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The Impact of Windows on Residential Energy Use

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ABSTRACT

The goal of this work is to better understand the influence of window U-factor and solar heat gain coefficient on residential space heating and cooling energy use in the United States. We calibrated our simulation models with residential energy use data and evaluated the affect of window U-factor and solar heat gain coefficient on space heating and cooling energy use. U-factor and solar heat gain coefficient have a comparable impact on heating energy use, whereas U-factor has a minor impact and solar heat gain coefficient has a strong impact on cooling energy use. Homes in Madison, Wisconsin, and Baltimore, Maryland, that have mechanical heating and cooling show that total annual energy cost savings are comparable with the different types of low-e glazing that are on the market today for the same frame type. For homes without air conditioning, the low-e windows with a higher solar heat gain coefficient provide greater savings. In cooling-dominated climates, like Phoenix, Arizona, and Miami, Florida, windows with a low solar heat gain coefficient offer the greatest energy savings. More work is required to obtain better agreement between simulation models and actual cooling energy use, especially for dry, sunny climates.

INTRODUCTION

To better understand the impact of windows on residential energy use, it is important to have a good picture of the residential window market, housing in the United States, and how homes use energy. In 1996, 53% of the 45.9 million residential windows sold were for remodels and replacement applications, and 47% were for new construction (Swanson 1997). In 1995 80% of the residential windows sold were double-pane windows and 35% of all windows had low-e glass (AAMA 1996).

The references to regions in this paper are based on the U.S. Census regions (Figure 1). Of the 96.6 million existing homes (including single-family homes, apartments, and mobile homes), more than 60% of the windows are single pane and 35% are double pane (EIA 1996). In the South, more homes have single-pane windows than there are homes in the Midwest or the Northeast.

In 1996, 1.1 million privately owned homes were built. The greatest percentage of new homes were built in the South (44%), followed by the West (24%), Midwest (22%), and Northeast (10%). Housing starts in Florida, Georgia, and North Carolina accounted for almost 20% of the housing starts in 1996; California and Texas accounted for another 15% (U.S. Census Bureau Statistics 1996).

The Energy Information Administration (EIA) conducts the Residential Energy Consumption Survey (RECS) every three years. In 1993, more than seven thousand households were surveyed, representing the 96.6 million households nationwide (EIA 1996). The accuracy of each estimate is indi-

Figure 1 *U.S. Census regions.*

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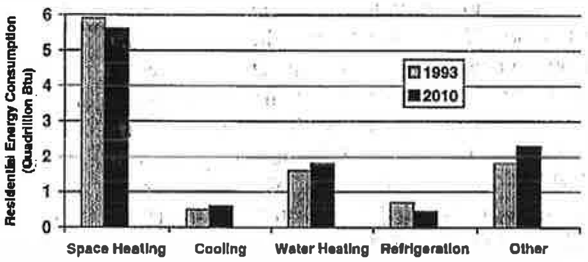

Figure 2 Residential energy consumption by end use (Cymbalsky 1995).

cated in the report by the relative standard error (RSE). No estimates were published that were based on fewer than ten sample households or that had an RSE greater than 50%. A nonlinear regression technique is used to disaggregate the space heating and cooling energy use from the total electric and gas energy reported in the survey. More information on the regression analysis is available in the Household Energy Consumption and Expenditures 1990 (EIA 1993).

Figure 2 shows a breakdown of residential energy consumption by end use for the U.S. (Cymbalsky 1995). Even though 35% of the existing housing units are located in the more temperate South, space heating energy use is more than ten times that of energy used for cooling. EIA projects that space heating use will decrease by the year 2010, and cooling energy use will increase. Nevertheless, energy use for space heating will still be almost ten times that for cooling. The cost of energy use is a stronger indicator of consumer choices than energy use alone and is factored into the analysis later in the paper.

In existing housing, 54% of homes have warm-air furnaces (U.S. Census Bureau 1996), and in new construction, 67% of the homes have warm-air furnaces (HUD 1994). The percentage of homes using natural gas is nearly identical. Existing homes in the Northeast have steam or hot water heating (50.5%), but this is the only exception in the U.S.

The 1993 RECS (EIA 1996) concluded that 68% of homes use air conditioning and 44% have a central system. The number of new homes built with central air conditioning

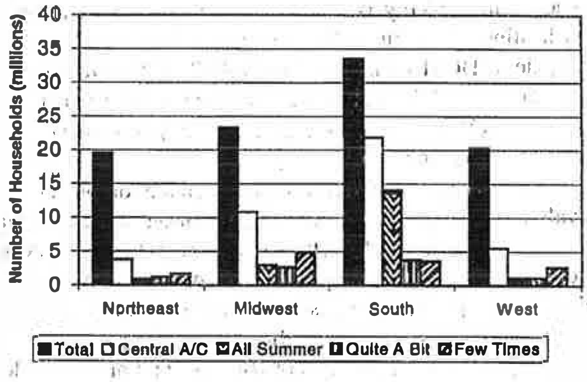

Figure 3 Usage characteristics for central air-conditioning systems (EIA 1993 RECS).

is increasing. This makes sense given that a relatively high percentage of new homes are built in the South.

As part of the 1993 RECS (EIA 1996), questions were asked as to how often people controlled their space heating and central air conditioning. An average of 44% of the households in the U.S. setback their thermostats at night during the heating season. As for air conditioning, 47% of the homeowners run their air conditioning all summer, 22% run their system quite a bit, and 31% only run the system a few times during the summer. The response that the air conditioning runs throughout the summer only dominates in the South where many of the climates are hot and humid (Figure 3).

APPROACH

In order to accurately assess the impact of windows on residential energy use, we first needed space heating and cooling energy use data for homes to which to calibrate our simulation models. The 1993 RECS (EIA 1996) contains such data on a regional basis and in energy use per heating or cooling degree-day per ft^2 of conditioned floor area.

To determine how good the data from the 1993 RECS (EIA 1996) is, space heating and cooling energy use data were collected from various sources. Table 1 compares findings for space heating and cooling energy use. The cooling energy use is that for homes with electric central air conditioning, and the

TABLE 1
Comparison of EIA 1993 RECS Data to Field Data

City	Space Heating Energy Use EIA 1993 RECS (therms/sf)	Space Heating Energy Use Other (therms/sf)	Cooling Energy Use EIA 1993 RECS (kWh/sf)	Cooling Energy Use Other (kWh/sf)
Denver	0.4	0.6 (ERHC)	0.3	0.3 (ERHC)
Miami			3.0	3.2 (SRC)
Orlando			2.4	2.4 (SRC)
Phoenix			1.8	1.8 (APS)
Sacramento	0.27	0.18 (CEC)	0.8	0.9 (CEC)

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space heating energy use is for homes with natural gas forced-air heating. The sources from which the data were obtained include ERHC (1997), APS (1996), FSEC (1997a), Rose et al. (1992), and the CEC (1990). Based on the limited data that are available, the EIA predictions appear to be good indicators of actual energy use in homes.

We used the DOE-2.1E building simulation program to evaluate the impact of windows, insulation levels, internal gains, infiltration, and duct losses on a 1540 ft^2, one-story house. There are 0.58 air changes per hour (ACH) and 10% duct losses to the attic in the summer and winter. The house has 8 lb/ft^2 of internal mass as specified by the 1995 Model Energy Code. Internal gains are 56,000 Btu/day and are scheduled according to ASHRAE Standard 90.2. During the heating season, the temperature setpoint is 70°F with a 65°F setback from 12 a.m. to 7 a.m. During the cooling season, the temperature setpoint is 78°F with a 79°F setup from 8 a.m. to 4 p.m. The furnace has an annual fuel utilization efficiency (AFUE) of 78%, and the air-conditioning system has a seasonal energy efficiency ratio (SEER) of 10. Natural ventilation through the windows is modeled as well.

A factor of 0.7 is used to adjust winter solar heat gain, and a factor of 0.5 is used to adjust summer solar heat gain through windows. These adjustments simulate the effects of exterior and interior shading on windows, such as neighboring buildings, landscaping, overhangs, and interior shades. There are a number of alternatives for handling shading, and there is no agreement on the best approach. The next edition of the Model Energy Code (ICC 1997) specifies adjustment factors of 0.9 for the winter and 0.7 for the summer. Others (CEC 1990; FSEC 1997b) recommend greater adjustments and are discussed later. The annual heating and cooling energy ratings being developed by the NFRC (1997) currently include no shading.

A worker at the FSEC (1997c) discovered that the DOE-2.1E part-load performance curve for air conditioners is inaccurate and replaced it with a curve that reflects actual measured equipment performance. The correction to the part-load curve reduces cooling loads by as much as 40%. This new curve was used in this work. We did not find anywhere else in the literature where the residential equipment performance curves have been verified.

We chose to compare Albuquerque, New Mexico, and Baltimore, Maryland, because they have similar heating and cooling degree-days and temperature profiles, but Albuquerque receives more solar radiation and Baltimore is much more humid in the summer. In Albuquerque and Baltimore, the house has an uninsulated basement, R-13 wall insulation, R-30 ceiling insulation, double-pane clear windows with aluminum frames (U = 0.75 Btu/h·ft^2·°F, SHGC = 0.62), and a 2.5 ton air conditioner.

Phoenix, Arizona, and Miami, Florida, are both cooling-dominated climates, but also have very different solar and humidity conditions. In Miami and Phoenix, the house is on an uninsulated slab and has R-11 wall insulation and R-19 ceiling insulation. In Miami, the house has single-pane windows with aluminum frames (U = 1.3 Btu/h·ft^2·°F, SHGC = 0.73) and a 2.5 ton air conditioner. In Phoenix, the house has double-pane clear windows with aluminum frames (U = 0.75 Btu/h·ft^2·°F, SHGC = 0.62) and a 3.5 ton air conditioner.

CALIBRATION

We attempted to calibrate the DOE-2.1E building simulation models to predict within 50% of the space heating and cooling energy use estimated in the 1993 RECS (EIA 1996). We found good agreement with the space heating results, but had difficulty with the cooling results (Table 2). Energy use has been shown to vary considerably from household to household; however, the models should predict average energy use in order to give some validity to the conclusions drawn from the results.

Table 2 shows the percentage difference between the simulated and the EIA RECS results. The simulated space heating energy use predictions are acceptable, whereas the simulated cooling energy use predictions are as much as 131% higher. Miami is the most humid of the four climates and Baltimore also is relatively humid, and these two cities give the best agreement in terms of cooling energy use. The simulated cooling energy use for the two dry climates, Albuquerque and Phoenix, are more than 100% off. Albuquerque and Phoenix receive more solar radiation and are less humid than Baltimore and Miami, which leads us to question the shading assumptions and the impact of humidity on occupant behavior.

Work by the FSEC (1997b) and the CEC (1990) to

TABLE 2
DOE-2.1E Results Compared to EIA Data

City	DOE-2.1E Space Heating Energy Use (MBtu)	EIA Space Heating Energy Use (MBtu)	% Difference in Heating Energy Use	DOE-2.1E Cooling Energy Use (kWh)	EIA Cooling Energy Use (kWh)	% Difference in Cooling Energy Use
Albuquerque	49.0	43.6	12%	1902	824	131%
Baltimore	69.8	76.1	−8%	1696	1243	36%
Miami	1.7	3.1	−45%	5434	4620	18%
Phoenix	11.0	13.9	−21%	5972	2772	115%

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compare cooling energy use with model predictions found that models typically overpredict cooling energy use. To address this discrepancy, FSEC determined the correct part-load ratio curve to use in DOE-2.1E and used a default window shading coefficient of 0.45 for a single-glazed aluminum window to include the effect of blinds, screens, and framing. This shading coefficient is adjusted for seasonal conditions using a multiplier of 0.9 in the winter and 0.7 in the summer. The resulting winter shading coefficient is 0.41, and the summer shading coefficient is 0.32 (Fairey 1997).

Wilcox compared monitored energy use data with simulations and found that, on average, the simulations predicted heating use was 20% higher than actual use and cooling use was 50% higher than actual use (CEC 1990). They recommend assuming a window shading coefficient of 0.57 when the drapes are closed and scheduling the cooling thermostat to operate the air conditioning only three days per week (40% conditioned).

Previous work in this area often overpredicted solar gain because center-of-glass solar heat gain coefficients rather than total window values were used. The simulation models used for this work employ total window performance indices, the correction to the part-load curve, and the adjustments to solar heat gain for the winter and summer. We did not schedule the use of the heating and cooling systems with the exception of the night setback in the winter and the day setup in the summer. The discrepancy between the simulation results and the 1993 RECS (EIA 1996) data for cooling energy use in the sunny, dry climates is alarming and requires further investigation before any other modifications are made.

IMPACT OF WINDOWS ON ENERGY USE

Elimination parametrics were performed to assess the impact of each component on space heating and cooling energy use. The parametrics entail running the standard case and then changing each component individually so there are no losses (or gains) associated with that component. The wall, ceiling, and basement R-values are all set to R-100, and the absorptance of the opaque surfaces is set to zero to negate losses or gains through the opaque surfaces. The window U-factor and solar heat gain coefficient also are set to zero. Because internal gains and window solar heat gains offset space heating loads, the house is assumed to have no window solar heat gain and no internal gains in order to assess the impact of each building component.

Figures 4 and 5 show the percentage each building component contributes to space heating energy use for Albuquerque and Baltimore, respectively. In both cities, less than 15% of the space heating energy use is attributable to the window U-factor, and more than 15% is attributable to window solar heat gain. A common belief is that U-factor has a greater impact on space heating than solar heat gain coefficient. These results show they are equally important and solar heat gain coefficient can have a greater impact than U-factor.

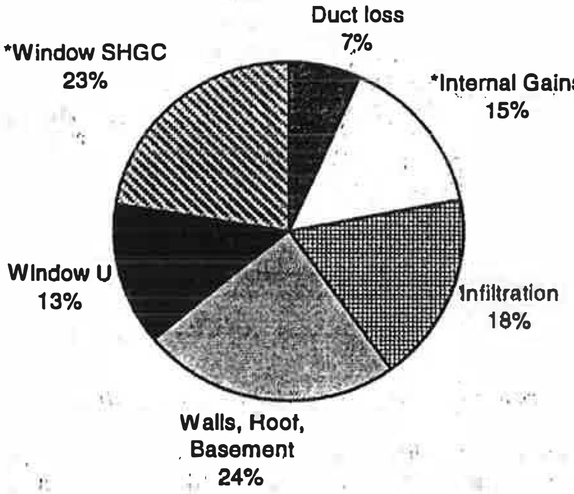

Figure 4 *Breakdown of space heating energy use into its components for Albuquerque.*

* Window solar heat gain and internal gains offset heating energy use, so comparison is to house with no solar gain and no internal gains.

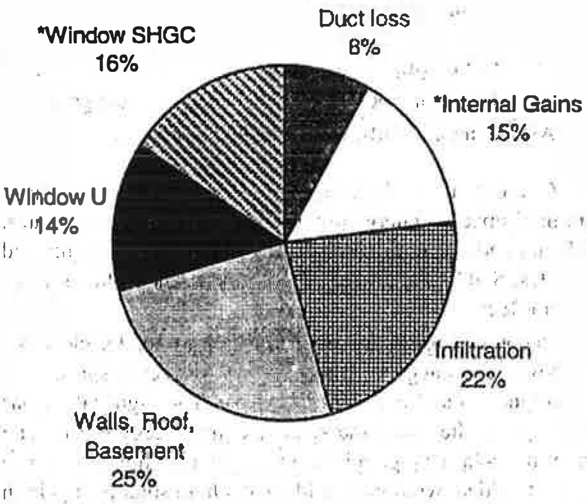

Figure 5 *Breakdown of space heating energy use into its components for Baltimore.*

* Window solar heat gain and internal gains offset heating energy use, so comparison is to house with no solar gain and no internal gains.

The authors ran the model in Miami where the simulated cooling energy use is only 18% higher than the EIA estimate (Figure 6). Solar heat gain through the windows has the greatest influence on cooling energy use, followed by internal gains. Window U-factor is relatively insignificant in terms of cooling energy use. Solar heat gain will have a much greater impact on cooling energy use than U-factor in any climate.

The results presented above do not answer the question of which window to select for a given home in a given climate.

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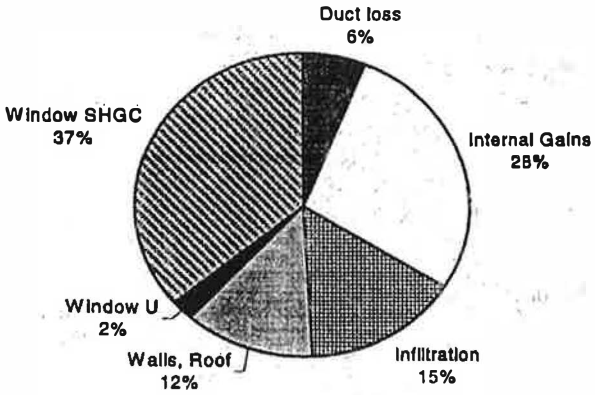

Figure 6 Breakdown of cooling energy use in Miami, Fla.

Figure 7 Comparison of annual space heating and cooling energy costs based on 1993 RECS data. The pie charts show the split between residential space heating and cooling energy costs for a number of cities.

The following addresses the driving forces behind selecting the appropriate product from an energy efficiency perspective.

WINDOW SELECTION

Determining which window is best suited for a particular application depends on many factors. If energy use is of primary concern, the following indices reflect the performance of a window:

- U-factor: thermal heat transfer
- Solar heat gain coefficient (SHGC): solar heat gain
- Air leakage: air infiltration through the window

Of these three indices, air leakage has been shown to have a minor impact on energy use. In heating-dominated climates, U-factor and SHGC are both important. In cooling-dominated climates, SHGC is of primary importance and U-factor has a minor effect.

In comparing Albuquerque and Baltimore, it is clear that window solar heat gain has a significant impact on space heating (Figure 4) and cooling energy use. The higher the solar heat gain is, the lower the space heating energy use is. The lower the solar heat gain is, the lower the cooling energy use is. So, the ideal window would have a high solar heat gain in the winter and a low solar heat gain in the summer. None of the commonly sold windows on the market today has these properties.

If you compare space heating and cooling energy use alone (Figure 2), space heating considerations would dominate the window selection process in most U.S. climates. Individual climates need to be considered, as well as the cost of energy.

Figure 7 applies the cost of natural gas to space heating and the cost of electricity to cooling energy use from the 1993 RECS (EIA 1996) data for a number of cities. The cost data are from NARUC (1996a, 1996b). This figure shows the influence climate has on energy use in terms of annual energy costs. Because electricity costs more than natural gas per unit of energy, cooling has a stronger influence on decisions concerning reducing energy use than if energy use was considered alone.

The breakdown of energy use into its building components indicates the relative importance of the different components. It does not reveal how to select between two comparable windows, such as one with a higher U-factor and higher solar heat gain coefficient than the other. We simulated a range of window types in Madison and Baltimore where the simulation results agree to within 30% of the 1993 RECS data. Table 3 lists the properties of the windows. All windows have a 0.5 air space between the glazing layers and a standard aluminum spacer.

TABLE 3
Window Properties

Glazing	Frame	U-Factor Btu/h·ft²·°F	SHGC
Clear IG	Thermally Broken Aluminum	0.62	0.64
(1) Clear IG	Vinyl	0.47	0.60
(2) Clear and Low-e (e = .15)	Vinyl	0.37	0.56
(3) Low-e (e = .08) and Clear	Vinyl	0.35	0.46
(4) Low-e (e = .04) and Clear	Vinyl	0.34	0.33

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In Madison, the simulated space heating energy use is 18% higher and the simulated cooling energy use is 44% higher than the 1993 RECS data (EIA 1996). The simulation model used for Madison has R-19 walls, R-38 ceiling, and R-11 basement insulation and the windows have clear, double-pane glazing with thermally broken aluminum frames (U = 0.64, SHGC = 0.62). U-factor and SHGC account for 15% of the space heating energy use, similar to Baltimore.

The space heating costs are twelve times the cooling energy costs in Madison and five times as much in Baltimore. A window with a low U-factor and a high solar heat gain coefficient would be the optimal choice for a climate where it is clear that space heating costs dominate the windows selection process, such as Madison. It is not clear what type of window would have superior performance in Baltimore.

Figure 8 shows the annual energy cost savings for heating and cooling for Madison and Baltimore for windows (1) and (4), as compared to the clear insulating glazing unit with a thermally broken aluminum frame (Table 3). Keep in mind that solar heat gain has less of an effect in both of these locations as compared to Albuquerque and other sunnier climates. The greatest heating energy savings are achieved with the low-e window (2) that has a high solar heat gain coefficient. A surprising result is that the low-e window (4) with the low solar heat gain coefficient, SHGC = 0.33, has lower heating energy cost savings than the clear IG with a vinyl frame, window (1), in Baltimore. In terms of cooling energy savings, the low-e window (4) with the lowest solar heat gain coefficient, SHGC = 0.33, saves the greatest amount, as expected.

The total cost savings are greatest with the low-e window (2) with the higher solar heat gain coefficient, although the low-e window (3) has nearly the same total savings. Notice, though, that the difference in total energy cost savings between all three low-e windows (2, 3, and 4) is fairly insignificant. It can be concluded that a home in Baltimore or Madison would realize comparable energy cost savings with any of the three low-e windows.

It would be revealing to run the same simulation in Albuquerque where the heating energy costs are only two times the cooling energy costs. If the simulation results gave better agreement with the EIA data, the conclusion may be the same as with Madison and Baltimore. However, because the simulations overpredict cooling energy use by more than 100%, any conclusions drawn from such results would be suspect.

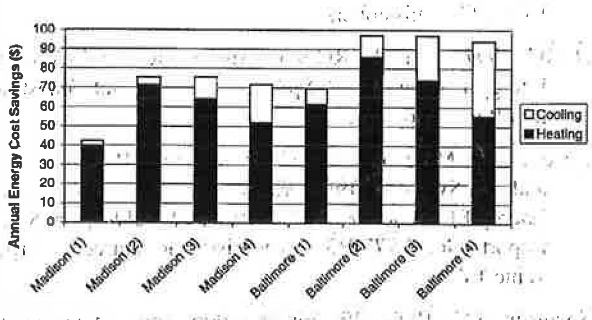

Figure 8 Annual heating and cooling energy cost savings as compared to the clear IG with a thermally broken aluminum frame in Madison and Baltimore.

In hot climates, like Miami and Phoenix, clearly the window with the lowest solar heat gain coefficient will have the greatest energy cost savings because cooling energy costs dominate in these climates. For climates with a ratio of space heating to cooling energy costs closer to 1.0, it is difficult to identify the most appropriate windows from an energy efficiency perspective. We did not calibrate the simulation models for any such climates. This is an area that deserves further work.

CONCLUSIONS

The goal of this work was to better understand the influence of window U-factor and solar heat gain coefficient on residential space heating and cooling energy use in the U.S. The energy used for residential space heating is ten times that used for cooling in the U.S., so one would conclude that heating considerations should drive the window selection process. However, homes are being built all over the country with the greatest number being built in the South where cooling energy use is significant. The replacement window market is equally important as the new construction market, although we did not find regional window sales data for the replacement market.

To assess the influence of window U-factor and solar heat gain coefficient on space heating and cooling energy use in a home, we collected data on actual energy use in homes and calibrated the simulation models. We show that the 1993 RECS data (EIA 1996) gives good agreement with field data collected by various sources.

We were able to match the 1993 RECS (EIA 1996) space heating energy use data for a number of climates to within 50%. On the cooling side, we obtained good agreement in humid climates but overpredicted the EIA cooling energy use by more than 100% in dry, sunny climates like Phoenix and Albuquerque. Furthermore, the simulations consistently overpredict cooling energy use, so potential cooling energy savings also could be overpredicted. More research is needed on cooling energy use behavior in order to improve the simulation models. A national laboratory is monitoring a number of houses in which they are comparing different windows. This work should be available in the next few months and should provide valuable insight into questions surrounding cooling loads and shading.

We found that U-factor and solar heat gain coefficient have a comparable impact on heating energy use, whereas U-factor has a minor impact and solar heat gain coefficient has a strong impact on cooling energy use. To reduce heating energy use, a higher solar heat gain coefficient is preferable. To reduce cooling energy use, a lower solar heat gain coefficient is preferable. No window on the market today has both.

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Comparing the energy cost savings from windows available on the market today, we found that for homes with gas heating and electric cooling, the three low-e products (Table 3) have almost equal total energy cost savings in Madison and Baltimore. They differ in space heating and cooling energy cost savings, but the total savings are comparable.

A homeowner with no cooling would be better off with a low-e window with a higher solar heat gain coefficient. There are other considerations as well, such as solar exposure, occupancy behavior, comfort, and price. These considerations may drive the selection process in another direction.

Future work is needed to address the discrepancy in cooling energy use between the simulations and field data, especially in dry, sunny climates. Also, it would be useful to investigate climates that have a space heating to cooling energy cost ratio closer to one to determine window selection criteria.

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