# The National Energy Requirements of Residential Windows in the U.S.: Today and Tomorrow

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This paper describes an end-use analysis of the national energy requirements of U.S. residential window technologies. We estimate that the current U.S. stock of 19 billion square feet of residential windows is responsible for 1.7 quadrillion BTUs (or quads) per year of energy use—1.3 quads of heating and 0.4 quads of cooling energy—which represents about 2% of total U.S. energy consumption. We show that national energy use due to windows could be reduced by 25% by the year 2010 through accelerated adoption of currently available, advanced window technologies such as low-e and solar control low-e coatings, vinyl and wood frames, and superwindows. We evaluate the economics of the technologies regionally, considering both climatic and energy price variations, and find that the technologies would be cost effective for most consumers.

## INTRODUCTION

Windows are a defining feature of buildings. Traditionally, they have been regarded as large and unavoidable contributors to building space-conditioning energy use. In the winter, they lose heat disproportionately to the environment compared to walls. In the summer, they allow unwanted heat from the sun to pass into conditioned areas. In both seasons, purchased energy to operate space-conditioning equipment is required to maintain comfort indoors. However, recent technological improvements hold the promise of drastically reducing or eliminating purchased energy requirements attributable to windows.

This paper describes an analysis of the national energy requirements of residential windows both today and under two scenarios for the future: (1) no change to current market share of available window technologies; and (2) accelerated adoption of advanced window technologies. The future market shares of technologies will, of course, be influenced by a variety of public and private actions; it is not our intent to predict the effects of any particular action. The two future scenarios, instead, serve to bound the range of possible impacts from policies, regulations, programs, or actions on the market shares of various window technologies over the next fifteen years.[1] In order to provide a basis for thinking about potential policies, we also present an analysis of the cost effectiveness of advanced window technologies.

This paper is organized as follows. For readers less familiar with the physical properties of windows that influence energy use and recent technological improvements to improve window energy performance, we provide a quick overview with references to more comprehensive technical treatments in the next section. For readers interested in the method used to estimate the national energy requirements of windows, we then summarize the major analytical steps and underlying methodological assumptions used to combine information on the physical properties of windows and their space-conditioning energy requirements with information on the current national stock and sales of windows. Next, we present our estimates of today's and possible future national energy requirements of residential windows. Finally, we present an economic analysis of the cost effectiveness of advanced window technologies in different regions of the country. We conclude with a short summary of our overall findings.

## WINDOW ENERGY USE TERMINOLOGY AND ADVANCED TECHNOLOGIES

This section provides a brief introduction to recent technological advances in the energy performance of windows. We begin by defining the technical terms used to characterize window energy performance.

### Characterizing the Energy Performance of Windows

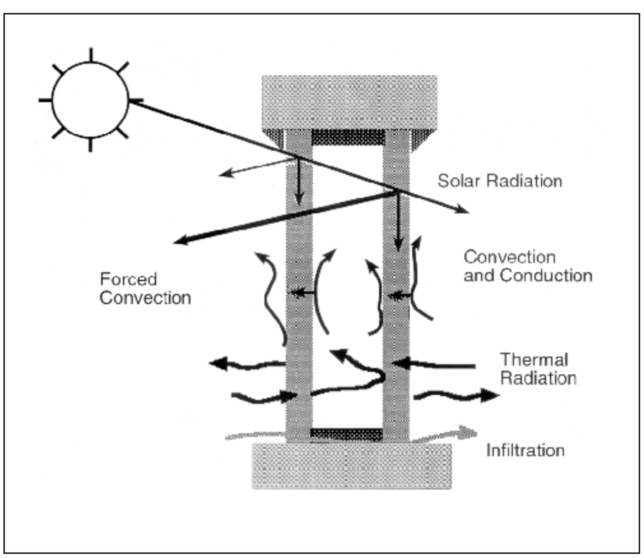
Windows are a critical part of the envelope that separates the indoor environment of buildings from the outdoors. In order to maintain a comfortable indoor environment, energy gained or lost through windows must be compensated for by mechanical means, such as furnaces for heating or air conditioners for cooling. Energy is transferred across windows by one of three distinct physical mechanisms (see

Figure 1): (1) as heat passing through the glass and frame of a window (thermal conductance, including convection, conduction, and thermal radiation); (2) as sunlight passing through the glass into the indoor space (solar radiation or transmittance); and (3) as hot or cold air leaking through cracks or openings at the edges of the glass or within the frame of the window (infiltration).

*Thermal conductance* actually consists of three linked forms of heat transfer, conduction through the materials of the window, forced and natural convection at the inner and outer surfaces of the window, and thermal radiation also from the surfaces of the window. Thermal conductance is measured by a total heat transfer coefficient or *U-value*, which accounts for the combined effect of all three heat transfer mechanisms. U-values are expressed in units of Btu/hr-ft$^2$-F (W/hr-m$^2$-C in SI). The smaller the U-value, the lower the rate of heat transfer.[2] A low U-value is of primary importance in cold climates because energy lost through windows is a major contributor to heating energy requirements. In hot climates, low U-values are comparatively less important because cooling requirements are dominated by the need to remove the unwanted heat passing through windows as sunlight.

The energy contained in sunlight passes through windows both as visible light and heat.[3] If it is not reflected back out of an interior space, it is converted to heat. If the added heat is in excess of other heat losses, it must be removed by air-conditioning equipment. Unwanted heat gains from solar radiation are the dominant contributor to the cooling energy requirements associated with windows. The ability of a window to pass solar radiation into an indoor space is measured by the *solar heat gain coefficient* or *SHGC*. The SHGC is expressed as a ratio of the amount of solar radiation passing through a window relative to the amount solar radiation incident upon the window.[4]

***Figure 1.*** *Modes of Heat Transfer Through a Window*




Air leaks into and out of indoor spaces through cracks or other air passages in the sash and frame of a window driven by air pressure differences between both sides of the window. The *air-leakage rate* or *AR* is a measure of the net flow of air through a window. AR is expressed in cubic feet per minute per square foot (or linear foot) or cfm/ft$^2$ (in SI, meters cubed per hour per square meter or m$^3$/hr.m$^2$). The air-leakage rate for windows is particularly important for residential buildings in heating climates; it can account for 5% of the heating requirements of a residence. Unlike the previous measures of window energy performance, air-leakage rates depend primarily on the installation of a window, rather than on its design.

While there is universal agreement on the mechanisms of heat loss/gain through windows, the window industry has only recently begun to adopt common procedures to represent the individual factors influencing window energy use. These procedures have been developed and are currently being promulgated by the National Fenestration Rating Council or NFRC, which is a voluntary association of glass and component manufacturers, window fabricators, utilities, state and federal agencies, and window experts (Arasteh et al. 1994). Universally accepted and reliable metrics of window energy performance are clearly an important prerequisite for informed window purchase decisions as well as for public policies to promote the adoption of better windows.

## Recent Advances in Window Technologies to Improve Energy Performance

Advanced technologies to reduce the energy lost or unwanted (solar) energy allowed to pass through windows were developed and commercialized in the late 1970s. Market adoption of these innovations has already led to a halving of the energy requirements of new windows sold today compared to those sold in the 1970s. This sub-section, adapted from Arasteh (1995), reviews six technological measures that, in appropriate combinations, can dramatically reduce or even eliminate the energy use requirements attributable to windows.

*Low-emissivity (or low-e) coatings* drastically reduce long-wave radiative heat transfer between glazing layers. The net result is a 20%-35% reduction in the U-values of glazed areas. They also reduce solar transmission in the ultraviolet or UV range of the spectrum (which may reduce damage to room furnishings) as well as bring the glass surface temperature closer to the ambient temperature (and thus increase comfort near the window and reduce condensation).

*Solar control low-e coatings and solar control tints (also known as spectrally selective coatings or tints)* are two means for reducing the amount of solar radiation that is allowed to pass through a window. Solar control low-e coatings reflect incoming, invisible solar infrared radiation, which is where the bulk of the direct heat from solar radiation lies. Solar control tints both reflect and absorb incoming solar radiation. Both can effectively halve a window's SHGC.

*Low-conductivity gas-fillings* reduce the thermal conductance between glazing layers in insulating glass units. Argon is the most common low-conductivity gas used in insulating glass units. Krypton is more expensive but is roughly twice as effective.

*Vinyl and other low-conductivity frames* reduce thermal losses through the frame. Vinyl, which has at least as low a thermal conductivity as wood, is often less expensive than aluminum with thermal breaks and therefore represents a very cost-effective alternative to aluminum frames.

*Low-conductivity spacers* between glazing layers help eliminate edge-of-glass thermal conduction effects caused by metal spacers.

*Suspended films* between glazing layers in a window are a simple way to create a window with three or more glazing layers without the weight of additional layers of glass. The suspended films are often combined with low-e coatings to produce a window with very low U-values.

These six technologies can be used independently or in combination with one another. When combined to produce a window with less than half the thermal conductance of a wood-framed, double-glazed window, they are sometimes referred to as superwindows (Arasteh & Selkowitz 1989). In heating climates, superwindows can convert a window from a net energy loser to a net energy gainer. That is, the modest amount of heat these windows lose to the outdoors is more than offset by the solar radiation they pass into a space; the net result is a reduction in the need for mechanical heating.

For this report, we examine the impacts on national energy requirements resulting from widespread adoption of a broader class of windows, which we call *energy-efficient windows*. Our definition is climate-dependent. A superwindow will be considered an energy-efficient window for northern, heating-dominated climates, while a different window with solar control features will be considered an energy-efficient window for southern, cooling-dominated climates.

## FROM INDIVIDUAL WINDOWS TO NATIONAL ENERGY REQUIREMENTS: AN END-USE APPROACH

This section provides a brief overview of an evolving method we are developing to estimate the national energy requirements attributable to windows.[5] The method is a ''bottom-up'' or end-use approach that involves two major steps. We begin by developing regional estimates of the heating and cooling energy requirements attributable to individual window types (e.g., double-glazed with a wood or vinyl frame, double-glazed low-e with a wood or vinyl frame, etc.). We next combine this information with regional estimates of the current portion of stock represented by each type of window to develop regional and national estimates of energy use.

### Estimating the Energy Requirements of Windows

We estimated the energy requirements of individual window types as follows: First, we defined a set of representative windows whose energy performance characteristics span the range of currently available windows (including energy-efficient windows). Second, we estimated the energy performance of the windows for a variety of climates representative of the U.S.

**Window energy performance characteristics.** We represented the current stock of residential windows using 19 distinct window types (see Table 1). In order to compare the performance of windows consistently, we modeled each type assuming a standard size and configuration. We then calculated each window's energy performance characteristics using WINDOW 4.0, which embodies the reference procedures adopted by the NFRC window performance rating system (Windows and Daylighting Group 1994).

We assumed that all windows were the standard size assumed by the NFRC rating system for residential windows (3 feet by 5 feet). We assumed all wood and vinyl frame widths were 2¾″, while all aluminum frame widths were 1 ½″. We assumed all glass was ⅛″ thick and, for insulating glass units, a glazing separation of ½″. Storm windows were treated as an extra glazing layer. The final derivation of representative U-Values and SHGCs was based on aggregations over individual, underlying window types (e.g., single hung, slider, casement, etc.), which we first weighted by the current sales.

**Window energy performance.** We estimated window energy performance using RESFEN, which is a reduced-form model developed from regression analyses of thou-

*Table 1. Residential Window Prototypes*

| Frame Type | Glazing Type | U-Value | SHGC |
|---|---|---|---|
| Wood/Vinyl | Single | 0.93 | 0.69 |
| | Double | 0.49 | 0.62 |
| | Double plus Low-e/Ar | 0.34 | 0.48 |
| | Triple | 0.38 | 0.54 |
| | *Double plus Solar Control Low-e/Ar* | 0.32 | 0.35 |
| | Single Tinted | 0.90 | 0.50 |
| | Double Tinted | 0.48 | 0.40 |
| | *Super Window* | 0.24 | 0.40 |
| Aluminum w/ Thermal Break | Single | 1.10 | 0.78 |
| | Double | 0.60 | 0.72 |
| | Double plus Low-e/Ar | 0.42 | 0.58 |
| | Triple | 0.46 | 0.64 |
| | Single Tinted | 1.07 | 0.56 |
| | Double Tinted | 0.59 | 0.46 |
| Aluminum w/o Thermal Break | Single | 1.23 | 0.84 |
| | Double | 0.73 | 0.76 |
| | Triple | 0.60 | 0.68 |
| | Single Tinted | 1.21 | 0.61 |
| | Double Tinted | 0.73 | 0.54 |

Notes: U-Value and SHGC are whole-window values calculated using Window 4.0 and standard assumptions about frame and glazing dimensions. Energy-efficient windows assumed in the efficient-windows scenario are *italicized*.

sands of DOE-2.1e simulations for ten U.S. cities (Windows and Daylighting Group 1995).[6] We used the RESFEN model to energy use for each window type using a single representative residential structure (1,540 square feet). We modeled window energy impacts as an average over four orientations (north, east, south, west) and as an average of four different shading types modeled in RESFEN (none, obstruction, overhang, and interior shade). Window area is 15% of floor area or about 230 square feet of window per house.

We estimated energy use for windows separately for twelve U.S. regions using either a single or a weighted average of the ten base cities included in RESFEN (see Table 2). We used the Energy Information Agency (EIA) residential energy consumption survey (EIA 1995) to develop information on the penetration of different heating, ventilating, and air conditioning (HVAC) equipment and on heating fuel choice. We used HVAC equipment efficiencies developed by Hanford and Huang (1993). Finally, we also used calibration

***Table 2.*** *RESFEN Model Cities Associated with Regions of Study*

| Region | RESFEN City Used |
|---|---|
| New England (NE) | Boston |
| Mid Atlantic (MA) | 2/3 Boston + 1/3 DC |
| East North Central (ENC) | Madison |
| West North Central (WNC) | 2/3 Madison + 1/3 Denver |
| South Atlantic (SA) | 1/2 Atlanta + 1/2 DC |
| Florida (FL) | 1/2 Atlanta + 1/2 Miami |
| East South Central (ESC) | 1/2 Atlanta + 1/2 Miami |
| West South Central (WSC) | Lk Charles |
| Mountain North (MN) | 2/3 Denver + 1/3 Madison |
| Mountain South (MS) | Phoenix |
| Northwest (NW) | Seattle |
| California (CA) | 67% LA + 18% Seattle + 7% Phoenix |

Notes: Fractions refer to fractions of regression coefficients added together to develop a hybrid regression coefficient more reflective of the particular region. The California (CA) values are based on a more detailed analysis of maps of CDDs, HDDs, and population weights; they do not sum to 100%.

factors developed by Hanford and Huang (1993) to reconcile RESFEN-predicted energy use with the totals developed by EIA.

## Estimating the National Energy Requirements of Windows

We estimated the national energy requirements of windows as follows: First, we estimated the size and composition of the current stock of windows. Second, we forecasted annual additions to and retirements from the stock. At the end of each step, we mapped the energy requirements of individual windows (described previously) to the total number and distribution of window types in each of the twelve regions. We also used this mapping to model various scenarios of future window energy use by holding the rate of overall window retirements and additions fixed, but changing the mix of window technologies sold.

We relied extensively on prior efforts in order to develop the information required for this phase of the analysis. Information on the size and composition of the stock and sales come from a variety of industry (e.g., American Architectural Manufacturers Association 1994) and government sources (e.g., EIA 1995).

**The current stock and sales of U.S. residential windows.** We estimate that, as of 1994, there were 19 billion square feet of windows in the U.S. residential sector (see Table 3). Annually, about 0.5 billion square feet of windows are sold. Sales are divided almost equally between replacement or remodeling in existing homes and new construction.

Figures 2, 3, and 4 present information on the regional distribution of the current stock of frame materials, numbers and types of glazing layers, and types of glazing coatings. Note that double-glazed includes both double-glazed insulating glass units and single-glazed units with storm windows. Similarly, triple-glazed includes triple-glazed insulating glass units, double-glazed units with storm windows, and insulating glass units with suspended films.

**Table 3.** *1994 Residential Window Stock and Sales*

| Region | (Billion sf) | Stock Mean U-Value | Mean SHGC | (Million sf) | Sales Mean U-Value | Mean SHGC |
|---|---|---|---|---|---|---|
| New England (NE) | 1.15 | 0.54 | 0.64 | 32 | 0.44 | 0.55 |
| Mid Atlantic (MA) | 3.00 | 0.57 | 0.65 | 84 | 0.44 | 0.55 |
| East North Central (ENC) | 3.66 | 0.55 | 0.64 | 102 | 0.44 | 0.55 |
| West North Central (WNC) | 1.42 | 0.54 | 0.64 | 40 | 0.43 | 0.54 |
| South Atlantic (SA) | 2.24 | 0.79 | 0.66 | 63 | 0.53 | 0.56 |
| Florida (FL) | 1.00 | 0.87 | 0.70 | 28 | 0.61 | 0.59 |
| East South Central (ESC) | 1.17 | 0.81 | 0.68 | 33 | 0.56 | 0.58 |
| West South Central (WSC) | 2.06 | 0.81 | 0.68 | 58 | 0.56 | 0.58 |
| Mountain North (MN) | 0.52 | 0.83 | 0.70 | 15 | 0.53 | 0.60 |
| Mountain South (MS) | 0.29 | 0.85 | 0.68 | 8 | 0.55 | 0.57 |
| Northwest (NW) | 0.62 | 0.89 | 0.74 | 18 | 0.53 | 0.59 |
| California (CA) | 2.08 | 0.90 | 0.74 | 58 | 0.55 | 0.61 |
| U.S. Total | 19.21 | 0.70 | 0.67 | 538 | 0.50 | 0.57 |

**Figure 2.** *1994 Residential Stock—Frame Material*

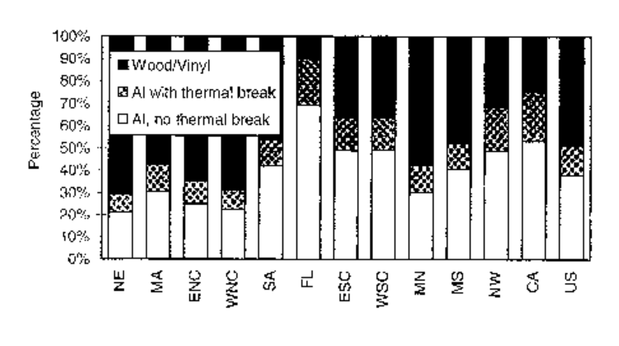
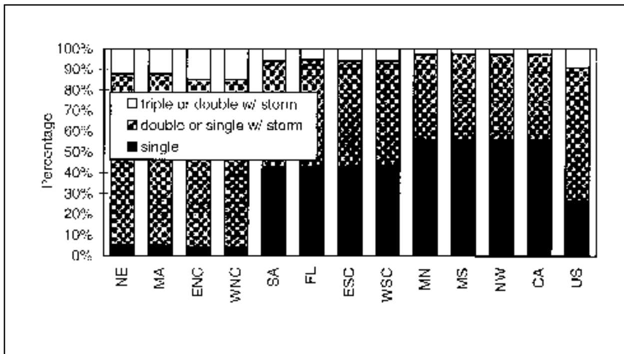


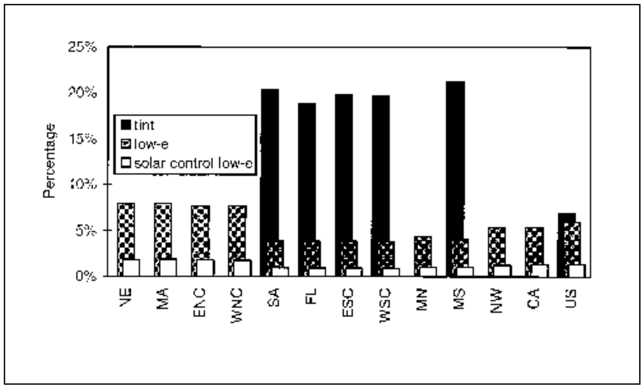

**Figure 3.** *1994 Residential Stock—Glazing Layers*




Regional practices vary, leading to significant differences in the stock of windows. The use of multiple-glazing layers, storm windows, and more insulating vinyl and wood frames is concentrated in the Northeast and Midwest regions. The use of tinted glazing is very prevalent in the southern regions.

On a national basis, the U-values of new windows sold is about 30% better than the stock. Over the past decade, the use of vinyl frames has increased dramatically. Sales of low-e coatings, too, have also increased, although the use of low-e coatings appears to have leveled out at about 30% of sales in the past four years.

*Figure 4. 1994 Residential Stock—Glazing Coatings*




### Forecast Additions to and Retirements from the Stock of U.S. Residential Windows

We made the following assumptions in developing our forecast. First, we assumed that windows have a mean life expectancy of 35 years. This assumption is equivalent to assuming that the entire stock of windows is either replaced or retired after 35 years. Second, we assumed that growth in sales of new windows would increase at the rate of 1%/year.

## THE NATIONAL ENERGY REQUIREMENTS OF RESIDENTIAL WINDOWS IN THE U.S.

We present our findings in two parts. First, we present our estimate of U.S. residential energy use today. Second, we present our results for two future scenarios of window energy use.

### Residential Window Energy Use Today

We find that residential windows are responsible for 1.7 quads[7] per year in primary energy use at a cost of $9.3 billion annually (see Table 4). The energy requirements consist of 1.3 quads heating and 0.4 quads cooling. In terms of energy intensity (i.e. energy use per square foot of glass), the current stock of windows is responsible for about 89 kBtu/ft$^2$.yr of primary energy use (or $ 0.5 per square foot of window area), while windows currently being sold are responsible for about 65 kBtu/ft$^2$.yr of primary energy use.

These results update previous findings presented in our earlier work (Frost et al. 1993). Table 5 summarizes the improvements we have made to the method presented in this earlier work.

### Residential Window Energy Use Tomorrow

We examined two scenarios for residential window energy in the year 2010. In the first scenario, we assumed that the current market shares of the various windows technologies would not change between 1994 and 2010. We refer to this scenario as the ''frozen'' efficiency case. In the second scenario, we assumed that only the most energy-efficient, currently available windows (i.e., ''energy-efficient windows,'' as indicated in Table 1, which today represent about 10% of new windows sales) are sold between 1994 and 2010. As described earlier, it is unrealistic to assume either that the market shares for existing windows will not change or that today's most energy-efficient windows will capture 100% of the market. For example, we do not consider the effect of even more efficient windows that are not yet available in the market.

Under the first scenario, we estimate that national energy requirements of windows will be essentially unchanged (see Table 4). While the total stock of windows will increase, total energy use is nearly offset by the increased energy efficiency of new windows entering the stock (i.e., some residences and their windows leave the stock, some older windows are replaced by newer more efficient ones, and all new construction consists of new windows). On net, we estimate heating primary energy use requirements of 1.3 quads with a slight increase in cooling requirements of 0.5 quads. Since we would expect the market share of more efficient windows to increase from that of today, this estimate provides an upper bound on the future national energy requirements of windows.

Under the second scenario, we estimate that the national energy requirements of windows would drop by 25%. Heating primary energy requirements fall to 1.0 quads; cooling primary energy requirements fall to 0.3 quads.

## THE ECONOMICS OF ADVANCED WINDOW TECHNOLOGIES

In considering the energy savings from various market share assumptions for advanced window technologies, the issue for public policy is whether the market for windows is functioning adequately. In this section, we present an economic analysis of advanced window technologies as one source of evidence on the functioning of this market.

For each region, we compare the energy operating cost of the ''energy-efficient'' window to the energy operating cost of the most popular window currently sold in each region. We took regional energy prices from EIA (1992) and projected them into the future using forecasts in EIA (1995). Separate calculations were made assuming different heating

*Table 4.* *Residential Sector Results*

| | Overall | | | | Per Square Foot | | | |
|---|---|---|---|---|---|---|---|---|
| | Heating quads/yr | Cooling quads/yr | Total quads/yr | Energy Bills $billion/yr | Heating kBtu/ sqft.yr | Cooling kBtu/ sqft.yr | Total kBtu/ sqft.yr | Energy Bills $/sqft.yr |
| 1994 Stock | 1.30 | 0.44 | 1.74 | 9.3 | 66 | 23 | 89 | 0.49 |
| 1994 Sales | n/a | n/a | n/a | n/a | 45 | 20 | 65 | 0.36 |
| 2010 Stock if market shares frozen at 1994 levels | 1.28 | 0.49 | 1.76 | 9.6 | 57 | 22 | 78 | 0.43 |
| 2010 Stock if only energy-efficient windows sold | 0.97 | 0.30 | 1.27 | 6.7 | 43 | 13 | 56 | 0.30 |

fuels and systems, as well as the presence or absence of central air conditioning.

Window pricing is very competitive and generalizations are difficult to defend. Much depends on regional circumstances and on purchase quantities. We chose not to estimate new window costs, but instead express our findings in the form of a break-even analysis. That is, we present-valued the differences in energy operating costs assuming an 8% discount rate. This present value, then, represents the maximum price premium that one could afford to pay for an energy-efficient window (over the price of the most popular window sold) in order for the additional cost to be just offset by the present value of future energy savings. If the additional price of an energy-efficient window is less than the break-even price, then the window is cost effective; i.e., the present value of energy saved will exceed the first-cost premium.

Our findings are presented by heating and cooling system type and by region in Table 6. We find that the break-even price varies considerably across and within regions. Among heating system types, the highest values are associated with non-gas systems. In several regions (West South Central, Mountain South, California, and Florida), the price premium exceeds $10/square foot. For central air conditioning only, the highest values are found in Florida and Mountain South. The central air conditioning values are generally additive when combined with various heating systems.

For perspective, it is useful to consider the price premium for energy-efficient windows in the Pacific Northwest where significant promotional activities have led to sizable market shares for energy-efficient windows. Lubliner (1995) finds a price premium of $1-3/square foot for energy-efficient windows in this comparatively mature market for windows. Anecdotally, we understand the price premium in other regions of the country may be $10/square foot or higher.

We conclude that, for many heating and cooling system combinations in most regions of the country, energy-efficient windows are likely to be cost effective. Given the low rates of market adoption for these technologies, public policies to promote greater rates of adoption may be warranted.

## SUMMARY

We estimate that the 1994 stock of 19 billion square feet of residential windows in U.S. is responsible for 1.7 quads per year of energy use—1.3 quads heating and 0.4 quads cooling energy—or about 2% of national energy consumption. There are a variety of advanced window technologies currently on the market today that have the potential to reduce the future energy requirements of windows dramatically. We estimate that rapid adoption of these technologies has the potential to reduce national energy requirements in the year 2010 by 25%. We find that public policies to accelerate the market adoption of these technologies may be warranted because, while they appear to be cost effective to the consumer, market adoption rates are low.

## ACKNOWLEDGMENTS

The work described in this paper was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies, Building Systems

*Table 5. Summary of Modifications to Method Presented in Frost et al. (1993)*

| Modification | Discussion | Effect on Energy Use |
|---|---|---|
| Exterior Film Coefficient | Recent work (Yazdanian & Klems 1995) has shown that DOE2 version 2.1D and previous versions (and thus the 1992 RESFEN version used in Frost et al. 1993) incorrectly estimate the exterior film coefficients for windows, thus overestimating heating loads. We have corrected the exterior film coefficient used in RESFEN for the present analysis. | 10 to 30% less heating losses, more so for high-U-Value windows |
| Duct Efficiencies | Recent work (Modera 1994) has shown duct losses to be between 10 and 35 percent. Frost et al. (1993) assumed 30 percent. We have used Modera s work to assign more accurate duct losses by HVAC type and region. | 15% less energy losses |
| Aluminum Frame Width | Frost et al. (1993) assumed 2.75″ frame widths for all windows. The current work assumes 2.75″ frame widths for wood and vinyl frames, 1.5″ frame width for residential aluminum frames. | 5% less heating losses through aluminum frames |
| Shading Treatment | Frost et al. (1993) assumed no shading as a RESFEN input and, instead, reduced the shading coefficient by 20%. We have assumed the presence of an overhang plus a 20% SC reduction in winter and a 37% SC reduction in summer to model the effects of drapes. | 10% less cooling and 10% more heating |
| New Market and Stock Data | We have relied on more recent sales data from AAMA (1994) and new regional glazing and frame stock data from RECS (EIA 1995). | More accurate stock composition estimates, better regional analysis of glazing sales composition |
| Calibration factors | We have applied calibration factors developed by Hanford and Huang (1992) that correct for discrepancies between whole building energy consumption forecasts and observed energy use. | 30% less heating and 45% less cooling |

and Materials Division of the U.S. Department of Energy under Contract No. DE-AC03-76F00098.

## ENDNOTES

1. See Eto, Arasteh, and Selkowitz (1996) for a discussion of lessons learned from utility market transformation programs that might be applied to accelerate the market adoption of advanced window technologies.

2. Sometimes, for example when describing wall insulation, the inverse of the U-value, called R-value, is used. When using R-values, which represent the resistance to heat transfer, a higher value denotes a product with higher resistance to heat transfer.

3. Sunlight, in the form of visible light, can also reduce the need for electric lighting within an indoor space. The ability of a window to pass visible solar radiation is measured by its *visible transmittance* or *VT*. The VT is dimensionless; it expresses the amount of visible solar radiation passing through a window relative to the amount that is incident on it.

4. The SHGC replaces an older measure of solar heat gain called the shading coefficient or *SC*. The SC is also dimensionless; it is a measure of the amount of solar

***Table 6a.*** *Present Values of Energy Cost Savings from Energy-Efficient Windows ($/square foot)*

| | New England | Mid Atlantic | East North Central | West North Central | South Atlantic | Florida |
|---|---|---|---|---|---|---|
| Glazing Type | Super Window | Super Window | Super Window | Super Window | Double SC Low-e | Double SC Low-e |
| Frame Type | Wood/Vinyl | Wood/Vinyl | Wood/Vinyl | Wood/Vinyl | Wood/Vinyl | Wood/Vinyl |
| U-Value/SHGC | 0.24/0.4 | 0.24/0.4 | 0.24/0.4 | 0.24/0.4 | 0.32/0.35 | 0.32/0.35 |
| *HVAC System/Fuel Type* | | | | | | |
| Electric Resistance | 6.6 | 7.9 | 2.1 | 2.8 | 7.9 | 19.3 |
| Gas Furnace | 3.6 | 3.9 | 1.2 | 1.6 | 4.0 | 6.0 |
| Oil Furnace | 5.0 | 5.5 | 1.6 | 2.4 | 8.7 | 21.7 |
| Other Heating | 5.5 | 6.1 | 1.8 | 2.6 | 9.7 | 24.0 |
| Central Air Conditioning | 0.7 | 0.8 | 0.0 | 0.0 | 1.2 | 3.2 |
| Electric Resistance-Central Air Conditioning | 7.2 | 8.7 | 2.5 | 3.3 | 9.1 | 22.5 |
| Gas Furnace-Central Air Conditioning | 4.3 | 4.7 | 1.6 | 2.1 | 5.2 | 9.2 |
| Oil Furnace-Central Air Conditioning | 5.6 | 6.3 | 2.0 | 2.9 | 9.9 | 24.9 |
| Other Heating-Central Air Conditioning | 6.1 | 6.8 | 2.2 | 3.1 | 10.9 | 27.1 |
| Heat Pump | 5.1 | 6.2 | 1.8 | 2.4 | 6.8 | 16.9 |

radiation passing through a window relative to the amount of solar radiation passing through a standard reference window consisting of a 1/8 inch (3 mm) thick piece of clear glass at normal incidence.

5. Earlier versions of the method are described in Brown et al. (1992) and Frost et al. (1993).

6. DOE-2 is a complex building energy simulation model that estimates annual energy use based on an hourly time-step (LBL 1993). It is the industry standard for building energy use estimation and has been validated in numerous studies. It is, however, a cumbersome program requiring detailed specification of building construction and operation. Reduced-form models based on DOE-2 offer an attractive alternative for aggregate-level studies such as this one. RESFEN is based on regression analyses performed using results from the latest version of the DOE-2 program (version 2.1e).

7. Quad is shorthand for one quadrillion (or 1e15) Btu/year. In 1993, U.S. primary energy consumption in residential buildings was estimated at 18.1 quads (DOE 1995).

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**Table 6b.** *Present Values of Energy Cost Savings from Energy-Efficient Windows continued ($/square foot)*

| | East South Central | West South Central | Mountain North | Mountain South | Northwest | California |
|---|---|---|---|---|---|---|
| Glazing Type | Double SC Low-e | Double SC Low-e | Super Window | Double SC Low-e | Super Window | Super Window |
| Frame Type | Wood/Vinyl | Wood/Vinyl | Wood/Vinyl | Wood/Vinyl | Wood/Vinyl | Wood/Vinyl |
| U-Value/SHGC | 0.32/0.35 | 0.32/0.35 | 0.24/0.4 | 0.32/0.35 | 0.24/0.4 | 0.24/0.4 |
| *HVAC System/Fuel Type* | | | | | | |
| Electric Resistance | 8.4 | 13.3 | 2.6 | 17.0 | 3.4 | 18.5 |
| Gas Furnace | 3.5 | 3.8 | 1.6 | 6.7 | 3.0 | 6.1 |
| Oil Furnace | 9.6 | 11.2 | 2.3 | 18.4 | 4.4 | 12.8 |
| Other Heating | 10.5 | 12.4 | 2.6 | 20.3 | 4.9 | 14.1 |
| Central Air Conditioning | 1.2 | 1.9 | 0.0 | 3.7 | 0.0 | 0.5 |
| Electric Resistance-Central Air Conditioning | 9.6 | 15.2 | 3.0 | 20.7 | 3.5 | 19.0 |
| Gas Furnace-Central Air Conditioning | 4.7 | 5.7 | 2.0 | 10.4 | 3.1 | 6.6 |
| Oil Furnace-Central Air Conditioning | 10.9 | 13.1 | 2.8 | 22.0 | 4.5 | 13.3 |
| Other Heating-Central Air Conditioning | 11.8 | 14.3 | 3.0 | 24.0 | 5.0 | 14.6 |
| Heat Pump | 7.2 | 11.3 | 2.2 | 15.8 | 2.4 | 13.2 |


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