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ABSTRACT

Windows in the U.S. consume 30 percent of building heating and cooling energy, representing an annual impact of 4.1 quadrillion BTU (quads) of primary energy[1]. Windows have an even larger impact on peak energy demand and on occupant comfort. An additional 1 quad of lighting energy could be saved if buildings employed effective daylighting strategies.

The ENERGY STAR® program has made standard windows significantly more efficient. However, even if all windows in the stock were replaced with today's efficient products, window energy consumption would still be approximately 2 quads. However, windows can be "net energy gainers" or "zero-energy" products. Highly insulating products in heating applications can admit more useful solar gain than the conductive energy lost through them. Dynamic glazings can modulate solar gains to minimize cooling energy needs and, in commercial buildings, allow daylighting to offset lighting requirements. The needed solutions vary with building type and climate. Developing this next generation of zero-energy windows will provide products for both existing buildings undergoing window replacements and products which are expected to be contributors to zero-energy buildings.

This paper defines the requirements for zero-energy windows. The technical potentials in terms of national energy savings and the research and development (R&D) status of the following technologies are presented:

- Highly insulating systems with U-factors of 0.1 Btu/hr-ft²-°F
- Dynamic windows: glazings that modulate transmittance (i.e., change from clear to tinted and/or reflective) in response to climate conditions
- Integrated facades for commercial buildings to control/ redirect daylight

Market transformation policies to promote these technologies as they emerge into the marketplace are then described.

Introduction

While today's efficient windows are much more efficient than windows from prior decades, they are still significant energy liabilities. Improved high-performance window systems are critical to converting windows into the role of zero energy building components. Achieving zero-energy windows means improving performance of current efficient windows by 60 to 80

[1] The term "Quad" is shorthand for 1 quadrillion (10^{15}) Btu = 1.056 EJ.

percent (Apte, Arasteh et al. 2003; Lee, Yazdanian et al. 2004). If all the window stock could be upgraded, savings of more than $300 billion could be realized in the 20 years following these performance improvements (US DOE BT 2006). While not specifically analyzed in this paper, we expect the development of zero energy windows to play a significant role in fulfilling the vision of zero energy buildings.

Windows can admit solar heat when it is needed to offset heating energy needs, reject solar gain to reduce cooling loads, significantly mitigate a building's peak electricity demand, and offset much of a building's lighting needs during daylight hours. To realize these benefits, windows must have better fixed properties, e.g., much lower U-factors than are standard today, but they must also incorporate dynamic capabilities that allow for tradeoffs between winter and summer conditions, glare and view, and daylight and solar gains. The benefits of daylighting must be captured in all climates in commercial buildings, which use the most lighting energy at times when daylight is available.

This paper describes three future window technologies that have "zero-energy" potential:

- Highly insulating windows with U-factors of 0.1 Btu/(hr-ft^2-°F);
- Dynamic windows (glazings that have the ability to modulate their transmittance, i.e., change from clear to tinted or reflective);
- Integrated façades for commercial buildings to control/redirect daylight.

We describe the status of each technology and estimate savings potentials from windows using these technologies in the existing stock. It is important to look at the effects of emerging window technologies in the existing stock since over 50% of window sales are to the replacement/renovation market (Eley Associates 2002; Ducker Research Company 2004). Future studies will look at these technologies in the context of emerging zero energy buildings.

Although we do not address this topic in this paper, it is important to note that technologies and systems are not inherently self-optimizing or self-assembling: manufacturers, architects, engineers, homebuilders, and homeowners need data and tools to guide their decision making. Because windows are intended to last 20 to 50 years, it is critical that good information be available to manufacturers before they design products and to building owners before they select and install products because initial decisions can be changed later only at great cost.

Energy Impacts of Today's Window Stock

Because windows are not directly connected to metered or purchased energy flows, their impacts on building energy use appear in the energy bills for other building systems, such as space conditioning and lighting. Windows are currently responsible for about 30 percent of building heating and cooling loads, representing an annual impact of about 4.1 quads of primary energy. This includes the impacts of unwanted conductive losses and gains (i.e. heat transfer due to temperature differences across the window), unwanted solar heat transmission, and infiltration. For this study, we exclude the impacts of infiltration. Infiltration's impact in the current stock is estimated at 0.5 quads. We do this because controlling window infiltration is primarily a matter of applying developed technologies to window production and installation. As advanced window technologies are applied, efforts must be made to ensure that infiltration savings from manufacturing and installation are realized. In this paper we focus on existing and developing technologies which can reduce the 3.6 quads of energy due to conductive losses/gains and unwanted solar heat gain. Details are shown in Tables 1 and 2.

Table 1: Annual Space-Conditioning Energy Consumption of Current U.S. Residential Window Stock (see Methodology section for methods).

	Total Annual HVAC Consumption [2]	**Window percent of HVAC Consumption, No Infiltration**	
	Quadrillion Primary BTU (quads)[3]	% of Total	Window quads
Residential Heat	6.90	19%	1.30
Residential Cool	2.41	39%	0.94
Residential Total	9.31	24%	2.24

Table 2: Annual Space-Conditioning Energy Consumption of Current U.S. Commercial Window Stock (see Methodology section for methods)

	Total Annual HVAC Consumption[4]	**Window percent of HVAC Consumption, No Infiltration**	
	Quadrillion Primary BTU (quads)	% of Total	Window quads
Commercial Heat	2.45	35%	0.85
Commercial Cool	1.90	28%	0.54
Commercial Total	4.35	32%	1.39

A brief history of today's efficient windows and their savings gives perspective to the current discussion. Developed during the 1970s and 1980s, low-emissivity (low-e) coatings dramatically reduce radiative heat transfer through double-glazed windows, thereby lowering window U-factors (increasing R-values). Some low-e coatings also reduce overall solar heat gain by reflecting incident solar infrared radiation (that half of the solar spectrum which does not stimulate the human eye), a tremendous benefit in cooling-dominated climates. Low-e coatings do not change the visible appearance of the window. Their market share has gone from a few percent during the 1980s to 50 percent or more in 2005. The National Research Council estimates that low-e windows were responsible for 6.1 quads of cumulative savings in residential heating energy consumption from 1983 to 2005, valued at $37 billion (2003 dollars) in direct energy cost savings (National Research Council 2001). This figure excludes both savings in the commercial sector and additional savings from reduced cooling energy demand.

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[2] As reported in the 2005 Buildings Energy Databook Table 1.2.3 (US DOE Office of Energy Efficiency and Renewable Energy 2005).

[3] Primary" energy consumption includes a site-to-source conversion factor of 3.22 for electricity to account for losses in transmission, distribution, and generation. All energy consumption is reported in primary terms unless otherwise noted.

[4] As reported in the 2005 Buildings Energy Databook Table 1.3.3 (US DOE Office of Energy Efficiency and Renewable Energy 2005).

Window Technologies of the Future

We describe below the current status and research needs of three families of window technologies currently under R&D. These technologies will save significant energy when commercialized.

Highly Insulating Windows:

To reduce heating energy losses through windows, we target development of windows with U-factors of 0.1 Btu/(hr-ft²-°F). These products are intended for use in northern (heating-dominated) climates, mostly in residences. Commercial buildings and residential applications in other climates will also benefit from highly insulating products, but the U-factor requirements for these applications are not as stringent.

Improving the insulating value of window glazing has been the subject of research since the 1980s. Three key research paths have focused on:

(1) **Aerogel**, a micro-porous insulating material currently under R&D worldwide. Minimizing haze and manufacturing cost remain major challenges.

(2) **Vacuum glazings** offer theoretically high performance by using a vacuum to eliminate all conduction/convection between the two layers of glass. (Most windows contain air or a gas to limit heat transfer, which is not as effective as a complete vacuum.) Performance is compromised by: structural spacers that keep the glass layers apart, edge "short circuiting," and the need to develop low-e coatings that can sustain high temperatures during the edge-welding process. Structural issues (glazing implosion) are also a concern. Manufacturing processes are being developed internationally. Vacuum glazing is now commercially available in Japan with insulating values of approximately 0.20 - 0.25 Btu/(hr-ft²-°F), which still falls short of our performance goal.

(3) **Gas-filled low-e windows**, which have three or more glazing layers. These products are available today and can meet the 0.1 Btu/(hr-ft²-°F) (center-of-glass but not total unit) performance goal. They use center layer(s) of either thin low-e coated polyester or conventional glass. Challenges include increased labor costs, the use of dual spacer systems (which also raise concerns about gas loss leakage), increased weight (with glass), increased overall insulating glass widths which preclude their use in many existing window frame cross sections, and manufacturing processes which are not optimized for such products. Current research at LBNL is focused on a new option: light-weight, thin, non-structural center glazing layers. To achieve a total window U-factor of 0.1 Btu/(hr-ft²-°F) will require development of highly insulating frames and spacers. Current research has focused on understanding frame heat transfer, which is essential for developing new designs. Two promising approaches are the use of hollow cavities to increase frame insulation and the use of insulated solids (i.e., foams) with durable skins.

Dynamic Glazings:

Optimizing residential and commercial window energy performance requires dynamic solar control that responds to daily, seasonal, and climatic differences. A residential window that admits sunlight to reduce winter heating must also reject sunlight during the summer peak-cooling season. A commercial window that admits diffuse light from an overcast sky must control daylight from a bright sky. The two approaches to dynamic control are: (1) glazings with intrinsic optical control and (2) add-on shading systems to supplement glazing properties.

Technologies include: passive dynamic glazings (photochromics, thermochromics), which change optical properties in response to environmental changes, e.g. presence/absence of sunlight; active dynamic glazings, which change properties in response to applied voltage, current, or certain gases; and dynamic façade controls, a.k.a. automated shading systems.

Integrated Facades for Daylighting

Integrated building facades for commercial buildings provide the combined benefits of control and redirection of daylight while preserving views for building occupants. Examples of existing technologies for integrated facades include: daylight redirecting technologies such as light pipes, light shelves and skylights that allow natural light to penetrate deep into the building space, automatic dimming of artificial lighting in response to daylight levels, and dynamically controlled shading devices or switching glass to regulate glare. The combined effect of these strategies could be net energy gain rather than loss through glazed facades.

The challenges of designing integrated facades are similar to those of designing highly efficient windows: minimizing winter losses of heating energy through the façade by maximizing solar gain; minimizing summer cooling loads by using daylighting to offset artificial light while managing solar gain and glare. In addition to designing appropriate glazing products, integrated façade designers must also design the control systems and software that will manage the performance of the various façade components so that they function reliably and cohesively. Performance of existing examples of integrated facades has not been well documented.

Methodology

In order to understand the potential benefits of the three advanced technologies described above, we developed a hybrid "top-down/bottom-up"[5] methodology to estimate energy savings, starting from the fraction of energy used by windows on a national basis (see Tables 1 and 2), based on the current stock of windows in the U.S. This process is presented conceptually in this section and described in detail in (Apte and Arasteh 2006). The technical potential numbers assume that all windows in the stock are changed overnight. Although this instant change is unrealistic, these data are useful in evaluating long-term benefits of these technologies.

[5] We refer readers interested in the energy savings from specific technologies in specific buildings (i.e., a bottom-up approach) to the following: Residential: (Arasteh, Goudey et al. 2005); Commercial: (Lee, Yazdanian et al. 2004; Lee, DiBartolomeo et al. 2005; Lee, Selkowitz et al. 2006).

The method presented here is applicable to both estimating the energy impacts from the current stock (see Tables 1 and 2) as well as estimating the energy savings from advanced technologies (presented in the Technical Potentials section which follows).

We started with a simulation procedure originally developed by Joe Huang and colleagues at Lawrence Berkeley National Lab (Huang and Franconi 1999; Huang, Hanford et al. 1999). This procedure estimated the contribution of specific building envelope components (such as windows) to overall space conditioning loads in the US building stock. For the purposes of this study, we expanded on this earlier work to address changes in the building stock and window sales over the past decade. These changes then led to new estimates of window-related loads in the residential and commercial building stock. We then normalized these new loads to total building loads to determine what we term the "Window Fraction," that is, the window-related fraction of building energy consumption. To estimate the total window-related energy use of the US, we multiplied our estimates of Window Fraction by top-down estimates of primary space conditioning energy use for the residential and commercial building stocks (US DOE Office of Energy Efficiency and Renewable Energy 2005).

Thus, our analysis revolves around the following equation:

Window End Use = Total End Use x Window Fraction

The Total End Use terms are total heating and cooling primary energy consumption for residential and commercial buildings, as presented in Tables 1 and 2. For each of these four end uses, the Window Fraction will vary for each window technology scenario considered. We then estimated the average U-factor and Solar Heat Gain Coefficient for first, the installed window stock, and then second for advanced products (see Technical Potentials below). After determining the window fraction corresponding to each of these scenarios, we estimated today's baseline window energy consumption and the energy savings potential of future technologies.

Huang's original work used parametric DOE-2 computer simulations of a large set of prototypical buildings to determine the relative contributions of internal heat gains and building envelope components to total space conditioning loads of individual buildings[6]. By weighting these building-level estimates with stock size data derived from the EIA Residential- and Commercial Building Energy Consumption Surveys (RECS, CBECS), the authors then developed aggregate estimates of total "component loads" for the U.S. building stock (Huang and Franconi 1999; Huang, Hanford et al. 1999; US DOE Energy Information Administration 1999; US DOE Energy Information Administration 2001).

We performed the following procedure for each window technology scenario, including the base case of window stock. First, we used Huang et al's simulation results to estimate the effects of windows on space conditioning loads for each prototypical building. Huang et al.'s

[6] The term "prototypical building" refers to a computer energy simulation model which captures average or typical characteristics some subset of the building stock. Huang et al. developed 200 prototypical buildings (120 commercial and 80 residential) which typify the energy performance of roughly 70% of the US building stock.

prototypical buildings were originally developed in the late 1980s and early 1990s, and as such needed to be updated. We developed estimates of the U-factor and SHGC for today's installed window stock[7] and for each window technology scenario (see Technical Potentials section). We then developed and applied a set of building- and window-specific correction factors to Huang et al.'s simulation results to account for our new assumptions about these properties[8]. Second, we used a set of prototypical building-specific efficiency factors developed by Huang to convert load estimates for each scenario into estimates of primary energy consumption. Third, we used data from the 1999 CBECS and 2001 RECS to estimate building populations corresponding to each of the prototypes developed by Huang et al. (US DOE Energy Information Administration 1999; US DOE Energy Information Administration 2001). For each scenario, we then aggregated our estimates of window and total building energy consumption to national estimates of primary residential and commercial heating and cooling energy consumption. Finally, we divided window energy consumption by total building energy consumption for each of these end use categories in order to calculate their respective "Window Fractions." These "Window Fractions" were then used to estimate potential energy savings (Tables 4 and 6) over the baseline case (Tables 1 and 2) under a given technology scenario.

Lighting Energy Savings from Integrated Facades

We estimate that approximately 50 percent of commercial building floor space is in perimeter zones; this is the area of commercial buildings which can benefit from daylighting. This estimate is based on the following assumptions and examination of the building stock. In terms of building size and form we assume that all single story buildings and the upper floor of low rise buildings can be daylit using skylights. Based on EIA data, approximately half of the U.S. commercial floor space is in buildings that are 50,000 sq ft in size or smaller; many of the larger buildings are big box retail and warehouses that can also be skylit. For larger high rise buildings we defined perimeter zones of 15 foot depth as the daylit zone. The potential daylit area then depends on the floor plan of the building and its geometry. Past simulation studies and limited field test data have shown that ***effective daylighting utilization*** can save 50 percent of lighting energy, typically higher in skylit spaces and lower in sidelit spaces. (It is the premise of this study that Integrated Facades with associated lighting and shading controls are needed for ***effective daylight utilization***.) Hence, we estimate the energy savings potentials from daylighting from skylights and windows as 50 percent of stock area x 50 percent savings = 25 percent of the U.S. lighting energy consumption. Current U.S. lighting energy savings are on the order of 4 quads. While electric lighting efficiencies are expected to increase, so is floor space and thus demand. Assuming that these trends balance each other, daylighting savings potential will remain at 1 quad. This savings potential could be smaller (if lighting efficiencies increase faster

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[7] Estimates of today's window stock U-factor and SHGC properties used those originally estimated by Huang et al. as a starting point. U-factor and SHGC estimates vary by prototypical building; here, we present national averages. Residential window stock average: U = 0.74 Btu/(hr-ft²-°F); SHGC = 0.68. Data are sparse for the commercial building window stock; we estimate the following average properties for the commercial building window stock: U = 0.75 Btu/(hr-ft²-°F), SHGC = 0.66. We believe that commercial average U-factor may be underestimated. If this is the case, our estimates of heating energy savings from scenarios are lower-bound estimates. See Apte and Arasteh (2006) for a detailed description of the methods used to estimate these properties.

[8] We scaled window conduction loads linearly with respect to U-factor, and solar gains linearly with respect to Solar Heat Gain Coefficient. For example, if the U-factor in a particular window technology scenario was 50% lower than that originally estimated by Huang, then we reduced window conduction losses correspondingly by 50%.

than lighting demand based on floor space growth), or the savings potential could be greater if the reverse is true. While these are admittedly crude estimates, in the context of this study they adequately define performance potentials. As better data become available they will be updated.

Technical Potentials

In this section, we define future products that incorporate one or more of the advanced window technologies described earlier in this paper. We then use the methodology presented above to estimate technical potential (complete “overnight” stock replacement).

Residential Buildings:

Residential window technology scenarios utilizing highly insulating glazings and dynamic glazings are identified in Table 3, with technical potentials in Table 4.

Table 3: Residential Window Technology Scenarios Considered

Window Type	U-factor Btu /(hr-ft²-°F)	Solar Heat Gain Coefficient (SHGC)
Sales (Business as usual)	0.46	0.42
Energy Star (Low-e)	North: 0.35 North/South Central: 0.4 South : 0.65	North/North Central: 0.40 South/South Central: 0.4
Dynamic Low-e	0.35	0.15 / 0.40
Triple Pane Low-e	0.18	0.40
Mixed Triple, Dynamic	Northern U.S.: See Triple Low-e properties Central/Southern U.S.: See Dynamic Low-e properties	
High-R	0.10	0.40
High-R Dynamic	0.10	0.15 / 0.50

Table 3 notes:
Sales – The average properties of windows sold today.
Energy Star - Typical windows meeting the current Energy Star specification.
Dynamic Low-e – A two pane low-e window with dynamic solar heat gain control. Such a product is now available from Sage Electrochromics but current costs make it appropriate only for high value applications.
Triple Pane Low-e – Today’s highest-performance product; triple pane low-e in a wood/vinyl frame.
Mixed Triple, Dynamic – Triple pane low-e windows in northern U.S., dynamic two pane low-e in the south.
High-R; High R Dynamic – Very highly insulating windows, with/without dynamic solar heat gain control.

Table 4: Annual Energy Savings Potential of Residential Window Technologies

Window Type	Energy Savings over Current Stock		
	Heat, quads	Cool, quads	Total, quads
Sales (Business as usual)	0.49	0.37	0.86
Energy Star (Low-e)	0.69	0.43	1.12
Dynamic Low-e	0.74	0.75	1.49
Triple Pane Low-e	1.20	0.44	1.64
Mixed Triple, Dynamic	1.22	0.55	1.77
High-R Superwindow	1.41	0.44	1.85
High-R Dynamic	1.50	0.75	2.25

Stock use is 1.30 quads Heating, 0.94 quads Cooling. See Table 1.

We offer the following observations on energy savings potentials in the residential sector:

- The "ENERGY STAR" scenario offers relatively modest energy savings beyond the business-as usual case (0.3 quads). This is due to the large fraction of ENERGY STAR windows which make up current sales.
- Triple pane low-e windows, today's highest-performers, offer 0.8 quads of savings beyond the business-as-usual case, focused mainly in heating dominated climates.
- Next-generation "High-R Superwindows" offer energy savings significantly beyond sales (1.0 quads), with savings again mostly in heating applications.
- Even deeper energy savings can be achieved by coupling dynamic solar heat gain control with highly insulating windows. High-R Dynamic windows offer ~1.4 quads of energy savings beyond sales. Here, the entire U.S. window stock would result in zero net heating energy consumption on a national basis, while cooling energy consumption would be reduced by 80% from current values.

Commercial Buildings:

Commercial window technologies utilizing dynamic glazings, highly insulating glazings, and integrated facades are identified in Table 5, and technical potentials are presented in Table 6.

Table 5: Commercial Window Technology Scenarios Considered

Window Type	U-factor Btu /(hr-ft²-°F)	SHGC
Sales (Business as usual)	0.62	0.48
Low-e	0.40	0.29
Dynamic Low-e	0.40	0.10 / 0.40
Triple Pane Low-e	0.20	0.25
High-R Dynamic	0.15	0.05 / 0.50
Integrated Facades	0.15	0.05/ 0.50

Table 5 notes:
Sales – The average properties of windows sold today.
Low-E – A typical two pane spectrally selective low-e window in an aluminum frame.
Dynamic Low-e – A two pane low-e window with dynamic solar heat gain control.
Triple Pane Low-e – Today's highest-performance product; triple pane low-e in aluminum frame.
High R Dynamic – Very highly insulating windows with dynamic solar heat gain control.
Integrated Facades – These systems are intended to use highly insulating and dynamic products and to save additional energy through daylighting (hence their potentials for lighting saving)

Table 6: Annual Energy Savings Potential of Commercial Window Technologies

Window Type	Energy Savings over Current Stock			
	Heat, quads	Cool, quads	Lighting, quads	Total, quads
Sales (Business as usual)	0.03	0.17	-	0.20
Low-e	0.33	0.32	-	0.65
Dynamic Low-e	0.45	0.53	-	0.98
Triple Pane Low-e	0.71	0.31	-	1.02
High-R Dynamic	1.10	0.52	-	1.62
Integrated Facades	1.10	0.52	1.0	2.62

Stock use is 0.85 quads Heating, 0.54 quads Cooling. See Table 2.

We offer the following observations on the potentials in the commercial sector:

- Significant energy savings from low-e window technology are possible in the commercial buildings sector where the current penetration of low-e technology is modest. Full adoption of low-e technology would save 0.4 to 0.5 quads over sales.
- Both triple pane low-e and dynamic low-e product scenarios offer substantially larger energy savings than what would be possible with low-e products. Either scenario offers potential energy savings of approximately 0.8 quads over sales. Dynamic low-e products appear particularly promising, as they offer peak demand reductions.
- Adding dynamic solar heat gain control to the High-R Superwindow technology scenario dramatically improves cooling season energy performance. We estimate that this scenario offers energy savings of approximately 1.4 quads over the business as usual case.

The estimates presented in this paper were developed using the best data and methods available to us. However, these results are strongly dependent on estimates of the properties of the current window stock and estimates of the properties of windows being sold. The estimates of the stock properties and sales properties are from different sources; as a result the relative certainty between estimates of going from stock to sales should be considered less than the certainty between sales and future scenarios, or between different future scenarios. The savings estimates are also a strong function of the basis for the methodology, which is an understanding of heat flows through conventional windows in the current building stock. As product scenarios deviate more and more from conventional products, the uncertainty in our calculations increases. The utilization of solar gains with highly insulating windows, which leads to windows with positive heating energy flows offsetting building heating needs from other components, makes theoretical sense but needs to be evaluated in the context of buildings with other advanced components where there may be less heating needs generated. Cooling estimates presented with dynamic products are a large fraction of the total cooling load calculated. Our methodology may overestimate cooling savings from dynamic products (perhaps by up to 10%) due to the disconnect between analyzing advanced products with a data set developed for conventional products.

Market Transformation for the Next Generation of Windows

The market conditions, manufacturing challenges, and product development to date are currently different for the two core technologies that will become the next generation of windows: highly insulated windows and dynamic windows. Thus, the market transformation requirements are different for each.

Highly insulating windows are available today with U-factors as low as 0.14 Btu/(hr-ft^2-°F) (National Fenestration Rating Council 2004), but these products are costly for most applications. Market barriers include their significantly thicker sashes and added weight relative to standard windows as well as multiple gas seals that raise concerns about durability. These products are costly because they have not been designed for mass production and, because consumer demand is currently limited, manufacturers cannot take advantage of economies of scale.

If a new highly insulating product can be developed for mass production, consumer demand must be elicited. Most consumers do not "see" or "feel" the energy and other benefits of windows that have U-factors lower than 0.35 Btu/(hr-ft²-°F), so transforming the market to the next generation of highly insulating windows may be challenging unless energy prices escalate significantly beyond expected forecasts (US DOE Energy Information Administration 2006).

This is in contrast to the consumer experience when the previous generation of efficient windows was introduced. When industry moved from single-pane to double-pane windows or added features like low-e with argon, there were significant, easily perceived non-energy consumer benefits such as reduced condensation, improved comfort, reduced noise, etc.

Dynamic windows were recently introduced to the market and are being installed by a handful of early adopters (Sage Electrochromics 2006). Dynamic windows may spark consumer demand because building occupants can readily see the benefits. Furthermore, these products can control glare, allow natural daylighting, and improve thermal and visual comfort. They also allow occupants to see outdoors without obstruction, which blinds and solar shades do not.

Dynamic windows are technically challenging and will require long-term effort to achieve price premiums of $5- to $10-per-sq.-ft. However, it is likely that consumer demand can grow as price premiums decline from current highs of around $75 to $100 per sq. ft. even though these products may not be cost effective at these prices based solely on energy saving and peak demand mitigation.

Any new window product that is developed for both the existing and new construction markets will sell more than a product developed for only one market, but cost effectiveness in these two markets may be very different. Using highly insulated and/or dynamic windows can reduce costs of other building systems (e.g., space conditioning), which produces savings in the design phase of a new building. These savings can be used to offset window price premiums before these advanced window technologies achieve large economies of scale. For these reasons, new construction is a promising venue for early adoption of advanced windows if the tendency of builders to install the least-performing product that just meets codes can be overcome[9]. Existing homeowners, in contrast, have demonstrated willingness to make investments in energy-efficiency products in their replacement window selections.

Market Transformation Policies

ENERGY STAR is the nation's most well-known voluntary labeling program, administered by the Department of Energy and the Environmental Protection Agency. The program is mainly based on retrospective analysis of market conditions; that is, certain market conditions must exist for program criteria to be established and product categories to be

[9] Low-e penetration for existing window replacements is much higher than new construction sales (Ducker Research Company, 2004).

promoted. These conditions usually include product availability from more than one supplier to promote competition at cost effective prices.

Consistent with many building codes, ENERGY STAR specifies a U-factor of 0.35 Btu/(hr-ft^2-°F) for windows in northern climates. ENERGY STAR has not considered lower U-factors because products with significantly lower U-factors are not viewed as cost effective for the majority of consumers. Industry has been reluctant to invest in R&D and cost-effective manufacturing for lower U-factor products because of the lack of recognition in the current ENERGY STAR windows criteria for products with U-factors under 0.35 Btu/(hr-ft^2-°F). This has lead to a stalemate in market demand for lower U-factor products.

How can the next generation of efficient windows be encouraged? Possible answers include a dedicated R&D fund to seek competitive proposals to refine product designs over a three-year timeframe, combined with progressive ENERGY STAR specifications so that applicants to the R&D fund would know that their designs would have the benefit of ENERGY STAR labeling (and conventional low-e products would no longer qualify as more efficient products came on the market). Utility rebate programs or federal tax credits are conventional policy mechanisms that could also be used. These mechanisms are important to have in place before conventional programs such as ENERGY STAR can play a role. Demand-side management programs may also encourage efficient windows based on the potential of peak demand through dynamic solar controls.

Pursuing highly insulating windows in northern climates will produce the greatest energy savings. Heating fuel choice plays a role in which type of incentive program would be most appropriate. Because fossil fuels rather than electricity are the most common heating fuel, conventional electric utility "demand-side management" programs are not generally the most likely avenue for promoting highly insulating windows. Electricity is the dominant heating source in some local markets, however, so there may be local opportunities to capitalize on highly insulating window technologies. Highly insulating windows help avoid peak gas demand and thus reduce pressure on transmission bottlenecks and gas spot markets, so rebate programs could be designed based on these benefits. Federal tax credits could be offered based on avoidance of foreign natural gas and oil imports as a result of energy savings from highly insulating windows. In view of the gas industry's success in promoting increased penetration of gas as a fuel for residential heating, gas "demand-side management" programs could be pursued.

Conclusions

Windows in the United States are responsible for approximately 4.1 quads of space conditioning energy use, over 4 percent of the total energy use in the U.S. Infiltration accounts for 0.5 quads of this and can be greatly reduced with known technologies and installation procedures. This paper focuses on technologies to reduce the 3.6 quads due to conductive losses and unwanted solar heat gains. Three technologies have been identified, which, if successfully commercialized and marketed, could reduce this 3.6 quads to significantly under 1 Quad. Additional savings of up to 1 Quad from lighting savings offset by the effective use of daylighting is also possible. (Note that these estimates are Technical Potential reductions and are based on calculations that assume the entire stock of windows is changed "overnight." Although this instant change is unrealistic, the results are useful in evaluating long-term benefits.)

The technologies identified are:

- Highly insulating windows having U-factors of 0.1 Btu/(hr-ft^2-°F);
- Dynamic windows—glazings that have the ability to modulate their transmittance (i.e., go from clear to tinted and/or reflective);
- Integrated façades for commercial buildings to control/redirect daylight.

Overall, the next generation of high performance "zero-energy" windows has potential for significant energy and peak electricity and natural gas demand savings. In addition to continued basic and applied R&D, policy makers will need to assemble a package of deployment programs to increase the penetration of these new technologies and lead to their incorporation in conventional programs and policies, including building code revisions.

The savings presented in this paper were for buildings with characteristics of the existing stock. Over 50% of windows sold are installed in existing buildings, so it is important to look at the potentials for zero-energy windows in the existing stock. We expect that these products will also be excellent candidates for Zero Energy Buildings under development, although the specifics for such an analysis is the subject of future work.

It is estimated that research and market transformation efforts to bring these products to near universal use will take twenty years or more, depending on the urgency with which such initiatives are pursued. This time frame is consistent with expectations for the development of cost-effective zero energy buildings. Similar past investments have produced large savings over long time periods – it took 20 years to move low-E technology from laboratory R&D to 50 percent market share. Since the savings potentials are very large, and decisions regarding window selection have long term energy impacts associated with product lifetimes of 20-50+ years, we have no time to lose in launching efforts to reach these goals.

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