantly for the different building types because of the window to wall ratio: warehouses have few windows and therefore small overall savings, while small offices have a larger window to wall ratio and can achieve total energy savings of 4% a year. In certain specific cases retrofits may be more cost effective than shown here. For example, since windows tend to be only on one side of strip malls, as shown in Figure 30, the building orientation (facing the western sun, for example, or facing north so there is no passive solar heating) will change the solar heat gain and therefore have an impact on energy use.

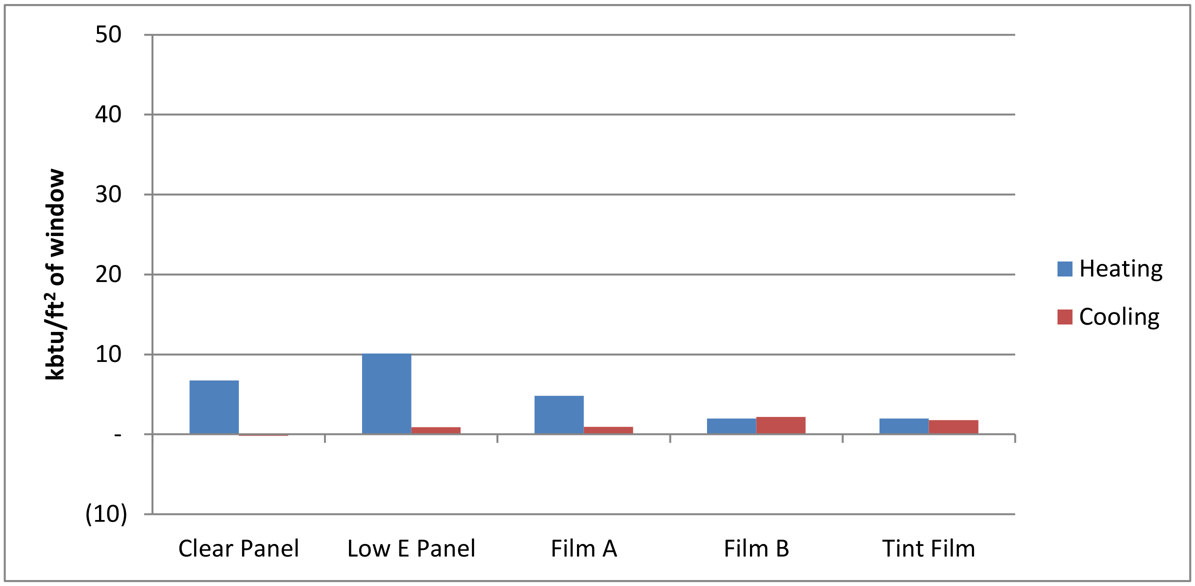
Figure 30. Strip Mall Building (Inver Grove Heights, MN) and Reference Building. CEE Photo

The estimated paybacks are extremely long and often exceed the lifetime of the retrofit products. The one building type which may offer greater potential is the stand alone retail store. According to the KEMA study (KEMA 2013), as many as "40% of the windows in small retail stores are single paned," so their owners may be particularly interested in improving window performance using window retrofits. However, it should also be noted that most of the self-installed products are limited to the smaller windows (i.e. residential sizes) and professional installation of custom sized retrofits may be necessary for standalone retail stores. As shown in Figure 2 and Figure 46, savings are typically twice as large when the existing windows are single pane.

Hotels

Hotels do not offer any significant potential for savings from window retrofits, according to the simulations modeled.

Figure 31. Heating and cooling energy savings by window retrofit type in hotel buildings



The low-e panel provides the best savings, but it is less than 1/3 of the typical savings of 30 kbtu/ft^2 seen in other building types for this retrofit (Figure 31). As a result, the paybacks are very long (Table 19).

Table 19. Window retrofits in hotels

Hotels		**Energy Saved (%)**		**Energy saved by end use and fuel source (kBtu/ft^2)**		**Installation Payback (Years)**	
	Retrofit	**Total**	**Heating & Cooling**	**Heating/ Gas**	**Cooling/ Electric**	**Self**	**Pro**
Large Hotel	Clear Panel	0.4%	1.1%	7	(0)	NA	740
Large Hotel	Low-e Panel	0.7%	2.0%	11	1	NA	360
Large Hotel	Film A	0.4%	1.1%	6	1	NA	76
Large Hotel	Film B	0.4%	0.9%	4	2	NA	126
Large Hotel	Tint Film	0.3%	0.9%	4	2	NA	95
Small Hotel	Clear Panel	0.3%	1.0%	5	(0)	113	185
Small Hotel	Low-e Panel	0.4%	0.9%	3	1	88	149
Small Hotel	Film A	0.2%	0.2%	(0)	1	NA	340
Small Hotel	Film B	0.0%	-0.6%	(6)	3	87	260
Small Hotel	Tint Film	-0.0%	-0.7%	(5)	2	250	590

Schools

Primary and secondary school buildings are very similar to one another (Figure 32 and Figure 33). Both have windows in all classrooms which run like a ribbon around the building. The primary school reference building in the DOE simulation is single story whereas the secondary school reference is two stories. The number of students is less in primary than in secondary schools. Primary school facilities (e.g. gyms) are also smaller than those in secondary schools. Secondary schools have longer hours of activity; they are occupied most nights and weekends while primary schools are not. Secondary schools also contain more computers and mechanical equipment. All these factors mean that secondary schools are expected to use more energy than primary schools; however the windows behave similarly in both.

As previously discussed, changing the SHGC in the EnergyPlus simulations of these buildings led to anomalous results which were excluded from the report. [11] As a result, only the clear window panels are shown here.

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[11] It appears that in these buildings, as well as healthcare buildings, humidity control (which is not part of most of the reference building models) is affected by the changes in SHGC. There is a change in humidification energy when SHGC changes, and it could not be held constant. Heat conduction through several walls also changed even though there were no changes made to the walls' properties. Because of these internal building energy levels changes the total energy results generated were not due only to a variation in the windows and have been omitted.

Figure 32. Primary and Secondary School Reference Buildings used for simulations.

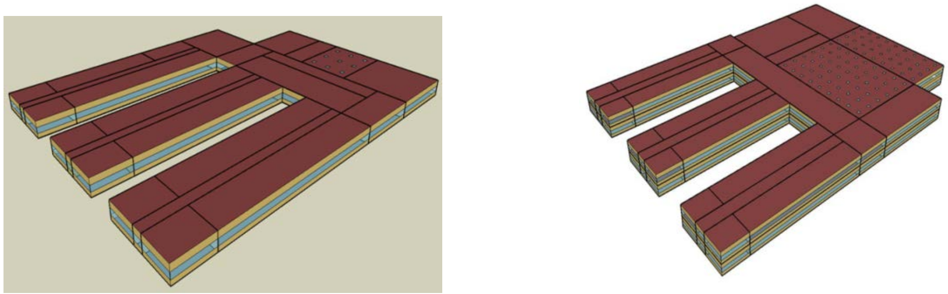
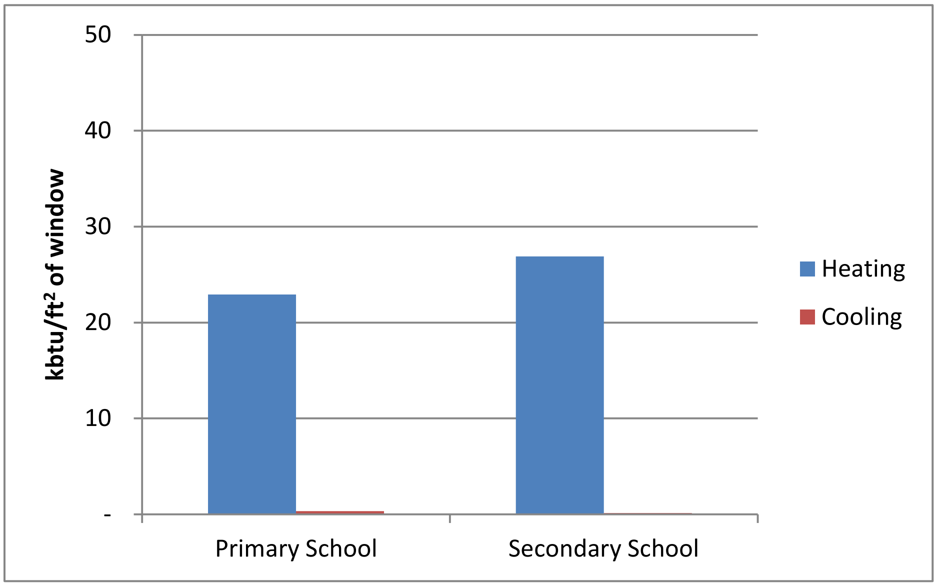


Figure 33. Minnesota School Buildings. Primary school in West St. Paul, MN. These windows are partially operable, and some are protected by a four foot overhang. CEE photo.

The energy savings offered by clear window panels for heating and cooling energy use is shown in Figure 34. They are comparable to the most other building, about 25 kbtu/ft^2.

Figure 34. Total window retrofit energy saved per square foot of window area for schools in zone 6A (Minneapolis-St. Paul).



Because of the large window area in schools and the total number of buildings throughout the state, the building level energy savings of about 3% has the potential to have a measurable impact on state-level energy savings. However, the payback times shown in Table 20 far exceeds the product (or even the building) lifetime; while it is likely that the savings with low-e panels would be about 20% larger, based on the results with the other building groups, the payback from energy savings alone would not justify installation.

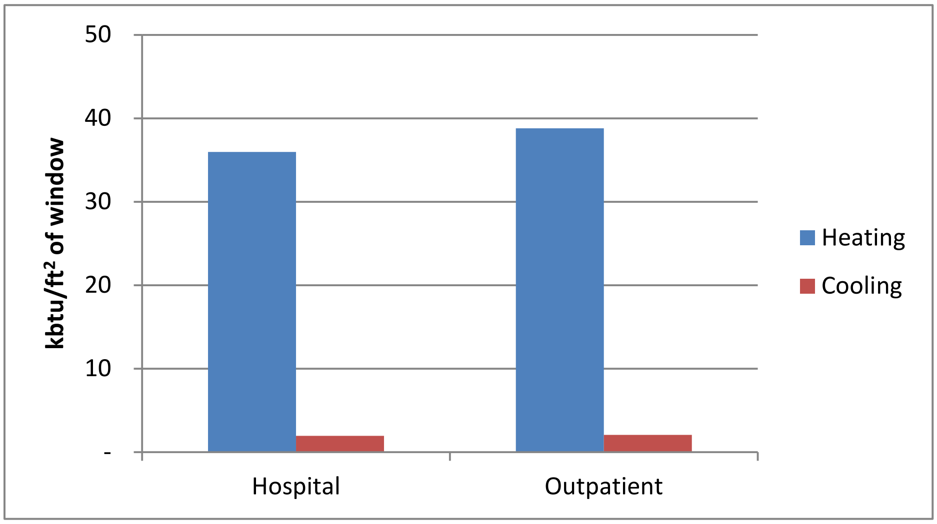
Table 20. Energy savings and paybacks for clear window panels in school buildings

School Buildings		**Energy Saved (%)**		**Energy Saved kBtu/ft^2**		**Installation Payback (Years))**
	Retrofit	Total	Heating & Cooling	Heating	Cooling	Professional
Primary	Clear Panel	3.4%	7.5%	23	0	200
Secondary	Clear Panel	2.7%	4.4%	27	0	180

Health Care Buildings

Healthcare facilities have higher than average energy savings from clear window panels. While they are only about 1% of the total energy use of these buildings, they are also the highest savings per square foot of window area of any building types[12]. It is likely that low-e window panels would provide about 20% greater savings than the clear window panels, based on the results in other buildings.

Figure 35. Heating and cooling energy savings for clear window panel in healthcare buildings



The outpatient reference building is assumed to have electric reheats in the VAV boxes. According to the simulation, 42% of the heating energy saved would be from the electric reheats, which is the reason the

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[12] As previously discussed, changing the SHGC in the EnergyPlus simulations of these buildings led to anomalous results which were excluded from the report. Only the clear window panels are shown here.

paybacks are faster than for the hospital, which is assumed to have hydronic reheats (heated with hot water from a natural gas water heating system). For this reason in Table 21 both heating and cooling savings as well as gas and electric savings are shown, because they are not the same for the outpatient building. This difference illustrates the impact of fuel source on payback. Because healthcare buildings serve the public, we assumed that custom professional installations of retrofits would be required, a cost about 4 times as high as the standard products ($42 per square foot, vs. $9 for a residential grade product). If the less expensive products can be used, the payback will drop to about ten years.

Table 21. Energy savings and paybacks for window retrofits in healthcare buildings

Healthcare Buildings		**Energy Saved (%)**		**Energy saved by end use (kBtu/ft^2)**		**Energy saved by fuel source (kBtu/ft^2)**		**Installation Payback (Years)**
	Retrofit	Total	Heating & Cooling	Heating	Cooling	Gas	Electric	Pro
Hospital	Clear Panel	0.9%	1.9%	36	2	36	2	114
Outpatient	Clear Panel	1.2%	2.1%	39	2	23	18	53

Effect of Construction Date on Savings Estimates

Building simulations were performed using the three different periods of building construction available for the reference buildings. These periods are: pre-1980, 1980 to 2004, and post-2004 (also called "New"). They reflect the construction practices typical of each period for features such as wall and roof insulation, types and efficiencies of heating and cooling systems, and lighting power density. Simulations were run on a subset of the reference buildings (large offices, small offices, strip malls, primary and secondary schools and mid-rise apartments) to test the impact of the date of construction. Figure 36 shows that the energy savings provided by the building retrofits is fairly constant for each building type in all areas of Minnesota, even though, as Figure 37 shows, the overall energy use of all the buildings decreased by an average of over 20% largely due to improvements in lighting and insulation.

Figure 36. Energy Savings for a Clear Panel window retrofit with different periods of construction in climate zones 6A and 7.

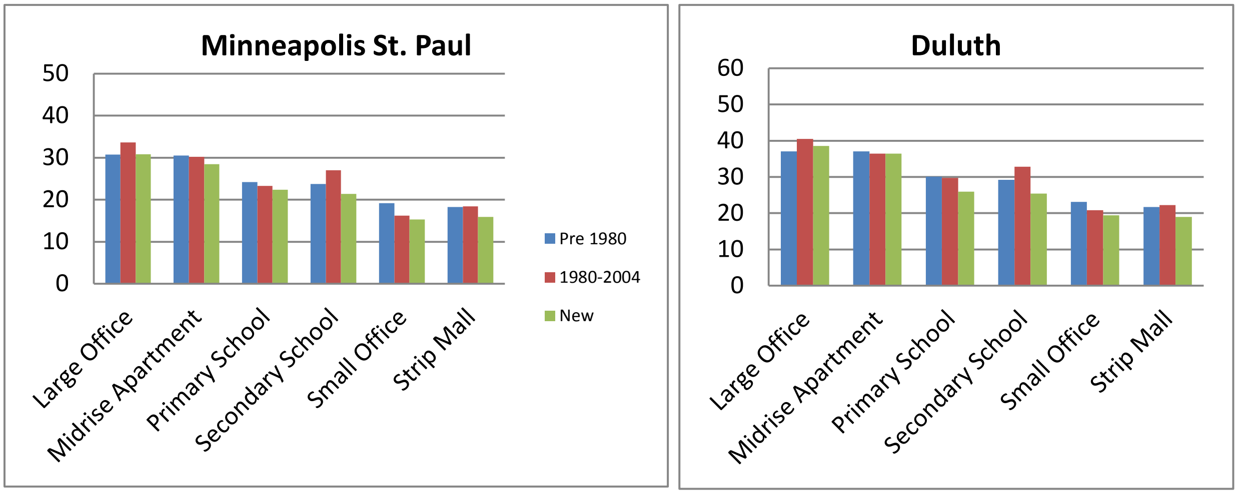
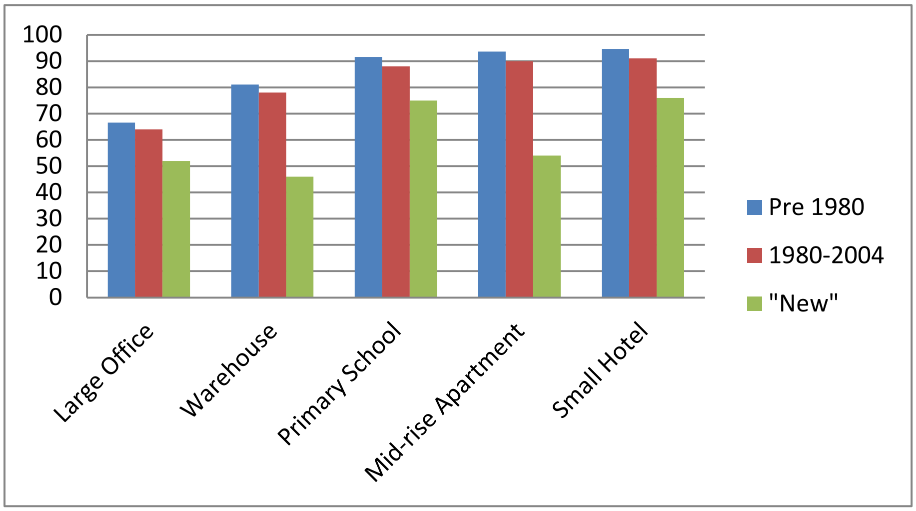


Figure 37. Energy Use Index (EUI) for Reference Buildings with different construction dates. “New” buildings have lower energy use than the 1980-2004 period, a 22% average decrease



These results are typical of both types of window panels, and the two low-e applied films (Film A and Film B), although the variation is higher for the films. The relative values of the energy savings and EUI for all of the construction date-retrofit combinations are shown in Table 22. The plus or minus values are equal to one standard deviation. The savings from window retrofits are consistent in magnitude even when other improvements have been made to the building’s construction and operations. The two older construction periods have very similar results In terms of the energy saved by retrofitting windows, especially with window panels. The benefit is slightly smaller (about 10%) in new buildings, but within the range of accuracy of the overall simulation results (see below for comments on precision and accuracy).

Table 22. Average and standard deviation of normalized energy savings of window retrofits with changing date of construction

Retrofit	**Pre 1980 Value**	**1980 - 2004**	**New**	**Change: 1980 to New**
Clear Panel	1.03 +/- .05	1.04 +/- .05	0.94 +/- .04	-9%
Low-E Panel	1.04 +/- .09	1.04 +/- .08	0.92 +/- .10	-12%
Film A	1.10 +/- .45	0.92 +/- .23	0.98 +/- .46	-12%
Film B	0.93 +/- .20	1.05 +/- .25	1.02 +/- .34	+9%

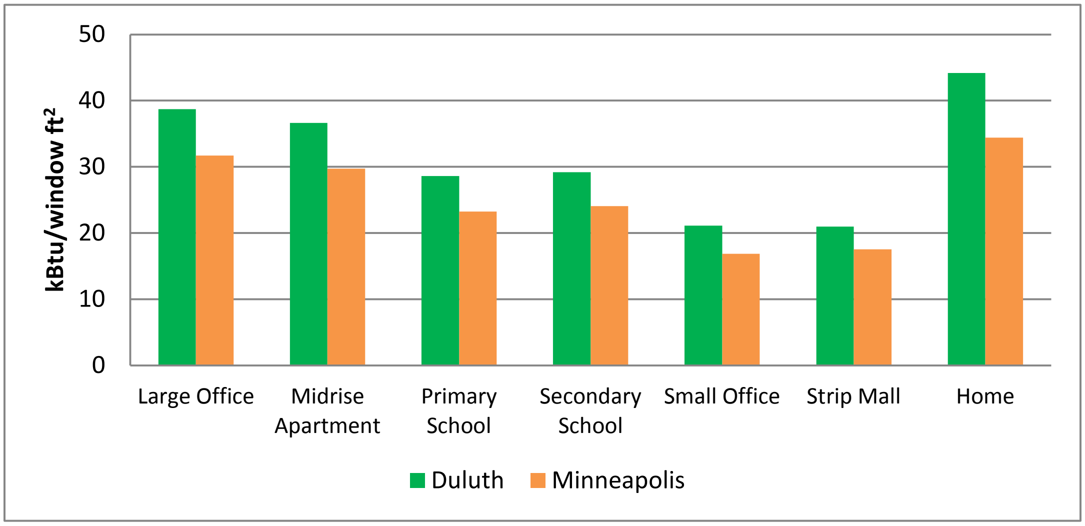
In These results are typical of both types of window panels, and the two low-e applied films (Film A and Film B), although the variation is higher for the films. The relative values of the energy savings and EUI for all of the construction date-retrofit combinations are shown in Table 22. The plus or minus values are equal to one standard deviation. The savings from window retrofits are consistent in magnitude even when other improvements have been made to the building’s construction and operations. The two older construction periods have very similar results In terms of the energy saved by retrofitting windows, especially with window panels. The benefit is slightly smaller (about 10%) in new buildings, but within the range of accuracy of the overall simulation results (see below for comments on precision and accuracy).

Table 22 the average savings for each retrofit is normalized to allow the building types to be compared and the standard deviation is the variation in the results across the five building types. The energy savings results for both climate zones 6 and 7 were used in the analysis. There was less than 2% change in the results between the first two construction periods (before 1980 and 1980-2004), most of the variation is in the post-2004 construction period. The variability of the savings for the window films across periods and building types is much higher than for the window panels: the standard deviations are 33% for the two window films compared to 7% for the panels.

Effect of Climate Zone on Energy Savings

Simulations were performed for seven selected building types in climate zones 6A and 7 (Figure 38). The savings are greater in zone 7 (Duluth weather data) which has about 19% more heating degree days (base 65) than zone 6A (Minneapolis-St. Paul weather). Duluth has about 10,000 HDD and Minneapolis-St. Paul about 8,400. Across all window retrofits, the savings per square foot of window area is 27% higher (+/- 11%) in Duluth compared to the Twin Cities. The difference in cooling energy has a small overall effect - Duluth averages only 180 Cooling Degree Days compared to Minneapolis St Paul which has 737, or 4 times the need for building cooling.

Figure 38. Comparative energy savings for existing windows with a clear window panel retrofit in common buildings types: energy savings average 27% more in zone 7 than zone 6A



Factors affecting the precision and accuracy of the results

The normalized energy savings values presented in this white paper should be accurate within +/- 10% for most retrofit projects, excluding the impact of climate zone, discussed in the previous section. The range of variation that will be seen in a specific project can be caused by many factors, including the specific window retrofit product selected, the thermal characteristics of the actual building, the operating characteristics of the building, and the particular way the retrofit is installed. The results are intended to present the most likely costs and savings.

Fuel prices vary both by fuel type and seasonal fluctuations. Unfortunately, fluctuations in prices are common; therefore the correct financial value of energy savings requires the use of current local prices.

(The cost of each major heating fuel has varied by at least 10% in the past four years.) Historically, homes heated with natural gas have lower energy costs, and therefore savings from window retrofits in these homes are correspondingly lower. However, 30% of Minnesota homes are heated with fuels other than natural gas (electricity, propane, heating oil), and these fuels cost between 2½ and 3½ times as much as natural gas, so savings from window retrofits are higher. For example, a home in northern Minnesota (Zone 7) that has both electric resistance heating and single pane windows can save over $450 a year by retrofitting (interior or exterior) low-e window panels (Cort and Culp (2013), Larson website (2014)). The same retrofit on a house with double pane windows and natural gas heating will save about $75 (and therefore take six times as long to pay back).

Construction costs vary over time and by region of the state. These variations will have an impact on the payback times of any retrofit. However, the relative savings and payback times for different retrofits will not change. Residential costs were used for products and installation for most building types (not just residential houses); the exception is large offices, large hotels and healthcare buildings, all of which were assumed to require professional installation from dedicated window companies, at a significantly higher cost (about 4 times the residential contractor costs).

The numbers presented in this report should provide good first estimates for projects.

Summary: Results by Window Retrofit Type

In this section the results are summarized for each of the five window retrofits. The properties of the retrofits as used in the simulations are shown in Table 23 (repeated from Table 12) along with the ENERGY STAR Qualification Criteria for the Northern United States.

Table 23. Characteristics of the Window Retrofit compared to Base Window and ENERGY STAR

Window Description (Retrofits followed by replacement windows)	**Commercial Window (Metal frame)**		**Residential Window (Wood/vinyl frame)**	
	U- Factor	**SHGC**	**U- Factor**	**SHGC**
Clear Panel	0.40	0.59	0.32	0.51
Low-e Panel	0.30	0.45	0.26	0.47
Moderate gain Low-e Film	0.47	0.46	0.39	0.46
Low gain Low-e Film	0.52	0.30	0.435	0.30
Tinted Film	0.60	0.40	0.51	0.40
Standard Window	0.60	0.60	0.51	0.57
Clear Panel	0.40	0.59	0.32	0.51
ENERGY STAR (Version 6.0, 2014)			0.27	Any
ENERGY STAR (Equivalent Energy Performance)			0.30	>0.42

The largest energy savings was usually provided by low-e window panels which were as high as 43 kbtu/ft^2 in residential houses, but as low as kbtu/ft^2 in hotels. Clear window panels offered relatively consistent savings of 25 to 30 kbtu/ft^2 in most buildings, but did not have much impact on cooling. The window films were more effective at saving cooling energy, but often caused total annual energy use of the building to increase (although still saving money in many cases because it uses electricity, not natural gas which is currently much less expensive per unit of energy).

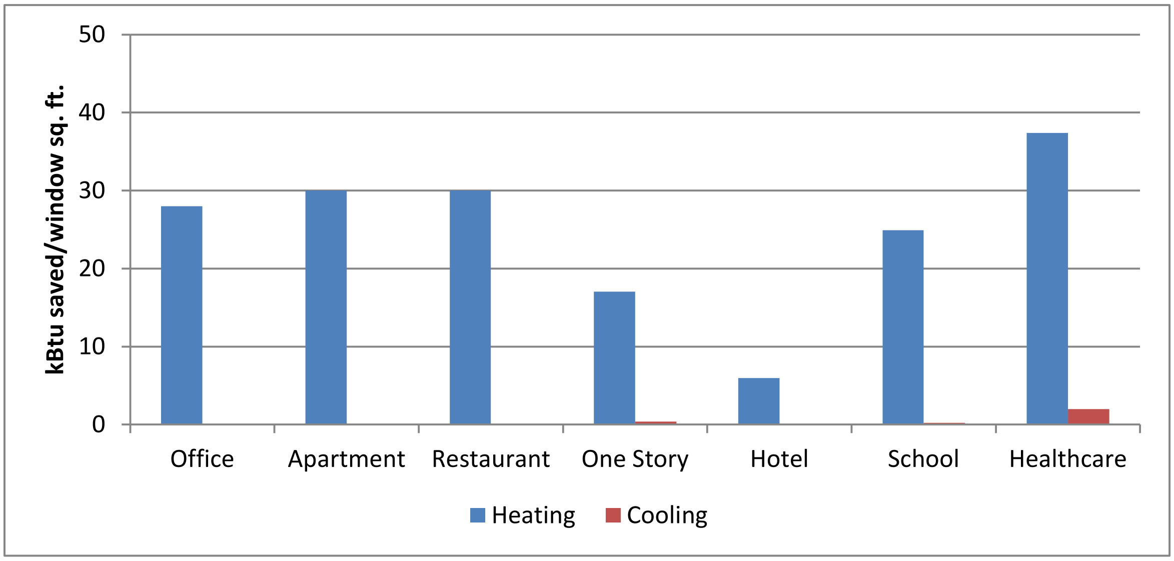
Clear Window panels

Clear window panels effectively save energy in all building types in Minnesota. These results are consistent with previous field studies that found the energy benefit of adding a window panel (inside or outside) was equivalent to replacing a window with a new model that has one more panel than the original window (Cort, K.A. and Culp, T. 2013). Clear window panels save an average of 34 kbtu/ft^2 in houses and 24 kbtu/ft^2 in commercial buildings in climate zone 6.

Clear window panels decrease the U-factor without significantly changing the SHGC. The self-installed cost of clear window panels ranges from $5.50 to $14 per square foot of window area for residential sized windows. For comparison, the cost of an installed residential replacement window starts at about $34 per square foot. The cost of installation can be much higher, up to $50 per square foot, in commercial settings where custom sizes and mounting are needed.

Figure 39 illustrates the range of savings for seven representative building types. The majority of the savings is for heating. The heating and cooling values are also reported separately in Table 24 for those retrofit-building combinations that have total energy savings of 10 kbtu/ft^2 or more. Savings in Duluth (Zone 7) are about 20% greater than for Zone 6A.

Figure 39. Average heating and cooling savings per square foot of window area for clear window panels on commercial buildings in Minneapolis St. Paul (Zone 6A).

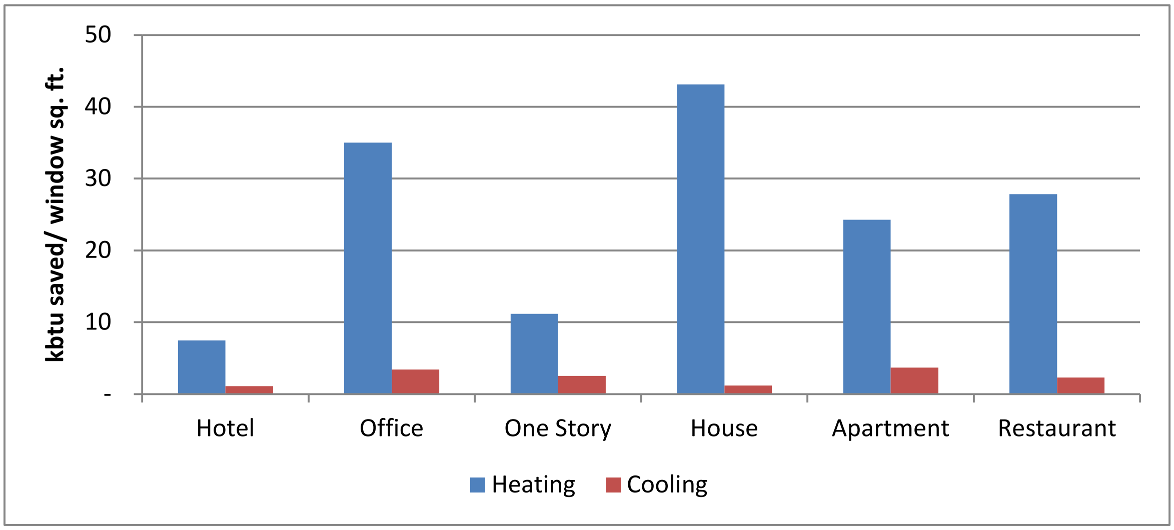


Glass window panels are assumed to have a lifetime of twenty years, although with proper care most will last much longer. Plastic window panels typically have a ten year warranty against yellowing of the plastic glazing area, but also may be kept in use for a longer time.

Low-e Window Panels

Window panels with a low-e coating offer the greatest energy savings of any of the retrofits considered. The low-e coating further improves the window U-factor providing a way to achieve ENERGY STAR performance when properly installed over existing double pane windows. Low-e window panels save an average of 43 kbtu/ft^2 in houses and 33 kbtu/ft^2 in commercial buildings in climate zone 6. As Figure 40 shows, there is substantial variation by building type.

Figure 40. Energy Savings for low-e window panels on six different building groups in Minneapolis- St. Paul (Zone 6A).



Low-e panels cost about $2 per square foot more than clear panels, so the materials cost for residential retrofits ranges from $7.50 to $13 per square foot[13]. There are many products readily available for less than $10 per square foot (excluding installation). Retrofits in commercial settings (such as multistory offices and public buildings) are often much more expensive, with costs ranging from $35 and $50 per square foot installed. Our simulations assumed a coating with a moderate SHGC; it may be necessary to look at several product lines for the best U-factor/SHGC combination (see discussion below). Low-e storm windows are now included in ASHRAE 90.1-2013 as a product that should be included in residential building codes for use with windows that do not already have a low-e coating (Boldt, J. 2014).

The savings by building group separated into heating and cooling savings are shown in Table 24 and Figure 40. While all building types have savings with this retrofit, there is a great deal of variability by building group because of the impact of reduced solar heat gain. In order to obtain the cooling savings, Low-e panels must be left in place all year long. This may affect product selection as not all panel mounting systems will allow the original window to be operated when the panel is in place.

Low-e Applied Window Film with Moderate Solar Heat Gain (Film A)

There were two window films with low-e coatings that are also NFRC rated at the time of this report; we designated them “A” and “B”. In general, low-e applied window films are not yet in common use, having come onto the market in the past three years. Film A has very low-emissivity (0.07) and moderate SHGC (0.46). This film can save energy in many buildings, but only about one-quarter as much as adding a low-e window panel. Film A had the best combination of insulating properties and SHGC of any applied

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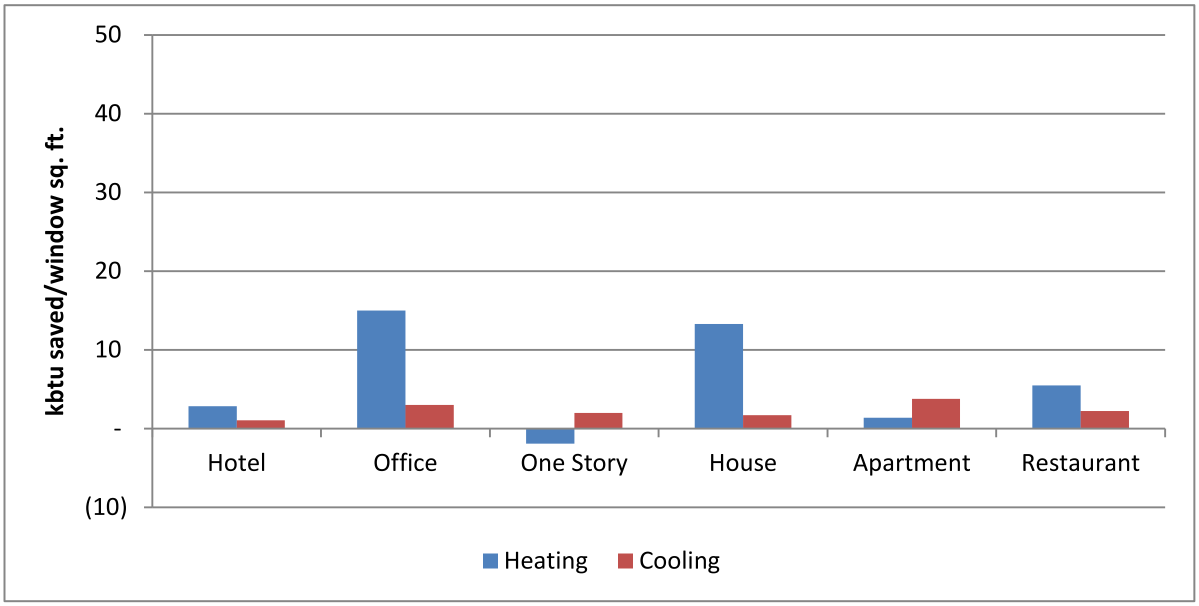
[13] The cost of low-e panels is based on commercially available products, which come only in specific sizes, while the clear panels can be custom made. As a result, the range of cost per square foot of clear panels is larger.

window film for Minnesota. Still, results are highly variable by building type, so it cannot be universally recommended for use. Figure 41 shows the savings by building group. This film saves an average of 14 kbtu/ft^2 in houses. Minimal savings (and increased energy costs in some cases) were found in one story commercial buildings.

Film A is currently represented by only one product on the market. No information about specific installations or customer experience is yet available. This film requires professional installation (and removal) with an installed cost of $12 to $20/ft^2. The cost is the same or higher than owner installed window panels (clear or low-e coated), with lower savings. It may produce electric demand savings by reducing cooling needs in some buildings on the hottest days of the year. (This is the scenario that has made this an excellent retrofit in hot, sunny climates like Phoenix).

Figure 41. Energy Savings for Window with Moderate Solar Heat Gain (Film A) on selected building groups in Minneapolis- St. Paul (Zone 6A)



Window Film A does produce cooling energy savings which saves more money per unit of energy saved than heating. A benefit of window films is that they can be permanently applied to the windows without affecting operability.

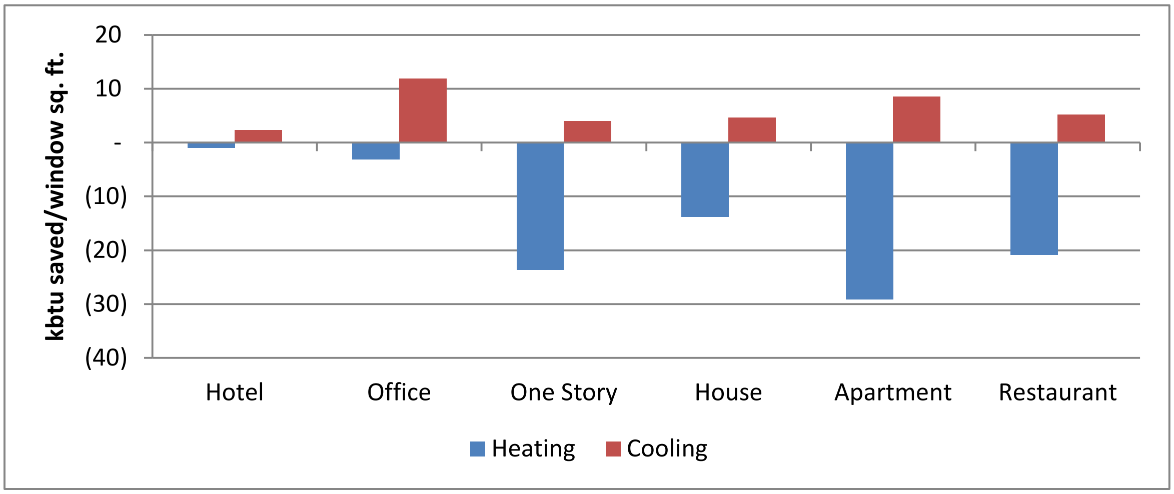
Window films have an expected life of ten to fifteen years, with a typical warranty of ten years. The actual lifetime is due to many factors; and signs of aging include discoloration, detachment from the glass surface, or formation of bubbles under the surface (between the film and the glass).

Low-e Applied Window Film with Low Solar Heat Gain (Film B)

Window Film B is also NFRC rated, with a moderate emissivity (e = 0.35) and low solar heat gain (SHGC = 0.30). This film blocks seventy percent of the incident solar radiation, reducing passive solar heating (see Figure 17 and Figure 18). Results for six building types are shown in Figure 42: for most buildings this film does not lead to total energy savings. In all cases it increases heating energy requirements. This low solar gain window film does produce significant cooling energy savings that can more than offset the increased heating costs. Film B is found in some Minnesota buildings because it can improve occupant comfort in summer and help reduce peak summer electrical demand.

Because of the difference in cost between electricity and natural gas installing Film B may benefit an electric utility, but not a natural gas one. Film B is only available with professional installation. It is slightly less expensive than Film A, about $7 per square foot. The film can be removed with water and therefore does not require professional removal, which reduces its lifetime cost. It has an expected life of about 15 years.

Figure 42. Energy Savings (Loss) for Window Film B on different building groups in Minneapolis- St. Paul (Zone 6A).



Tinted Window Film

Tinted window films are included in this report because they are often advertised as an energy saving product. While this is true in southern climates, in Minnesota these products do not save energy.[14] The tinted film we simulated loses an average of 18 kbtu/ft^2 (Figure 43).

Tinted films are very popular in locations where solar heat gain is excessive. In hot sunny climates they are effective at moderating afternoon temperature rise in south and west facing rooms by as much as ten to twenty degrees. Tinted films reduce solar heat gain but do not change the window U-factor. Building energy modeling should be used with building specific information to identify appropriate windows for film application. The Commercial High Performance Windows website has a calculator, the Façade Design Tool, which allows modeling of individual walls facing different directions to compare window retrofits, including applied window films

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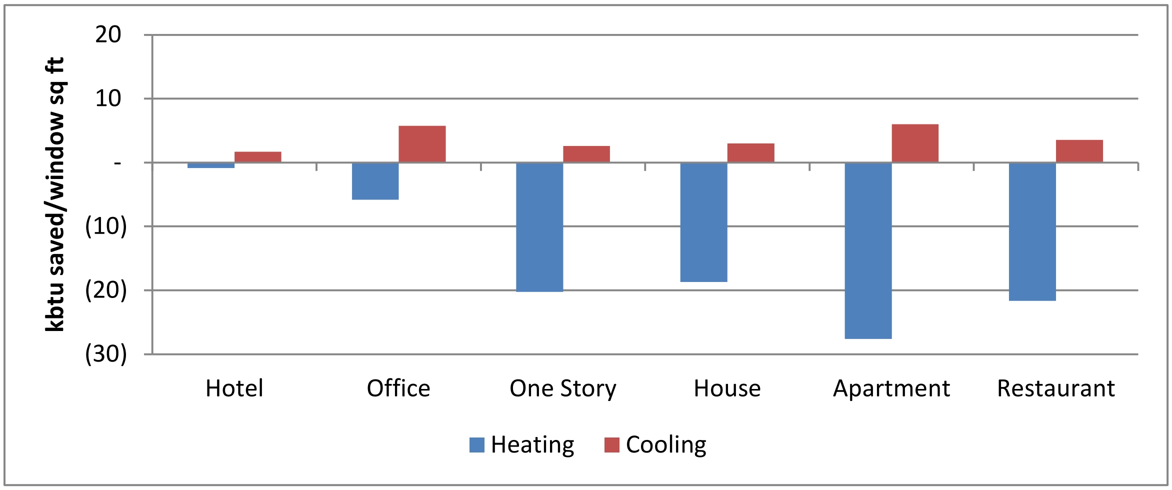
[14] There are similarities between these tinted films and the "heat reflecting blankets" which the Department of Energy Resources has advised consumers against using. See, for example, Better Business Bureau, "Department of Commerce, BBB warn of salespeople pitching energy savings from radiant barriers" April 8, 2014.

Figure 43. Energy Savings (Loss) for Tinted Window Film on different building groups in Minneapolis-St. Paul (Zone 6A)



Comparative Summary of the Window Retrofits

The five window retrofits are shown in Figure 44 against a background of equal building energy contours (this figure is based on Figure 5). While these specific contour lines are for a house, the general interaction of U-factor and solar heat gain coefficient in window retrofit products is representative of many buildings in Minnesota. The numbers in diamonds represent each of the window retrofits discussed in this report, and their relative positions are indicative of the amount of energy each can save, or lose, relative to a standard double pane window, indicated by #1. Moving along a contour line does not change the energy use, moving perpendicular to the contour lines does; generally moving towards the bottom of the figure means using less energy. In this figure, the energy savings (from best to worst) is #3 (Low-E panel) > #2 (Clear panel) > #4 (Moderate gain low-e applied film) > #1 (existing double clear window) > #5 (Low gain low-e applied film) > #6 (Tinted applied film).

The contour lines are separated by roughly equal amounts of energy use: by this scale the moderate SHGC film with very low emissivity (#4) saves about half as much as the low-e window panel (#3), and the clear window panel (#2) saves about 75% as much.

The most promising combinations of retrofits and building types are listed in Table 24. The selection criteria for inclusion in the table were that the combinations have both heating and cooling energy savings, and total annual savings of at least 10 kBtu/ft^2 (1.5 therms per year for a 3' by 5' window). The low-e window panels attain this level of savings in all building groups[15], and the clear panel was almost as effective, with the exception of hotels. The savings for applied window films were lower; the film with moderate solar heat gain only met the criteria in houses and multistory office buildings, and with savings of about half that provided by the window panels in those buildings. Total energy savings of 10 kBtu/ft^2 were not found with either the low gain window film or the tinted window film.

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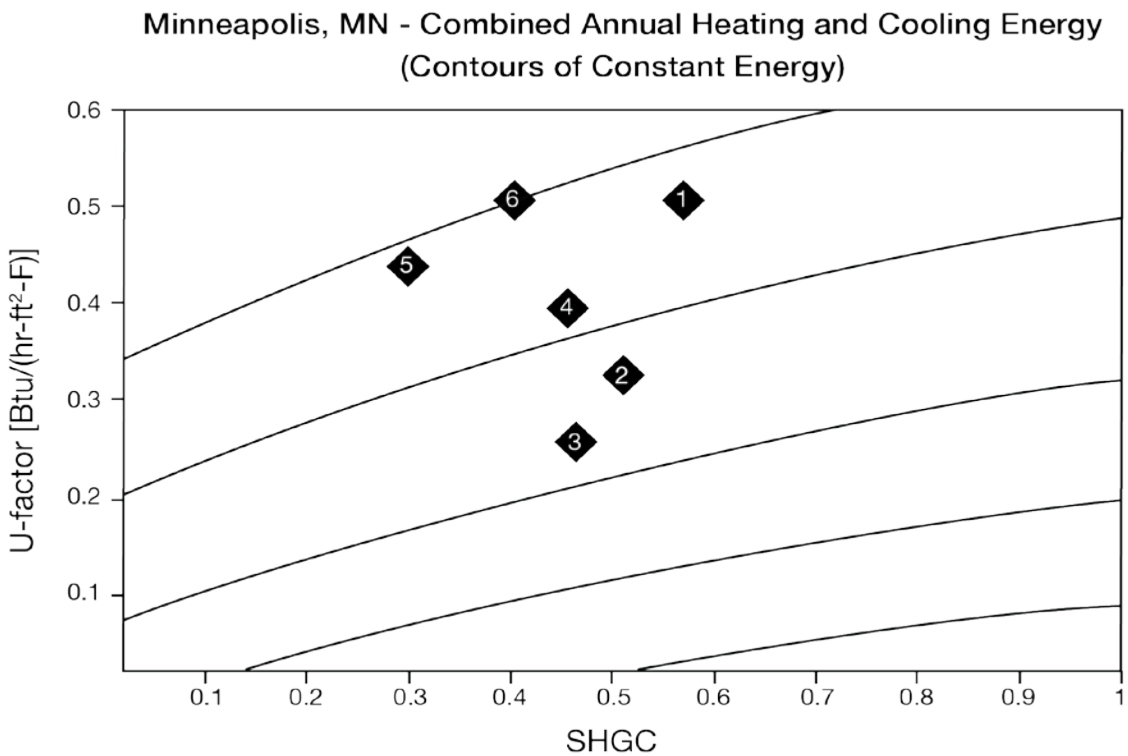
[15] It is assumed that this would also include schools and healthcare buildings; however they have been excluded from these results, as discussed previously.

Figure 44. Combined effect of U-factor and SHGC for a typical Minnesota house. after Arasteh, D. K. et al. 2006.



1 = Double clear (base case)	2= Clear window panel	3 = Low-e window panel
4 = Moderate SHGC, low-e film	5 = Low SHGC, low-e film	6 = Tinted window film

Table 24. Heating and Cooling Savings for Selected Retrofit/Building Group Combinations in Zone 6 with total savings at least 10 kBtu/ft^2

Retrofit	**Building Group**	**Heating (kBtu/ft^2)**	**Cooling (kBtu/ft^2)**	**Total (kBtu/ft^2)**
Clear Panel	Health Care	38	2	40
	House	34	1	34
	Restaurant	30	0	30
	Midrise Apartment	30	0	28
	Schools	26	0	26
	Multistory Office	25	0	25
	One-story buildings	17	0	17
Low-e Panel	House	43	1	44
	Multistory Office	31	4	35
	Restaurant	28	2	30
	Midrise Apartment	24	4	28
	One-story buildings	12	3	15
	Hotel	10	1	11
High Solar Gain Low-e Film (A)	Multistory Office	12	4	16
	House	13	2	15

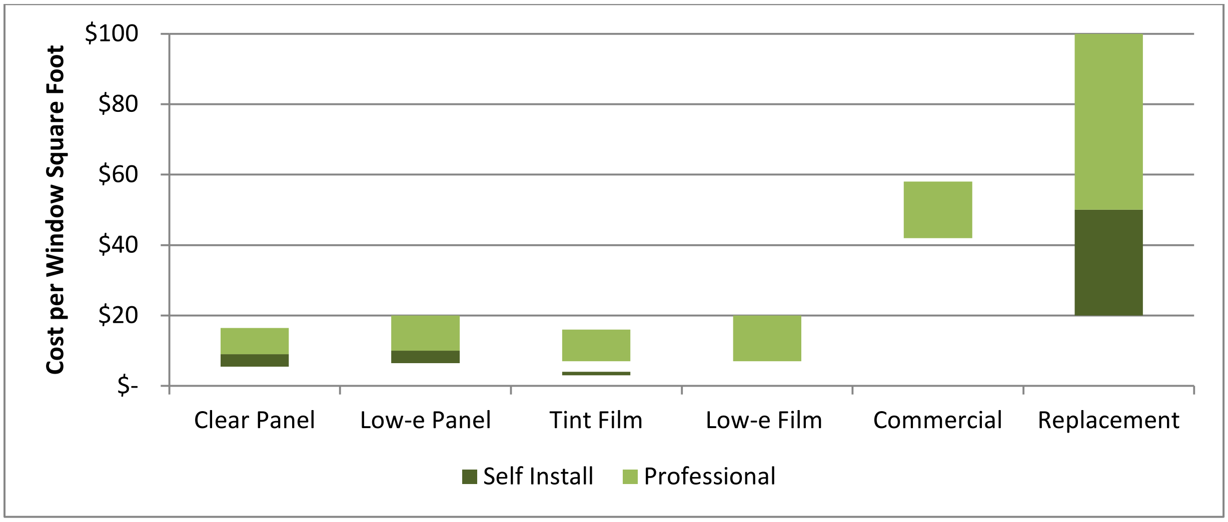
Cost Benefit Analysis of Window Retrofits

Product Costs

Costs of window retrofits were gathered from manufacturers, installers, retail stores and published literature. Many of the products are designed to be self-installed, which reduces the reported cost. The cost of professional installation, on average, is about equal to the material costs, roughly doubling the total cost. There are two exceptions to this generalization: (1) most large commercial and public buildings are likely to require professional installation; and (2) the NFRC certified low-e window films are only available with professional installation.

Window retrofits, like many construction-related products and services, have a very large range of costs. Figure 45 summarizes the cost data. Window panel costs range from $5.50/ft^2 for a self-installed window panel to $42/ft^2 for professionally installed custom commercial glass panels. Because professional installation is required for the moderate SHGC film (A) no self-installed option is shown. There are low-e films (without NFRC ratings) sold through retail channels that appear to have properties like those of Film B, at a cost of about $3/ft^2. This is the lowest cost window retrofit, but is not recommended for Minnesota utility conservation programs because it does not produce total energy savings in most Minnesota buildings.

Figure 45. Cost of window retrofit options, per square foot of window area.



Prices were provided by multiple sources including a commercial window company (multistory office window panel retrofits), window panel manufacturers (large and small producers), manufacturer-certified window film installation companies, internet searches and interviews with installation contractors. The costs for installation in residential houses may be 20 to 30% higher than in commercial buildings because of both the relatively small window area and the custom nature of residential work (there is a large variety of custom window sizes and shapes in homes). While each individual retrofit project will vary, the costs presented here should be good first estimates. Costs are normalized to dollars per square foot, just like the reported savings.

The maximum cost of self-installed product often overlaps with the minimum costs of professional installations. One large manufacturer reports that 80% of their sales of interior window panels are direct to homeowners for do-it-yourself installation (Cort and Culp, 2013). DIY retrofit costs are compared to the cost of replacement windows in Table 25; the retrofits cost are about 80% less.

Table 25. Window replacement vs. window retrofit: cost comparison. From NREL Efficiency Measures Database and installer interviews

Replacement Window	Cost/ft^2	U-factor, SHGC	Retrofit (over base window)	Material Cost/ft^2	U-factor, SHGC
Double pane, moderate gain, low-e, Ar fill	$ 34 ($22 to $43)	U= 0.37 SHGC = 0.53	Clear panel	$ 5.50 ($4 to $7)	U= 0.32 SHGC = 0.51
Double pane, moderate gain, low-e, Ar fill	$ 39 ($26 to $50)	U= 0.29 SHGC = 0.56	Low-e panel	$ 6.50 ($6 to $ 10)	U= 0.26 SHGC = 0.47
Triple pane, clear, Ar fill	$ 88 ($61 to $110)	U= 0.29 SHGC = 0.56	NA		

Payback Analysis

There are only four retrofits that have a payback less than 15 years, and they represent just two types of buildings: 1. houses with electric heat and 2. medium offices (which also use a higher than average amount of electric heat). The retrofits are 1. low-e panels and 2. clear window panels, self or professionally installed. Four additional building types, houses with natural gas heat, apartments and both kinds of restaurant buildings have paybacks with some retrofits in the 15 to 25 year range. While these are comparable to product lifetimes, they would not be characterized as attractive paybacks.

Table 26. Window retrofit projects that payback in 25 years or less, zone 6 (Minneapolis)

Retrofit	Type of Building	Total H+C Energy Saved (%)	kbtu/ft^2 saved by retrofit	Building Gas Savings Dt	Building Electric Savings kWh	Payback-self install	Payback – prof. install
Paybacks under 15 years							
Low e Panel	House (electric heat)	8.1%	44		2,292	5.7	10
Clear Panel	House (electric heat)	6.2%	34		1,776	6.3	10
Low e Panel	Medium Office	5.9%	31	(406)	74,790		10
Clear Panel	Medium Office	4.2%	23	11	46,330		12
Paybacks of 15 to 25 years							
Low e Panel	House (gas heat)	8.1%	44	10	76	16	27
Clear Panel	House (gas heat)	6.2%	34	8	39	18	29
Film B	Medium Office	1.6%	6	(917)	38,997		18
Low e Panel	Quick Service Restaurant	0.6%	33	86	206	19	32
Clear Panel	Quick Service Restaurant	0.5%	33	91	16	19	32
Low e Panel	Midrise Apartment	2.5%	28	599	2,834	20	33
Clear Panel	Midrise Apartment	2.6%	30	749	85	21	35
Low e Panel	Full Serve Restaurant	0.5%	27	126	311	23	39
Clear Panel	Full Serve Restaurant	0.4%	28	138	17	23	38

The Effect of Heating Fuel on Window Panel Paybacks

The cost of home heating is dependent on the type of fuel used. Heating with electric resistance or delivered fuels is about three times as expensive as heating with natural gas. As a result, the heating fuel has a larger effect on the payback time for all window retrofits than the starting window configuration (Figure 46).

Figure 46. The annual cost of heating energy lost through a typical 3' x 5' window in a Minnesota house, showing the impact of heating fuel

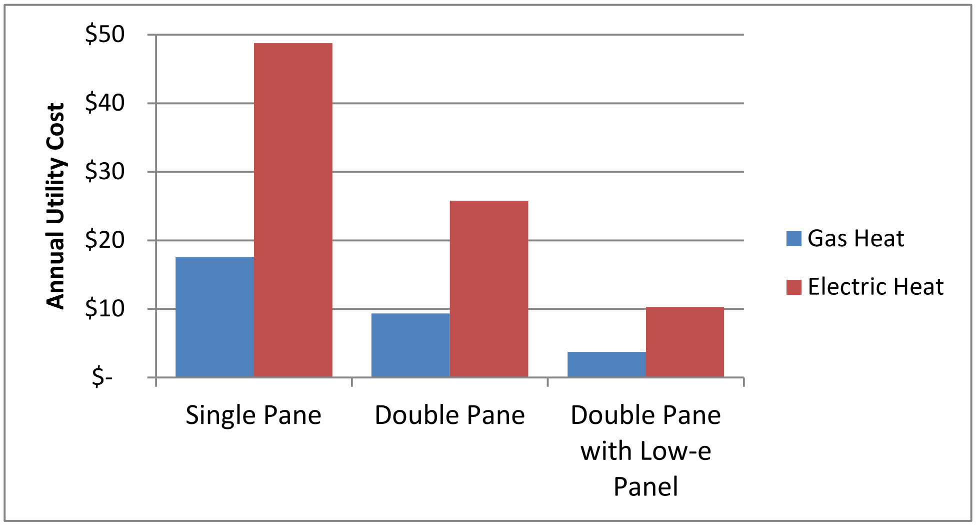


Table 27. Payback of a Window Retrofit Project in Climate Zone 7. From RESFEN

Fuel	**Market Cost**	**Unit Cost ($/100 kbtu)**	**Annual Savings for a home in Zone 7 with low-e window panel retrofit**	**Payback of $2,500 Investment (years)**
Natural gas	$0.85/therm	$ 0.85	$ 108	23
Electricity	$0.11/kWh	$ 3.25	$ 319	8
Propane	$2.62/gal	$ 2.85	$ 282	9
Fuel Oil	$3.83/gal	$ 2.76	$ 273	9

This example is for a single family house in Minneapolis (Zone 6A). The heat energy loss was calculated by RESFEN and normalized for a single window.[16] A home with gas heating that adds Low-E panels to existing double pane windows will save about $6 per window per year, while a home with electric heating will save about $14 per window per year. While the financial savings is modest, it should be noted that adding the low-e panel over an existing double pane window (cost of about $100) brings the window to ENERGY STAR criteria at a much lower cost than a new triple pane replacement window. The costs used in this report are shown in Table 27, along with an example of a payback analysis for a house in Duluth, using fuel costs from the EIA's March 2014 Energy Outlook. The retrofit is low-e window

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[16] The annual heat loss is 21 Therms for the single pane window, 11 Therms for the double pane and 4 Therms for the double pane with a Low-e panel. The cost of energy is taken from the U.S. Department of Energy's March 2014 forecast and is $0.111/kWh and $0.85/ therm.

panels wth professional installation at a cost of \$11/ft^2. The energy savings are from RESFEN. The annual whole house energy savings is 99 therms (44 kbtu/ft^2 saved * 225 ft^2 window area). The total project cost is \$2,500. The cooling savings were about \$2 per year (18 kWh) in this example.

Savings Potential for Minnesota

Window retrofits have the technical potential to save about 13 trillion Btu's annually in Minnesota buildings if the best retrofit is used on each building type without regard to cost. However, the cost-effective potential is smaller than this, 3.4 trillion Btu with a payback of less than 15 years or 26% of the technical potential. If the paybacks are extended to 25 years, then 90% of the technical potential can be reached. The majority of the savings (90%) is in houses. Table 28 summarizes the total potential savings. For most building types the low-e panel savings are used as they are the highest of the different retrofits. In the case of healthcare and school buildings, where the EnergyPlus models gave anomalous results, the clear panel savings are used.

Table 28. Energy savings potential in Minnesota buildings with window retrofits

Type of Building	kbtu/ window sq. ft.	Gas therms/ building	Electric kWh/ building	Savings per building (MMBtu)	Buildings in MN	MN Savings Potential (Dth)	MN Savings Potential (MWh)	MN Savings Potential (Gbtu)	Self-install	Pro install
House (elec., zone 7)	55	-	2,874	10	24,300	-	69,838	238	5	8
House (elec., zone 6)	44	-	2,292	8	130,000	-	297,960	1,017	6	10
Medium Office	31	(406)	74,790	215	1,557	(63,218)	116,448	334	6	10
House (gas, zone 7)	55	130	18	13	140,300	1,823,900	2,525	1,833	14	23
House (gas, zone 6)	44	100	76	10	737,000	7,370,000	56,012	7,561	16	27
Quick Serve Restaurant	33	86	206	9	2,953	25,405	609	27	19	32
Midrise Apartment	28	599	2,834	70	12,500	748,340	35,424	869	20	33
Full Service Restaurant	27	126	311	14	1,594	20,046	496	22	23	39
Total					1,050,204	9,924,473	579,313	11,901		
Others w/Low-e panels (hotels, large office, one-story buildings)					29,156	516,595	26,341	606	Over 25 Years	
Others w/Clear panels (schools, healthcare)					3,643	619,473	36,251	743		
Total with payback over 25 years					32,799	1,136,068	62,593	1,350		

The house savings are broken down by climate zone (6 and 7) and heating fuel (electric and natural gas). Because there are not CIP programs for customers receiving delivered fuels (propane and fuel oil, which together are estimated to be used in 20% of all houses) those houses are not included, although their energy savings potential and payback is similar to the houses with electric resistance heating.

Non-Energy Benefits and Market Barriers

This report has focused on the energy saving aspects of window retrofits. These products also offer additional benefits which are discussed here. There are also aspects of the products that may be barriers to their wide-spread adoption; such as aesthetics, perception, and the current market environment.

A non-energy benefit of all the window retrofits is the reduction of ultra violet (uv) solar radiation. Lower levels of uv radiation lead to improved indoor air quality, because uv light causes chemical reactions of airborne materials that can create toxic and carcinogenic substances. Reducing uv light also help preserve interior surfaces and furnishings as uv light causes colors to fade and fabrics to become brittle. Window panels also reduce the build-up of condensation on interior window surfaces.

Interior window panels provide noise reduction, and that is currently their primary target market in many locations. They also offer a particular benefit to historic buildings which are often not allowed to change the appearance of their exteriors, forcing them to keep old inefficient windows and incur the associated high energy costs and uncomfortable interior conditions. Interior window panels allow the window performance to be improved without altering the exterior of the buildings (Frey, P. et al. 2012). Because many historic buildings have single pane windows with higher levels of infiltration, the window panel savings can be twice the savings estimated for the buildings in the present study. Churches with stained glass windows also are good candidates for interior window panels that allow the visual character of these windows to remain while reducing their energy loss.

A secondary energy benefit of window panels, which was not factored into our calculations, is that they can reduce the level of air infiltration of an existing window assembly. Because infiltration is caused by the way individual windows are installed as well as the structure of the window assembly, the reduction of infiltration will vary window to window. In some older houses, for example, infiltration associated with windows is a larger source of thermal losses than the radiative losses that are addressed by improving the U-factor. Case studies have measured a 10 to 15% reduction in whole house air leakage with the addition of storm windows (although these were on top of single pane windows) (Hefty, M.G., et al. 2013). A recent field study of window panels found that the measured savings were much higher than the calculated savings (19% actual vs. 10% expected); the author of this study postulates that the additional savings is due to the fact that increased comfort, primarily due to reduction of cold air drafts coming off of windows, allowed the homeowner to lower the temperature setpoint (Sailor, 2013).

Window panels and window films are not currently eligible for ENERGY STAR ratings which limits customer acceptance (the ENERGY STAR rating is seen a validation of savings claims). In addition window retrofits have not been eligible for financial incentives such as tax rebates. There is good reason for the lack of the ENERGY STAR designation under current definitions: it is based on the performance of the entire window assembly and it is not possible to guarantee that the final window assembly, including a retrofit, will meet ENERGY STAR standards because the condition of the existing window is unknown. The lack of the ENERGY STAR designation was cited by the Consortium on Energy Efficiency's residential working group as a significant barrier to market acceptance. The lack of ENERGY STAR status also meant that funds from the American Recovery and Reinvestment Act (ARRA, also known as the Federal Stimulus program) were not able to be used to pay for window retrofits, even though this report has shown that they can be as successful as window replacements in saving energy at a quarter to half the cost. In Minnesota approximately \$3.5 million of rebates were provided for residential window replacement projects with an average cost of \$9,484 house[17]. The rebates averaged 32% of the total project costs. In comparison, the average cost to retrofit a house with professionally installed low-e window panels was under \$2,500 and can have the same (or greater) energy savings potential.

One barrier to window panels is their product image. They are not generally viewed as enhancing the value of a building in the same way that replacement windows are. This perception is especially true with home owners and is a reason that remodeling contractors are unlikely to suggest window retrofits in place of window replacements. Window retrofits are also less profitable for contractors because of the lower total cost and need for less installation labor required. Some potential customers may have the perception that a window retrofit would be seen as a sign of a problem with the existing windows,

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[17] Data was not provided on window area per house; however if the 225 ft^2 average is used this is a cost of \$42/ft^2.

rather than as a sign of a more energy-efficient building. Interior window panels may interfere with operable windows, or be difficult to mount because there is not an unbroken plane inside the existing molding. For example, this occurs with existing casement windows - the window cranks are located in a place that makes the installation of a rectangular panel on the interior edge of the existing molding impossible. When window panels are installed to be removed seasonally (to have operable windows in the non-heating months) they need to be put on and taken off and stored annually, another potential disadvantage. In addition, the lowest cost window panels lack the level of finish that many consumers expect in their homes and those with plastic panels may be scratched by normal cleaning activities.

Window films that have low-e properties are shiny in appearance because they reflect both visible and infrared radiation. The picture of the office building in Figure 47 below shows the appearance of a building with highly reflective glass walls as an example. The majority of the low-e window film's reflectivity is in the non-visible regions of the spectrum (Figure 4), but there is also noticeable visible reflection. This is not a "look" that all consumers want for their windows. Another drawback of window films is that they cannot be installed on some windows that are partially shaded by an overhang or other solid object. When the shading creates a "line" across the window due to an overhang that shades the top portion of a window during the sunny hours of the day, for example, a temperature gradient is created in the glass at the sun shade line that can cause the glass to break. Professional installers are trained to avoid this problem, and it is a reason that film manufacturers require professional installation; they are concerned that inappropriate consumer applications will have potential failures that harm their brand image.

Figure 47. Normandale Lake Business Center, Bloomington, MN. Photo by CEE

Recommendations for Market Transformation

Few potential customers are aware of these retrofit products or the fact that they offer savings comparable to full window replacement at a fraction of the cost. We found that replacement windows cost three to ten times as much as window retrofits for the same (or smaller) energy savings. Both experience and research have shown that energy savings with window retrofits is persistent. The lifetime of a window panel is at least 15 years, with 25 years not unreasonable to expect. Applied window films have a shorter lifetime; they are warrantied for 10 to 15 years.

One recommendation is to provide education and information through reports like this one for window retrofits. Recently the Division of Energy Resource's Consumer Guide, *Home Envelope: an energy guide to help you keep the outside out and the inside in* (Minnesota Department of Commerce, Division of Energy Resources Staff. 2014) was updated to include window retrofits.

An additional way to increase market adoption of these products is through utility rebates. These are suggested primarily as a way to communicate utility confidence in the effectiveness of window retrofits to customers. For this reason, modest rebates are suggested for whole house retrofits. Because of the large range of savings seen in commercial buildings, we recommend that custom rebates be offered for them, based on calculations like those used in this report. Table 29 shows suggested rebates for residential customers: these vary by three factors: the retrofit selected the climate zone, and the primary heating fuel. Using current prices of $8.50/ Dth a natural gas rebate level of $5/Dth will shorten project paybacks by approximately half a year, an enhanced rebate of $10/Dth will reduce the payback period by just over one year. The enhanced rebate is shown in the table. Similarly, an electric rebate of $.045/kWh (based on $400/implied kW) will reduce the electric payback time by a little less than half a year. Because of the relatively short payback for those houses with electric heat, an enhanced rebate is not recommended.

The unit size for calculating the window retrofit rebates in the table below is 100 ft^2 of window area.

Table 29. Proposed utility rebates for residential customers.

Retrofit	**Climate Zone**	**Savings per 100 ft^2**	**Primary Heating Fuel**	**Rebate per 100 ft^2 of window area**
Low-e Window Panel (Interior or exterior)	6	4.3 Dth	Natural Gas	$34
		1,010 kWh	Electricity	$35
	7	5.6 Dth	Natural Gas	$34
		1,280 kWh	Electricity	$58
Clear Window Panel (Interior or exterior)	6	3.4 Dth	Natural Gas	$34
		785 kWh	Electricity	$35
	7	4.4 Dth	Natural Gas	$44
		1,005 kWh	Electricity	$45
Window Film A (Professionally installed)	6	1.3 Dth	Natural Gas	$13
		340 kWh	Electricity	$15
	7	1.8 Dth	Natural Gas	$18
		445 kWh	Electricity	$20

Potential Topics for Additional Research

Our report did not include emerging window retrofit technologies that are currently not readily available in the marketplace. A number of these may merit additional research in a few years. Some examples are electrochromic windows, custom window films that refract incoming sunlight to reduce glare and carry it further into a building (improving daylighting and reducing the need for lighting energy), rare gas window fills as a retrofit, and solar energy concentrators that can be placed between window panes (see Ulavi, T, et al. 2014). These and other new window technologies are discussed in greater detail in a recent report from the Department of Energy's Building Technology Office, *Energy Savings from Window Attachments* (Curcija, D.C., et. al. 2013). In addition, we did not find formal research on the savings potential of residential non-adhered plastic films (shrink wrap window kits) which are used seasonally; they were not included in this project because of the lack of persistent savings (they are designed to be discarded each year).

The computer simulations of commercial buildings using Energy Plus showed that some building types have much greater savings potential than others, even after building size and window area are taken into account. Field studies that measured the actual effects of these retrofits on building energy use, under controlled conditions, would be useful. These studies would lead to a better understanding of how window retrofits perform in real buildings and might also identify additional selection criteria for identifying projects with the best savings potential.

Conclusions

Energy modeling combined with literature sources was used to show that selected window retrofit products can provide energy saving in almost all Minnesota buildings. The savings are comparable to those provided by window replacements at a fraction of the cost. Retrofits are effective in all areas of the state (climate zones 6A and 7) and in buildings of all ages. Most consumers are aware that better windows can save them energy, but are unfamiliar window retrofit products. Above all, they are not aware that these products can effectively save as much (or even more) energy than replacement windows. Low-e window panels retrofits are suitable for the majority of windows in Minnesota, and can improve existing windows to a level that meets current ENERGY STAR standards. Market transformation efforts can help address this gap.

While heat loss is the dominant factor in energy performance of windows in Minnesota, solar heat gain reduces the need for heat energy in the winter months. Current window research shows that properly engineered windows can even be net energy sources for buildings. Energy modeling was used to study many combinations of retrofit products and building types; it was found that there is not one "best retrofit," because of individual building characteristics. Balancing the effects of solar heat gain and U-factor is different for various building types and should be considered in any new construction project. Computer simulations using WINDOW, THERM, COMFEN, RESFEN and EnergyPlus were successfully used with the Department of Energy's Reference Buildings to quantify the potential savings of five window retrofits (although problems were found in the models of schools and healthcare buildings and those results were removed from the results).

Existing buildings in Minnesota already have windows that perform substantially better than the national average, so the magnitude of savings provided by retrofits is smaller than in other regions of the US. It is estimated that over 95% of the 300 million square feet of windows in the state are double glazed. The savings from the best window retrofit, the low-e coated window panel, are comparable to those provided by triple pane windows.

The study included five window retrofits: two types of window panels and three kinds of applied window films. These products were chosen because they are readily available commercially and do not require frequent human intervention (unlike window shades, blinds, curtains or awnings). Three of these window retrofit products (i.e. low-e window panels, clear window panels and moderate SHGC low-e window film) are recommended for utility Conservation Improvement Programs (CIP), primarily in residential homes, because they will save energy for many years following their installation. Two did not lead to energy savings except in very site specific situations and are not recommended for general use in Minnesota.

Window panels were the most effective at saving energy. The magnitude of savings was independent of the placement of the panels (inside or outside of the existing window) and glazing material (glass or plastic) because the insulation value is provided by the air space added to the existing window system. The best savings were provided by low-e coated glass window panels (the current coating process only works on glass), 39 kbtu/ft^2 as a weighted average value (for all windows in all building types). The low-e coating reduces heat transfer so the savings are better than clear window panels, 31 kbtu/ft^2. The reduced heat transfer effectively improves the u-factor of the panel. The two types of window panels save energy in all building types.

Applied window films produced variable results depending on the direction the window faces (the most benefit is on east or west sides of buildings) and the type of building. There are only a small number of commercially available films with low-e coating currently sold, and two were studied, a moderate SHGC film (0.46 vs. 0.60 for the base window) and a low SHGC film (0.30). The film with moderate solar heat gain provided savings in most buildings, with a weighted average saving of 13 kbtu/ft^2. In contrast, the film with low SHGC led to an energy penalty in most cases, due to the reduction in passive solar heating during the winter months; the weighted average *increase* in energy use was 7 kbtu/ft^2 of building window area.

Tinted films, without a low-e coating, were also modeled because they are advertised as energy saving products. While they are effective in hot, sunny climates where solar heating causes increased cooling loads, in Minnesota they lead to *increased* heating requirements averaging 13 kbtu/ft^2. They are not recommended as a window retrofit to save energy in Minnesota.

In houses, low-e window panels reduced heating and cooling energy use by an average of 14%; clear panels by 11% and the applied low-e film with moderate SHGC by 5%. Electric resistance heating is used by about 12% of Minnesota houses, and these buildings can save up to $346 a year in northern Minnesota (climate Zone 7) by installing low-e window panels. In contrast for a house in zone 6 with natural gas heat and 20% fewer heating degree days, the annual savings is only about $91, leading to a 16 year payback for self-installation or 26 years if the panels are professionally installed.

The magnitude of savings for window panels was highest, between 30 and 40 kbtu/ft^2 of window area, in houses, office buildings, apartment buildings, schools, healthcare buildings and restaurants. Smaller savings of 10 to 20 kbtu/ft^2 were seen in one-story buildings and hotels had savings under 10 kbtu/ft^2. Overall, over 90% of the savings is due to reduced heating, regardless of building type. Cost savings does not track energy saving because of the large difference in cost between electricity and natural gas, leading to the occasional counterintuitive result that a product, like the low solar heat gain window film in medium office buildings, can save money and increase natural gas use at the same time. There is not a simple one-size fits-all solution: the retrofit that saves the most energy is not always the most cost-effective and the most effective retrofit (by either cost or energy savings) is different for different types of buildings.

The cost of window retrofits varies between $3 and $10 per square foot for self-installed products, with most between $3 and $7. Professionally installed applied window films cost between $7 and $20 per square foot, professionally installed window panels cost between $10 and $20 per square foot. These costs should be compared with replacement window costs that range from $34/ft^2 for a double pane high gain, low-e window (that will perform slightly better than an existing single pane window with a storm window over it) to $88/ft^2 for an ENERGY STAR triple pane window. Especially when self-installed, window retrofits will cost about 20% of the cost of replacement windows, and thus offer a good short term option for homeowners wishing to save energy and improve comfort while deferring the cost and inconvenience of window replacement until the existing windows have reached their full useful life.

There are a number of non-energy benefits of window retrofits, including the reduction of ultraviolet radiation which is linked to skin cancers and deterioration of furniture and fabrics. Window panels also provide noise reduction, decrease drafts off of existing windows, and reduce infiltration in some instances. The largest barrier that window retrofits face is the lack of awareness of their existence. Other barriers are some product attributes: window panels may make it harder to open otherwise operable windows, applied window films have a shiny appearance, and in certain installations window films have caused the window to will break because of thermal stress.

Incentives are recommended as a validation of the energy saving potential of the products, as window retrofits offer a way to meet a significant part of the state's energy savings goals. The largest contribution would come from houses, which have 80% of the total window area of all buildings. The impact of window retrofits in commercial buildings is dependent on the principal building activity (office, retail store; warehouse; school, health care, etc.), construction characteristics, and window orientation. The primary building activity is the most important factor because the activities produce differing amounts of internal heating and cooling loads.

Approximately 3.4 trillion Btu annually can be saved with window retrofits that pay back in 15 years or less (the economic potential). If the payback period is extended to 25 years, which is a realistic lifetime for a window, then 90% of the technical potential savings can be achieved, or almost 12 trillion Btu per year, which is 1.6% of Minnesota's annual residential and commercial energy use.

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Appendix A. Window retrofit manufacturers and suppliers

The list below includes a number of suppliers and manufacturers who offer window retrofit products. They are divided by retrofit type to match the report.

The list is for informational purposes only. These products have not been tested as part of this project and this listing is not an endorsement, and is not complete.

Window Panels: Glass

Larson Manufacturing Company. Available at Home Centers (Home depot, Lowe's, Menards)

QuantaPanel

Allied Window

For professional installation in commercial buildings: Maine Glass

Window Panels: Plastic

Climate Seal

Energy$avr

Advanced Energy Panels

Indow Windows

Magnetite

Applied Window Films

General Information can be obtained from the International Window Film Association.

Film A, the moderate gain, low-e film is available as Vista EnerLogic VEP70 SR CDF

Film B, the low gain, low-e film is available as 3M Amber 35 LowE

Film installers such as Russel Williams, Columbia Window Film,
For self installation (not NFRC rated): Gila

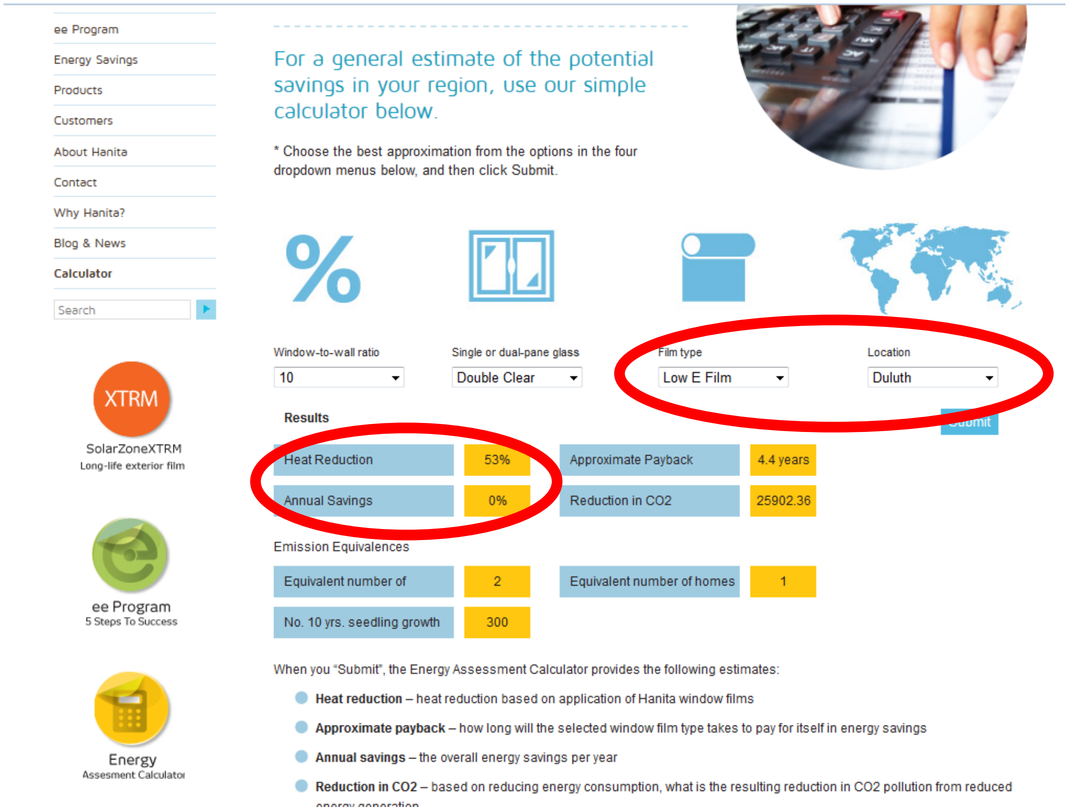
Appendix B. Resources for more information on modeling software

The software tools used in this project all have websites with supporting information, facilities to download the software itself, documentation and help. Many of them are available through the Windows and Daylighting Software tools website of Lawrence Berkeley Laboratory. They include:

Window 6	for analyzing window thermal and optical performance
THERM	for analyzing two-dimensional heat transfer through building products
Optics	for analyzing optical properties of glazing systems
International Glazing Database	Optical data for glazing products used by WINDOW 5.2 and Optics5.1 including NFRC approved products
COMFEN	A PC Program for calculating the heating and cooling energy use, and visual and thermal comfort, of commercial building facades.
EnergyPlus	whole building modeling software that enables building professionals to optimize the building design to use less energy and water
jEPlus 1.4	a simulation manager for EnergyPlus allowing multiple parametrics to be run in a batch
RESFEN	A PC program for calculating the heating and cooling energy use of windows in residential buildings for analyzing with

Appendix C. Examples of window energy savings calculators

Each of the calculators was filled out for a residential house in Duluth, where annual air conditioning costs are minimal. Our simulations show that both films included here require additional heating energy, which is not mentioned on either calculator.



For a general estimate of the potential savings in your region, use our simple calculator below.

* Choose the best approximation from the options in the four dropdown menus below, and then click Submit.

Window-to-wall ratio: 10
Single or dual-pane glass: Double Clear
Film type: Low E Film
Location: Duluth

Results

Heat Reduction	53%	Approximate Payback	4.4 years
Annual Savings	0%	Reduction in CO2	25902.36

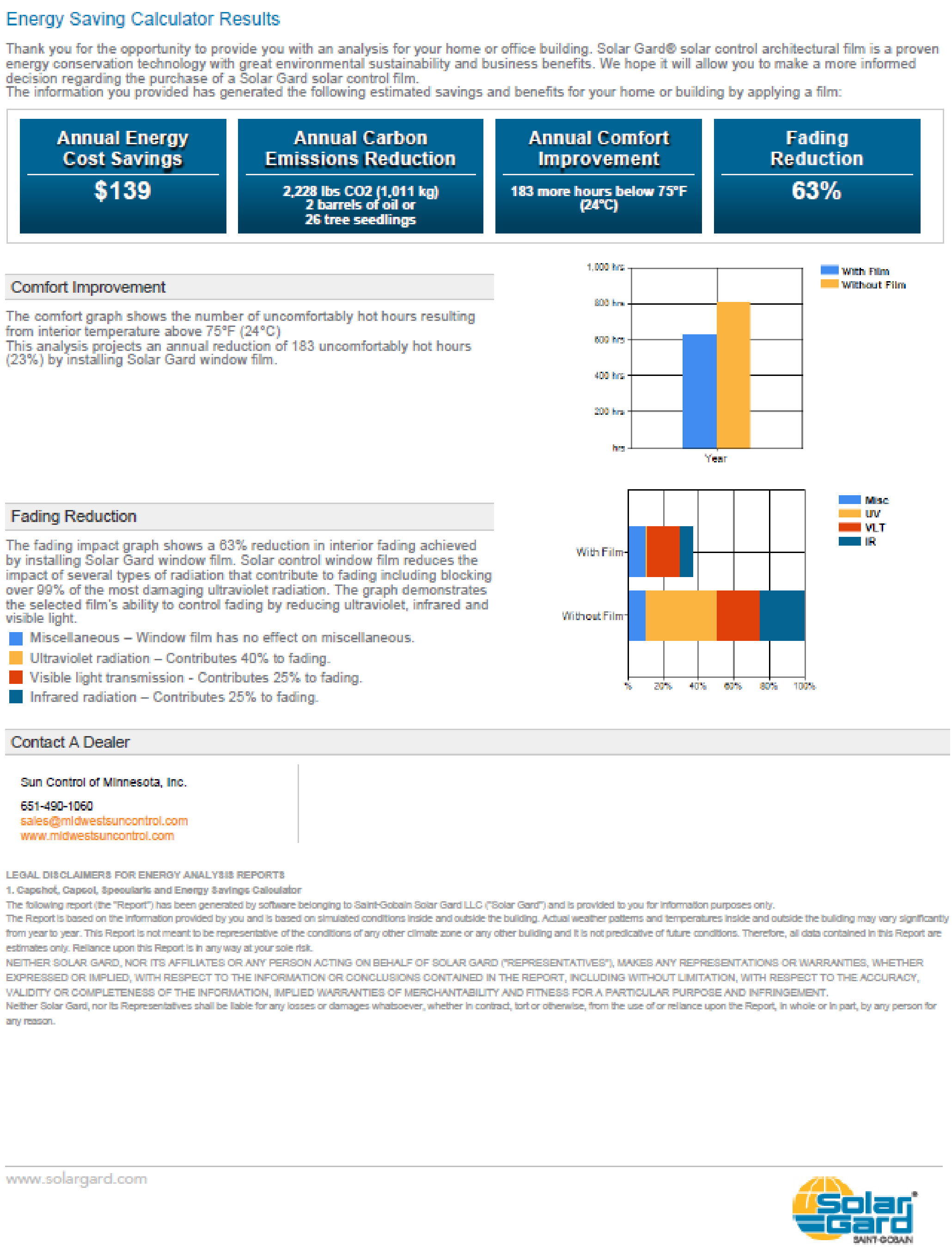
Emission Equivalences

Equivalent number of	2	Equivalent number of homes	1
No. 10 yrs. seedling growth	300		

When you “Submit”, the Energy Assessment Calculator provides the following estimates:

- **Heat reduction** – heat reduction based on application of Hanita window films
- **Approximate payback** – how long will the selected window film type takes to pay for itself in energy savings
- **Annual savings** – the overall energy savings per year
- **Reduction in CO2** – based on reducing energy consumption, what is the resulting reduction in CO2 pollution from reduced energy generation

This calculator shows a 53% heat reduction but 0% savings (so it is technically correct, but the claim of a 4.4 year payback with 0% savings means that savings is not paying for the project). The reduction in solar heating is year round, not just in summer. Source: Hanita Coatings Energy Assessment Calculator (http://www.hanitaenergy.com/energy-assesment-calculator)



Energy Saving Calculator Results

Thank you for the opportunity to provide you with an analysis for your home or office building. Solar Gard® solar control architectural film is a proven energy conservation technology with great environmental sustainability and business benefits. We hope it will allow you to make a more informed decision regarding the purchase of a Solar Gard solar control film.
The information you provided has generated the following estimated savings and benefits for your home or building by applying a film:

Annual Energy Cost Savings	Annual Carbon Emissions Reduction	Annual Comfort Improvement	Fading Reduction
$139	2,228 lbs CO2 (1,011 kg) 2 barrels of oil or 26 tree seedlings	183 more hours below 75°F (24°C)	63%

Comfort Improvement

The comfort graph shows the number of uncomfortably hot hours resulting from interior temperature above 75°F (24°C)
This analysis projects an annual reduction of 183 uncomfortably hot hours (23%) by installing Solar Gard window film.

Fading Reduction

The fading impact graph shows a 63% reduction in interior fading achieved by installing Solar Gard window film. Solar control window film reduces the impact of several types of radiation that contribute to fading including blocking over 99% of the most damaging ultraviolet radiation. The graph demonstrates the selected film's ability to control fading by reducing ultraviolet, infrared and visible light.

- Miscellaneous – Window film has no effect on miscellaneous.
- Ultraviolet radiation – Contributes 40% to fading.
- Visible light transmission - Contributes 25% to fading.
- Infrared radiation – Contributes 25% to fading.

Contact A Dealer

Sun Control of Minnesota, Inc.

651-490-1060
sales@midwestsuncontrol.com
www.midwestsuncontrol.com

LEGAL DISCLAIMERS FOR ENERGY ANALYSIS REPORTS

1. Capshot, Capsol, Specularis and Energy Savings Calculator

The following report (the "Report") has been generated by software belonging to Saint-Gobain Solar Gard LLC ("Solar Gard") and is provided to you for information purposes only.
The Report is based on the information provided by you and is based on simulated conditions inside and outside the building. Actual weather patterns and temperatures inside and outside the building may vary significantly from year to year. This Report is not meant to be representative of the conditions of any other climate zone or any other building and it is not predicative of future conditions. Therefore, all data contained in this Report are estimates only. Reliance upon this Report is in any way at your sole risk.
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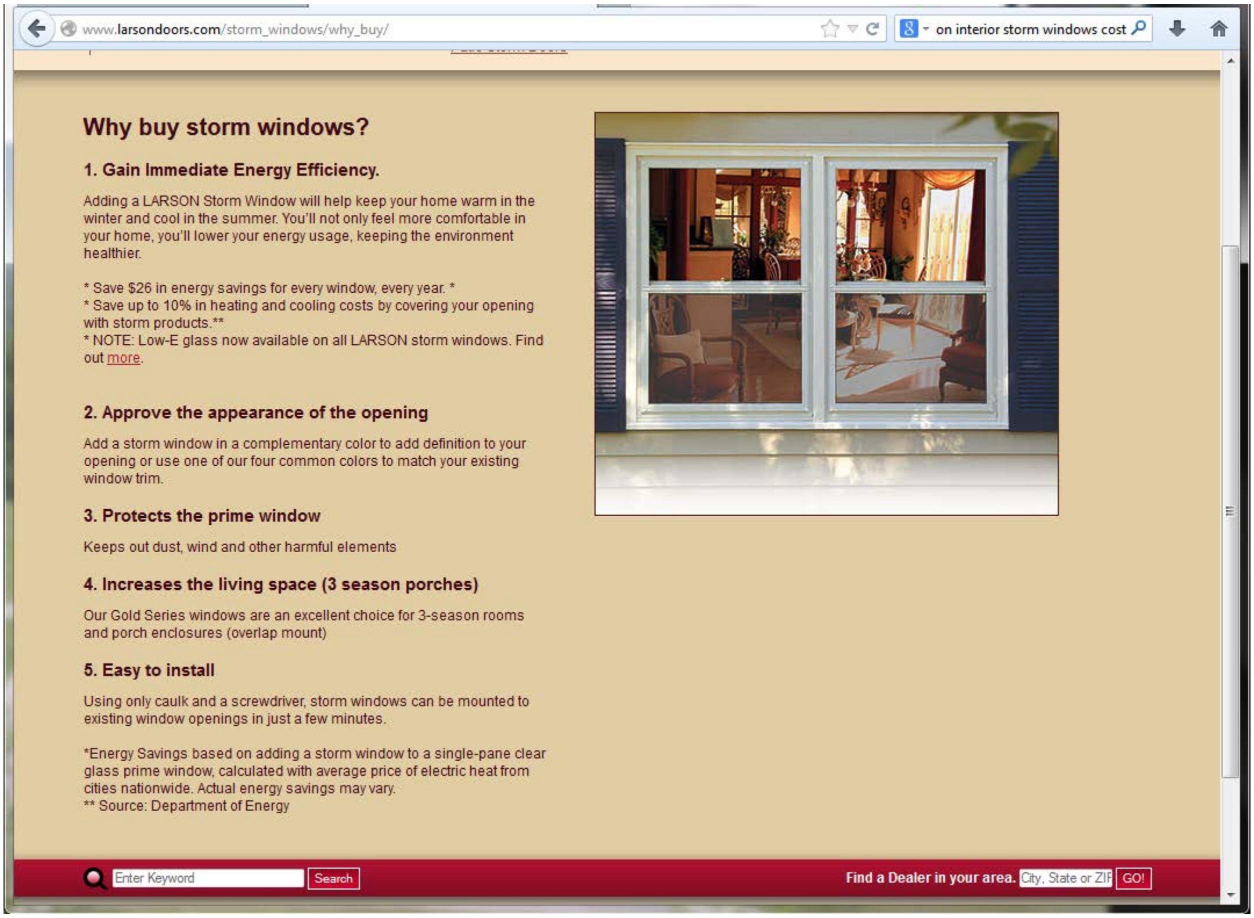
www.solargard.com

This is a calculator result for a 2,000 ft^2 home with 240 ft^2 of windows in Zone 6A area. The same house modeled using RESFEN in this report has an annual heating cost of $990; annual AC cost of $70. Savings seems too high given that they all come from reduced cooling (the film "increases hours below 75F"). Since the RESFEN results show that the cooling cost for this house is only $70 per year, it is unclear how savings of $139 could be achieved. Source: Solar Guard Energy Savings Calculator Results (**Error! Hyperlink reference not valid.**http://www.solargard.com/window-films/resources/energy-efficiency/energy-savings-calculator/EnergySavingsReport?cid=1839)



Why buy storm windows?

1. Gain Immediate Energy Efficiency.

Adding a LARSON Storm Window will help keep your home warm in the winter and cool in the summer. You'll not only feel more comfortable in your home, you'll lower your energy usage, keeping the environment healthier.

* Save $26 in energy savings for every window, every year. *
* Save up to 10% in heating and cooling costs by covering your opening with storm products.**
* NOTE: Low-E glass now available on all LARSON storm windows. Find out more.

2. Approve the appearance of the opening

Add a storm window in a complementary color to add definition to your opening or use one of our four common colors to match your existing window trim.

3. Protects the prime window

Keeps out dust, wind and other harmful elements

4. Increases the living space (3 season porches)

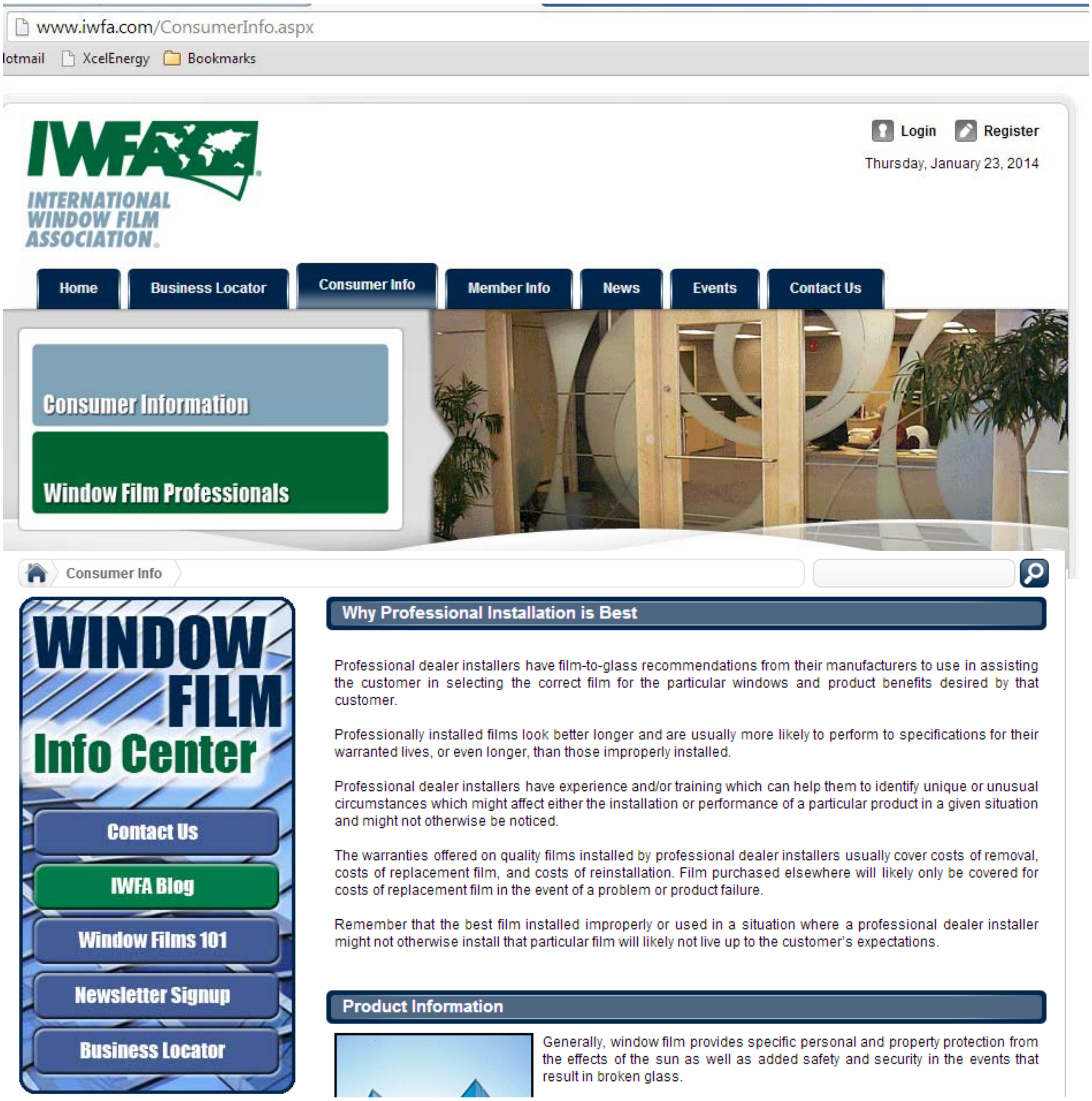
Our Gold Series windows are an excellent choice for 3-season rooms and porch enclosures (overlap mount)

5. Easy to install

Using only caulk and a screwdriver, storm windows can be mounted to existing window openings in just a few minutes.

*Energy Savings based on adding a storm window to a single-pane clear glass prime window, calculated with average price of electric heat from cities nationwide. Actual energy savings may vary.
** Source: Department of Energy

The savings quoted in this example are only true if the house has single pane windows and electric resistance heating. "Save $26 a year over single pane….based on all electric heat, national average prices."



Thursday, January 23, 2014

Why Professional Installation is Best

Professional dealer installers have film-to-glass recommendations from their manufacturers to use in assisting the customer in selecting the correct film for the particular windows and product benefits desired by that customer.

Professionally installed films look better longer and are usually more likely to perform to specifications for their warranted lives, or even longer, than those improperly installed.

Professional dealer installers have experience and/or training which can help them to identify unique or unusual circumstances which might affect either the installation or performance of a particular product in a given situation and might not otherwise be noticed.

The warranties offered on quality films installed by professional dealer installers usually cover costs of removal, costs of replacement film, and costs of reinstallation. Film purchased elsewhere will likely only be covered for costs of replacement film in the event of a problem or product failure.

Remember that the best film installed improperly or used in a situation where a professional dealer installer might not otherwise install that particular film will likely not live up to the customer's expectations.

Product Information

Generally, window film provides specific personal and property protection from the effects of the sun as well as added safety and security in the events that result in broken glass.

International Window Film Association Web Site: This section describes "why professional installation is best" and provides a list of the risks that come with do-it-yourself installations.

Appendix D. Additional information on the DOE Reference Buildings

Details, including the actual simulation software and building files, can be found on DOE's website under Commercial Reference Buildings (http://energy.gov/eere/buildings/commercial-reference-buildings):

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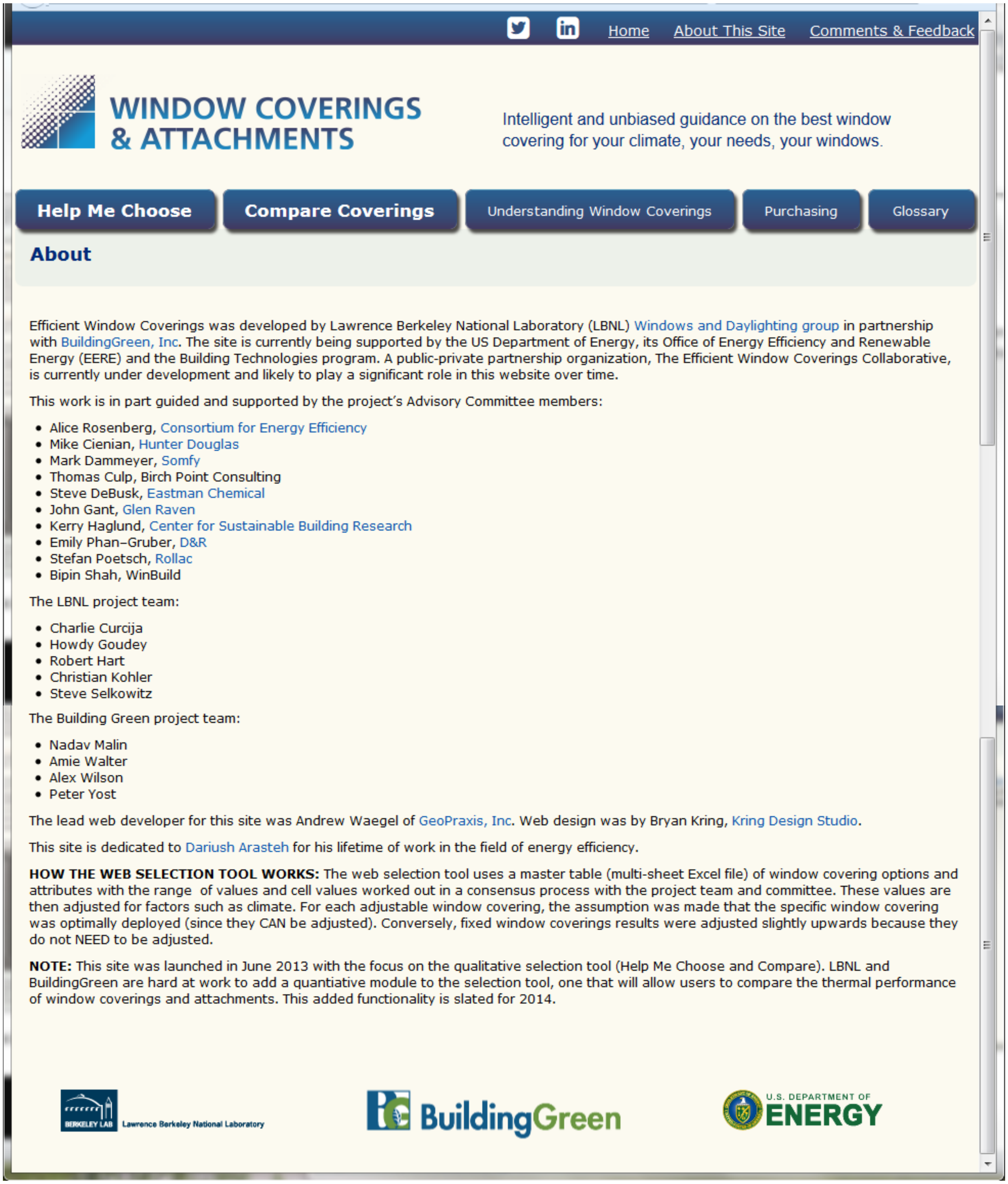
The individual model input categories are

Building Program	**Building Form**	**Building Fabric**	**Building Equipment**
• Location	• Number of floors	• Exterior walls	• Lighting
• Total floor area	• Aspect ratio	• Roof	• HVAC system type
• Plug and process loads	• Window fraction	• Floors	• Water heating equipment
• Ventilation requirements	• Window locations	• Windows	• Refrigeration
• Occupancy	• Shading	• Interior partitions	• Component efficiency
• Space environmental conditions	• Floor height	• Internal mass	• Control settings
• Service hot water demand	• Orientation	• Infiltration	
• Operating schedules			

Appendix E: Excerpts from efficient window coverings website

Source: Efficient Window Coverings website (http://www.efficientwindowcoverings.org/), developed by Lawrence Berkeley National Laboratory (LBNL) Windows and Daylighting group in partnership with Building Green, Inc. The site is currently being supported by the US Department of Energy.



Intelligent and unbiased guidance on the best window covering for your climate, your needs, your windows.

About

Efficient Window Coverings was developed by Lawrence Berkeley National Laboratory (LBNL) Windows and Daylighting group in partnership with BuildingGreen, Inc. The site is currently being supported by the US Department of Energy, its Office of Energy Efficiency and Renewable Energy (EERE) and the Building Technologies program. A public-private partnership organization, The Efficient Window Coverings Collaborative, is currently under development and likely to play a significant role in this website over time.

This work is in part guided and supported by the project's Advisory Committee members:

- Alice Rosenberg, Consortium for Energy Efficiency
- Mike Cienian, Hunter Douglas
- Mark Dammeyer, Somfy
- Thomas Culp, Birch Point Consulting
- Steve DeBusk, Eastman Chemical
- John Gant, Glen Raven
- Kerry Haglund, Center for Sustainable Building Research
- Emily Phan-Gruber, D&R
- Stefan Poetsch, Rollac
- Bipin Shah, WinBuild

The LBNL project team:

- Charlie Curcija
- Howdy Goudey
- Robert Hart
- Christian Kohler
- Steve Selkowitz

The Building Green project team:

- Nadav Malin
- Amie Walter
- Alex Wilson
- Peter Yost

The lead web developer for this site was Andrew Waegel of GeoPraxis, Inc. Web design was by Bryan Kring, Kring Design Studio.

This site is dedicated to Dariush Arasteh for his lifetime of work in the field of energy efficiency.

HOW THE WEB SELECTION TOOL WORKS: The web selection tool uses a master table (multi-sheet Excel file) of window covering options and attributes with the range of values and cell values worked out in a consensus process with the project team and committee. These values are then adjusted for factors such as climate. For each adjustable window covering, the assumption was made that the specific window covering was optimally deployed (since they CAN be adjusted). Conversely, fixed window coverings results were adjusted slightly upwards because they do not NEED to be adjusted.

NOTE: This site was launched in June 2013 with the focus on the qualitative selection tool (Help Me Choose and Compare). LBNL and BuildingGreen are hard at work to add a quantiative module to the selection tool, one that will allow users to compare the thermal performance of window coverings and attachments. This added functionality is slated for 2014.

Window Panels

Home About This Site Comments & Feedback

WINDOW COVERINGS & ATTACHMENTS

Intelligent and unbiased guidance on the best window covering for your climate, your needs, your windows.

Help Me Choose | Compare Coverings | Understanding Window Coverings | Purchasing | Glossary

Understanding Window Coverings : Interior Panel

Interior Panel

Description

Interior window panels function much like traditional exterior storm windows, adding an insulating layer to prevent heat loss from windows in cold weather, improving energy and comfort performance. The most common interior window panels are inexpensive, lightweight, clear plastic panels mounted in a frame sized to face-mount on the interior window casing or inset to mount on cleats installed in the window jamb. Low-e glass interior panels are also available. Interior window panels are much easier to install and remove than exterior storm windows, particularly on upper floors.

Interior window panels come in a variety of configurations to optimize performance for specific needs. They are typically installed in fall and removed in spring, but operable versions are available for year-round use. Ready-to-install panels as well as kits for do-it-yourselfers are available. Aluminum frames are most common, but some interior fixed window panels use steel, vinyl, or wood frames. Most include weatherstripping to ensure a relatively tight seal to the window casing or wall, and turnbuckles that secure the panels in place. Some steel-framed models use rubber-encased magnetic weatherstripping (like refrigerator gaskets) that hold the panels firmly in place without fasteners.

Plastic interior window panels are usually clear acrylic (e.g., Plexiglas®) or polycarbonate (e.g., Lexan®). Polycarbonate is stronger than acrylic but softer, so it scratches more easily. Acrylic used to yellow after a few years; today, ultraviolet (UV) inhibitors keep it clear for much longer. At least one interior panel is made with two layers of plastic, providing an additional air space for better insulating value (see www.windowattachments.org for product listings).

Interior glass window panels are heavier than plastic but more durable (although they can be broken), less likely to be scratched during cleaning, and available with low-emissivity (low-e) coatings that increase thermal insulation for improved energy efficiency and thermal comfort.

Terminology

The attachments described in this fact sheet are often called "interior storm windows," but that's a misleading term, since they really don't offer any storm protection. Here, we will refer to them as interior window panels.

Tracked interior window panels are just like exterior storms, but permanently installed on the inside of the window. With

Interior window panels can be tracked (as shown) just like exterior storms, or be fixed single panels. With integral screens, they adjust for ventilation. Made of glass, they are durable, clean easily, and are available with low-e coatings. Acrylic window panels are often face-mounted magnetically or inset with flexible, pressure-mount, perimeter gasketing.

Photo: Larson Manufacturing

When To Consider

- Historic codes, covenants, or condominium association rules preclude installation of exterior storm windows.
- Additional insulation needed for windows on upper floor where installation of exterior storm windows is difficult.
- Renters are reluctant to invest in more permanent window treatments, such as exterior low-e storm windows.
- Existing windows are leaky.
- Climate is moderate or cold and additional window insulation during heating season is desirable.
- Climate is hot, and interior window panel with solar heat gain control coating reduces need for interior cooling in warm season.
- Window egress is not an issue.

When to consider this retrofit—Ownership

✓	Homeowner
✓	Apartment Renter - Long Term
	Apartment Renter - Short Term
✓	Live in a Condo
✓	Live in a Historical District

When to consider this retrofit—Window conditions

Tracked interior window panels are just like exterior storms, but permanently installed on the inside of the window. With integral screens, they adjust for ventilation. Made of glass, they are durable, clean easily, and are available with low-e coatings.

Photo: BuildingGreen

Overall Thermal Performance

Interior window panels, when properly installed and deployed, bring a window's performance close to that of a double-paned clear window, by reducing air leakage and increasing thermal insulation. Interior glass window panels with low-e coatings bring a window's overall thermal performance close to the performance of a new double-paned low-e window.

When existing windows suffer from air leakage, a tight-fitting interior window panel helps prevent condensation in cold climates by reducing the moisture reaching the cold glass of the exterior prime window. As a result, condensation risk on either glazing layer is reduced. For hot humid climates, a tighter outer layer is preferable because the outer layer keeps most outdoor air and moisture from entering the air space between the layers. Condensation on the outermost glazing in a window assembly is more about obstructed view than durability.

Key Benefits

- Winter heat loss through windows reduced, comfort improved
- Condensation potential reduced with air tight panels
- Good visibility to the outdoors
- Noise control

Key Drawbacks

- Depending on installation system, may hamper egress (interior fixed panels)
- May require seasonal installation and removal, as well as storage when not in use (non-operable panels)

Aesthetics

- Most, but not all, panels are relatively unobtrusive

Tips/Cautions

- Clean windows and interior panels before installing.
- For interior plastic panels, use only cleaning agents appropriate for the type of glazing; ask manufacturer for cleaning recommendations.
- Label all panels for proper re-installation and allow space for seasonal storage.

When to consider this retrofit—Window conditions

✓	Existing window single-glazed
✓	Existing window double-glazed, no low-e*
	Existing window double-glazed with low-e

*low-emissivity coating

Recommended Installer

✓	Do it yourself
✓	Carpenter
	Manufacturer or supplier

Complementary Options

- Awnings or exterior roller shades or screens for controlling unwanted solar gain

Considerations

	1	2	3	4	5
Ease of Installation (1 = easier)		✓			
Availability (1 = more available)		✓			
Cost (1 = lower cost)	✓	✓			

Average Total Cost for 30- by 60-inch window

Plastic panels	$60
Low-e glass	$120

Energy Modeling Tools for Professionals

✓	RESFEN
	EnergyPlus
✓	WINDOW 6
	Other

References

"Measured Winter Performance of Storm Windows"
by Klems, J. Lawrence, Berkeley National Laboratory, 2003

Window Films

Intelligent and unbiased guidance on the best window covering for your climate, your needs, your windows.

Understanding Window Coverings : Applied Film

Applied Film

Description

State-of-the-art applied window films are designed to improve window performance by rejecting temperature increases from sunlight (solar heat gain), protecting against glare and ultraviolet (UV) exposure, offering a wide range of choices in the amount of light transmitted through the window (visible transmittance or VT), and in a few cases, increasing thermal insulation. Window films typically cannot be adjusted or readily removed. Because of the range of film types, there are products that are useful in almost every climate and for every window application.

Window films can be professionally applied by a skilled installer or are available for do-it-yourself projects at home improvement stores. Films are typically about 2–7 mils thick (50–175 microns) and come on rolls 36 to 72 inches (1–2 meters) wide. Films have a minimum of three layers: a pressure-sensitive or water-activated clear adhesive layer (against the glass), a polyester film layer, and a scratch-resistant coating. Films for safety/security function will be substantially thicker. A variety of other technologies that tune the film for different performance properties can be added to this basic configuration: tints, low-emissivity (low-e) coatings, and UV radiation blockers. Spectrally selective low-e coatings are preferred because they block some portions of the sunlight spectrum to reduce unwanted solar heat gain while allowing other portions of the spectrum to pass through the window, which maintains visibility. Some films absorb, rather than reflect, solar radiation. This reduces their effectiveness because the absorbed energy will heat the glazing surface and a portion of that energy will be transferred into the room. If the film is applied to the interior side of a window, this residual heat will be greater, negatively affecting the comfort for those in the room.

Rapidly developing window film technologies include low-e, thermo-chromic (changing transmittance with temperature), and electro-chromic (changing transmittance with an electric current) window films.

Reference Product		U-Factor		Solar Heat Gain Coefficient		Visible Transmittance	
Type	Glazing	W/O Film	With Film	W/O Film	With Film	W/O Film	With Film
Residential	Single Glazed Clear	1.09	1.01	0.71	0.40	0.74	0.57
	Double Glazed Clear	0.66	0.67	0.63	0.44	0.67	0.52
Non-Residential	Single Glazed Clear	1.02	0.93	0.72	0.43	0.78	0.60
	Single Glazed Gray	1.02	0.93	0.51	0.35	0.39	0.31
	Double Glazed Clear	0.60	0.53	0.62	0.47	0.69	0.54
	Double Glazed Gray	0.60	0.53	0.41	0.32	0.35	0.27

Manufacturer stipulates that these ratings conform to applicable NFRC procedures for determining whole product performance. NFRC ratings are determined for a fixed set of environmental conditions and a specific product size. NFRC does not recommend any product and does not warrant the suitability of any product for any specific use. Consult manufacturer's literature for other product performance information.
www.nfrc.org

Ⓐ This mark indicates that the product's energy performance has been rated and certified in accordance with NFRC's certification process.

Ⓑ This area is reserved for the name of the manufacturer and the product.

Ⓒ Consumers, building officials, and others should use the information in the Reference Product columns to choose the glazing system that most closely matches the product on which the film is applied.

Ⓓ U-factor measures how well a product prevents heat from escaping a home or building. U-factor ratings generally fall between 0.20 and 1.20. The lower the U-factor, the better a product is at keeping heat in. U-factor is particularly important during the winter heating season. This label displays U-factor in U.S. units. Labels on products sold in markets outside the United States may display U-factor in metric units.

Ⓔ Solar Heat Gain Coefficient (SHGC) measures how well a product blocks heat from the sun. SHGC is expressed as a number between 0 and 1. The lower the SHGC, the better a product is at blocking heat gain. Blocking solar heat gain is particularly important during the summer cooling season and in Southern climates.

Ⓕ Visible Transmittance (VT) measures how much light comes through a product. VT is expressed as a number between 0 and 1. The higher the VT, the higher the potential for daylighting.

Ⓖ This space provides details about NFRC's rating procedures.

NFRC's Window Film Energy Performance Label

Overall Thermal Performance

For a specific application, users can assess the amount of solar heat gain through a window with film based on the solar heat gain coefficient (SHGC) and visible transmittance (VT) rating listed on

Applied window films can be installed by do-it-yourselfers, but professional installation is recommended. After thorough and specialized cleaning, the installer will apply a solution to the window surface prior to rolling and squeegeeing the film.

Photo: Eastman Chemical Company

When To Consider

- Solar gain through existing window results in overheating or uncomfortable glare.
- Homeowner does not want to block key views with awnings or other window attachments that interfere with view.
- Home has large areas of glass that would be prohibitively expensive and/or awkward to replace or treat with other retrofits such as storm windows or insulating blinds.
- Homeowner is concerned about UV fading of artwork and furnishings near windows.

Where to use

- Sunny, clear-sky climates: medium to low SHGC and VT films
- Non low-e products: climates with moderate to significant cooling requirements
- Low-e products: all locations

When to consider this retrofit—Ownership

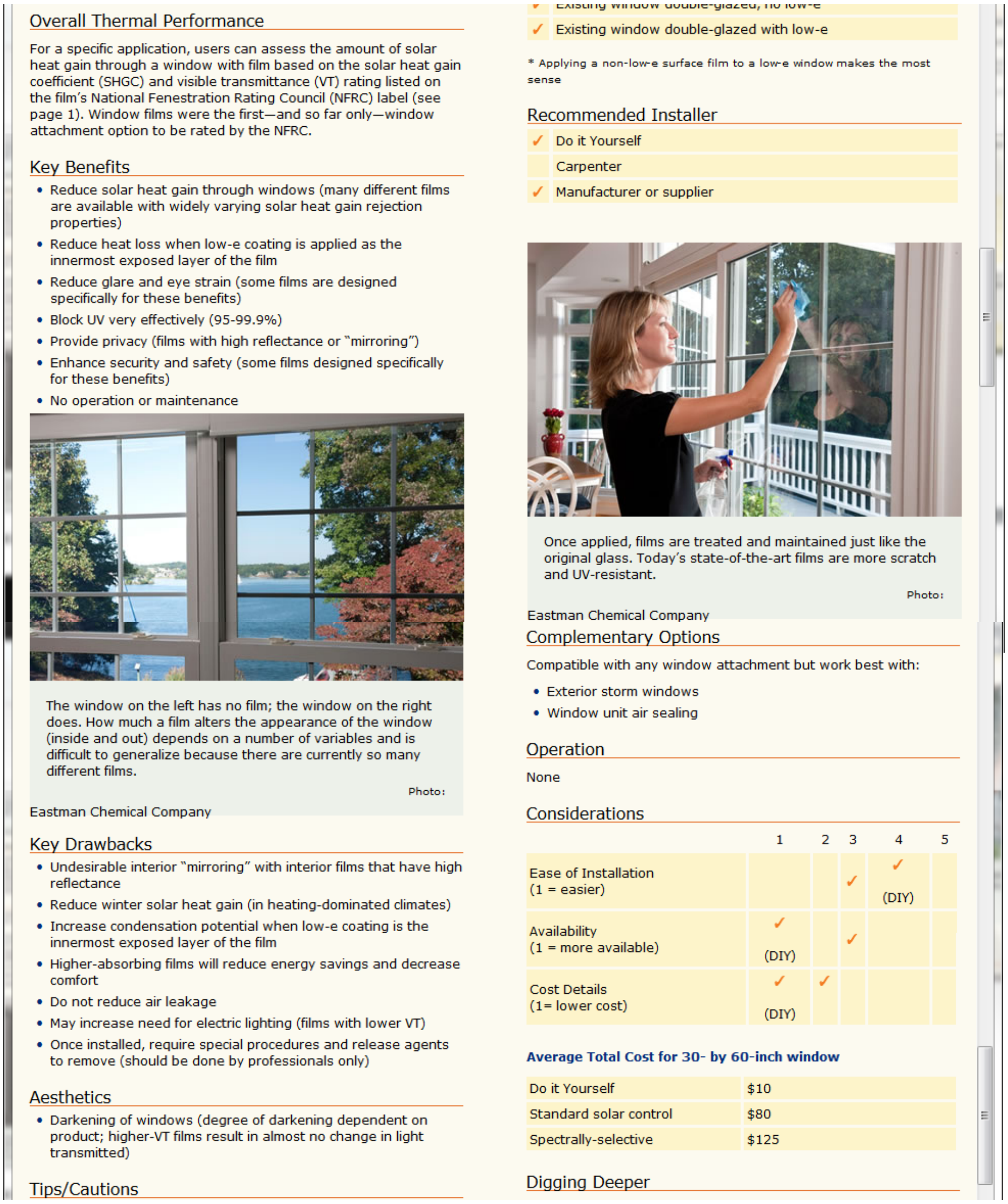
✓	Homeowner
	Apartment Renter – Long Term
	Apartment Renter – Short Term
✓	Live in a Condo*
✓	Live in a Historical District*

* Condominium regulations or historic building codes may require the use of higher-VT and lower-reflectance window films that maintain appearance from the outside.

When to consider this retrofit—Window conditions

✓	Existing window single-glazed
✓	Existing window double-glazed, no low-e*
✓	Existing window double-glazed with low-e

* Applying a non-low-e surface film to a low-e window makes the most sense



Overall Thermal Performance

For a specific application, users can assess the amount of solar heat gain through a window with film based on the solar heat gain coefficient (SHGC) and visible transmittance (VT) rating listed on the film's National Fenestration Rating Council (NFRC) label (see page 1). Window films were the first—and so far only—window attachment option to be rated by the NFRC.

Key Benefits

- Reduce solar heat gain through windows (many different films are available with widely varying solar heat gain rejection properties)
- Reduce heat loss when low-e coating is applied as the innermost exposed layer of the film
- Reduce glare and eye strain (some films are designed specifically for these benefits)
- Block UV very effectively (95-99.9%)
- Provide privacy (films with high reflectance or "mirroring")
- Enhance security and safety (some films designed specifically for these benefits)
- No operation or maintenance

The window on the left has no film; the window on the right does. How much a film alters the appearance of the window (inside and out) depends on a number of variables and is difficult to generalize because there are currently so many different films.

Photo:

Eastman Chemical Company

Key Drawbacks

- Undesirable interior "mirroring" with interior films that have high reflectance
- Reduce winter solar heat gain (in heating-dominated climates)
- Increase condensation potential when low-e coating is the innermost exposed layer of the film
- Higher-absorbing films will reduce energy savings and decrease comfort
- Do not reduce air leakage
- May increase need for electric lighting (films with lower VT)
- Once installed, require special procedures and release agents to remove (should be done by professionals only)

Aesthetics

- Darkening of windows (degree of darkening dependent on product; higher-VT films result in almost no change in light transmitted)

Tips/Cautions

✓	Existing window double-glazed, no low-e
✓	Existing window double-glazed with low-e

* Applying a non-low-e surface film to a low-e window makes the most sense

Recommended Installer

✓	Do it Yourself
	Carpenter
✓	Manufacturer or supplier

Once applied, films are treated and maintained just like the original glass. Today's state-of-the-art films are more scratch and UV-resistant.

Photo:

Eastman Chemical Company

Complementary Options

Compatible with any window attachment but work best with:

- Exterior storm windows
- Window unit air sealing

Operation

None

Considerations

	1	2	3	4	5
Ease of Installation (1 = easier)			✓	✓ (DIY)	
Availability (1 = more available)	✓ (DIY)		✓		
Cost Details (1= lower cost)	✓ (DIY)	✓			

Average Total Cost for 30- by 60-inch window

Do it Yourself	$10
Standard solar control	$80
Spectrally-selective	$125

Digging Deeper