Analysis Results for Performance-based Ratings for the ENERGY STAR® Windows Program

October 1, 2004

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Executive Summary

The ENERGY STAR® Windows program is based on a set of prescriptive thermal performance criteria for four distinct US climate zones. DOE and the window industry have asked if there are performance-based alternatives that might usefully complement the prescriptive requirements in order to extend the participation and impact of the ENERGY STAR program. Such an extension only makes sense if the performance-based criteria 1) can equal or exceed the nominal energy savings of the existing criteria, 2) have no other adverse market impacts, and 3) provide consistent and understandable results leading to enhancement of the value of the overall program, and 4) further DOE public policy interests in promoting further investments in energy efficiency.

At the request of DOE, LBNL has undertaken a short-term but intensive technical study to determine if these performance-based alternatives can be developed. Initial technical conclusions with engineering backup are provided in this paper to assist DOE in its policy decisions and to stimulate broader industry discussion. The industry interest was to examine the impact of relaxing the U-value requirement. The technical approach was to see if there were consistent changes in zone-wide SHGC values whose impact would just balance the increased annual energy use due to the change in U. We summarize our separate conclusions for each of the four ENERGY STAR climate zones.

Southern Zone: The technical basis for performance-based alternatives was developed for the Southern Zone, utilizing lower SHGC to compensate for increased U-factors. It appears that this trade-off approach could be implemented without other significant adverse impacts. Two zone-wide trade-off options have been developed, one resulting in equal energy use averaged over the zone, and another more conservative one requiring equal energy use in even the less advantageous locations with combined heating and cooling. However review of products that are now on the market that meet current ENERGY STAR SHGC requirements indicates that in meeting the critical SHGC value of .4, the U requirement of .65 is routinely met even for thermally unbroken metal frames. Thus it appears there are no compelling market reasons to add a tradeoff in the South zone.

South/Central Zone: This zone encompasses a very wide range of diverse climates. An increased U-factor can be compensated for in some climates by a decreased SHGC; in some by an increased SHGC, and in some not by any change in SHGC. A mathematically averaged trade-off solution was derived that would result in equal or lower energy for the entire zone, but it would increase energy use in some cities and decrease it in other

cities within the zone. Because of the way that the zone boundaries are currently defined it is not possible to define a single set of zone-wide trade-offs having the desired goals of no net energy impact and consistent savings in every city. However since almost all of the locations with opposing or no trade-offs are in California, an alternative approach is to disallow trade-offs in California and develop an average trade-off solution for the remaining cities in the zone. We demonstrate that such a tradeoff procedure produces reasonably consistent results and no net energy impact for the remaining non-California locations. A window with a U value of .42 requires an SHGC of .31 for zero energy impacts. Although products that meet the .31 SHGC requirements are not widely available today they do exist and can be widely supplied using existing technologies. Aluminum framing industry members have indicated in their prior comments that they can achieve the .42 U value.

An alternative approach suggested from stakeholders for this zone is to allow a single fixed U increment throughout the zone with no compensating SHGC change. The feasibility and impact of this strategy was also analyzed and found technically feasible (for non California cities) but it results in increased energy use and requires a change in existing ENERGY STAR values which was not allowed in the DOE guidance.

North/Central Zone: This zone also encompasses a wide range of climates within which the energy impacts of changing U-factor and SHGC vary widely. For many locations in this zone the current combination of U and SHGC represents a near optimal value. Thus there is no trade-off possible, i.e., any increase in U-factor cannot be compensated for by any change in SHGC. Therefore, a technically defensible trade-off procedure is not feasible for this zone.

Northern Zone: The technical basis for performance-based alternatives was developed for the northern zone, utilizing increased SHGC to compensate for increased U-factors. However, since the increased U-factors would not meet most code minimum thermal requirements, we believe that alternative criteria are not feasible in the Northern Zone at this time. However, should the ENERGY STAR criteria for U-factor in this zone be reduced below code minimum requirements in the future, an alternative trade-off procedure will be possible. An example of such a hypothetical future trade-off solution is presented in this report.

This technical analysis provides input into the DOE process for assessing the feasibility of developing a performance-based trade-off system and for determining potential trade-off criteria that could be used. It is based on extensive new simulation studies and addresses responses from industry to an earlier draft and to feedback obtained in various window industry forums. The overall market impact of these possible trade-off options for the Southern, South/Central, and future Northern zones were assessed using the analysis methodology in this paper, and that from a previous study by Barbour and Arasteh (2002). The first assessment showed that the trade-off options would result in equal energy use for each of the major cases considered (and results in energy savings for one of the options in the Southern Zone). The second assessment showed the trade-off options resulting in small increases in energy use. The reason for these different results is that the second method assumed significant amounts of electric resistance heating in the Southern and South/Central zones. Details of these comparisons are reported in an appendix to this report.

Background

The qualifying criteria for the current ENERGY STAR Windows program's are based on the two main window thermal indices typically used to quantify the energy performance of windows and other fenestration products: a maximum U-factor and Solar Heat Gain Coefficient (SHGC) for each of the four ENERGY STAR zones (except for the Northern Zone, which does not have an SHGC requirement). The ENERGY STAR web site (http://www.energystar.gov/index.cfm?c=revisions.windows_spec) provides more details on the ENERGY STAR program as updated in 2003. Figure 1 shows the climate zone boundaries as revised in 2003. The prescriptive requirements for a window to qualify as ENERGY STAR in each of the four zones are listed below in Table 1.

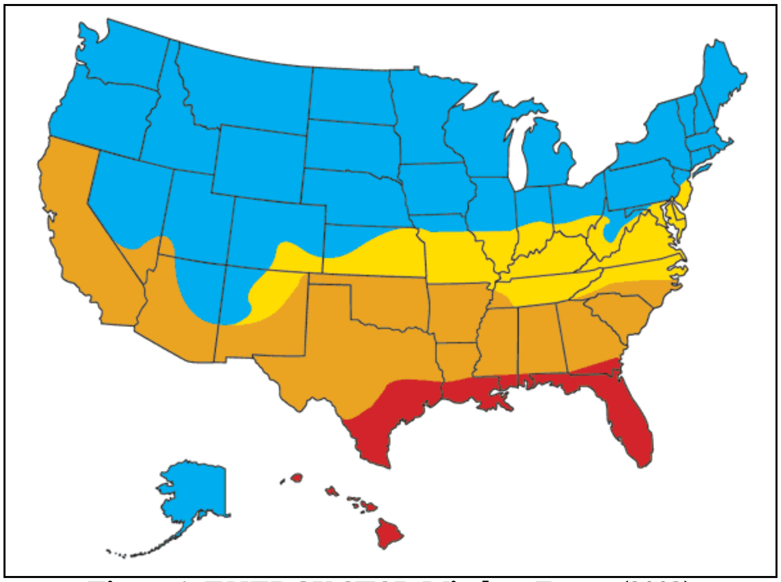


Figure 1. ENERGY STAR Window Zones (2003)

At the conclusion of the last set of updates to the ENERGY STAR criteria and in response to industry requests, DOE agreed to examine the concept of "performance-based alternatives" to the existing prescriptive criteria. LBNL prepared a background paper (Arasteh 2003) [1] to look at the issues associated with a performance-based rating for the windows program[2]. In that paper, the key performance issues were discussed, and several options for the performance-based trade-offs were proposed for consideration by a broad industry group that met in September, 2003. As a result of that meeting LBNL was asked to take the next step to develop and evaluate some specific performance-based alternative criteria. The primary tool used for the energy analysis was *RESFEN 3.1*, a computer program based on *DOE-2* that has been used by the industry for many years and considered by National Fenestration Rating Council for use in developing a national energy rating system.

Table 1. ENERGY STAR Qualification Criteria by Climate Zone

	Windows & Doors		Skylights	
Zone	**U-factor**	**SHGC**	**U-factor**	**SHGC**
Northern	≤ 0.35	Any	≤ 0.60	Any
North/Central	≤ 0.40	≤ 0.55	≤ 0.60	≤ 0.40
South/Central	≤ 0.40	≤ 0.40	≤ 0.60	≤ 0.40
Southern	≤ 0.65	≤ 0.40	≤ 0.75	≤ 0.40

In parallel with the LBNL evaluation of alternative criteria, a Task Group from NFRC's Annual Energy Performance (AEP) Subcommittee was formed in January 2004 to review and propose any changes to the modeling assumptions used in *RESFEN 3.1*. Because of critical time factors LBNL was asked by DOE to

[1] In this paper (http://www.govforums.org/e&w/documents/lbnl_analysis.pdf), references to ENERGY STAR are references to the ENERGY STAR Windows criteria, effective August 29, 2003.

[2] Throughout this white paper, the term *windows* will be used to refer to all fenestration products including doors and skylights. Proposed trade-offs are presented only for windows; ultimately, alternative trade-offs will have to be prepared for skylights and doors separately.

proceed with the development of candidate performance-based criteria using the existing *RESFEN 3.1* modeling assumptions while this Task Group proceeded with its review.

Although some members of the Task Group initially proposed six modeling changes – the two with the biggest impact being a 40% increase in the internal gains and lowering the cooling setpoint to 75ºF - the AEP Subcommitee ultimately decided at the NFRC Annual Meeting in March 2004 not to recommend any changes in the modeling assumptions because of the lack of hard data and DOE's deadline to complete the analysis. Consequently, the original *RESFEN 3.1* modeling assumptions were retained in developing the ENERGY STAR Window trade-off equations.

This paper expands on Option 2 (tables for trade-offs) and Option 3 (regression equations for trade-offs) described in the earlier LBNL background paper (Arasteh 2003). In this study, however, iterative *DOE-2* simulations have been used instead of regression equations to develop the trade-offs between window U-factor and SHGC in each of the four ENERGY STAR climate zones. The background paper showed that such trade-offs represented combinations of window properties that do not strictly meet the prescriptive U-factor and SHGC requirements for a given climate zone, but on average, have annual energy performances equivalent to window products meeting the prescriptive requirements. For example, in a southern climate, lowering the SHGC below the ENERGY STAR requirement will save additional cooling energy, and therefore, a slightly higher U-factor (leading to increases in heating energy) will still result in total energy use that is equivalent to that of an ENERGY STAR qualifying product.

Analysis Procedure

A DOS batch procedure is used with the *DOE-2* template file from *RESFEN 3.1* to generate the heating and cooling energy uses for a large number of window U-factor and SHGC combinations in 51 US cities for prototypical houses of two vintages (new and existing). The *RESFEN 3.1* template file is a *DOE-2.1E* text input file with heavy usage of *DOE-2* macros that parameterizes over 40 key building inputs, such as building type (one-story, two-story), building vintage (new, existing), wall construction (wood-frame, masonry), floor area, and HVAC system type (furnace/air-conditioner, heat pump). Since *RESFEN* was originally developed as an easy-to-use tool for the window industry and general public to analyze residential window energy performance, ¾ of the key inputs relate to the windows, including their size, orientation, thermal and solar properties, and shading conditions. Once these key inputs have been set by the user, either through the *RESFEN* user front-end or, as in this case, a DOS batch procedure, they are then inserted at the beginning of the template file. The *DOE-2* macros in the file will then produce individual input files tailored to the specified building and window conditions.

For the current analysis, the inputs are even more limited, since only the window U-factor and SHGC, building location, and vintage are varied, while the other inputs have been kept at constant default values. Because the DOS batch procedure is functionally identical to how *RESFEN* runs *DOE-2*, the resultant heating and cooling energy uses are also identical. Thus, all the results can be verified and checked by industry reviewers using *RESFEN*. The advantages of the batch procedure are the ability to quickly generate thousands of *DOE-2* results, and to imbed it into an iterative procedure to automatically calculate window U-factor/SHGC combinations having the equivalent total energy use (see description on page 6).

Modeling Assumptions

The modeling assumptions underlying this analysis are from the current version of *RESFEN 3.1*. Some parameters are fixed, while others vary with building location, type, and vintage. For example, the assumed thermal characteristics of the building shell and the equipment efficiency are different between new and existing construction in different parts of the country. This set of assumptions in *RESFEN* covers both technical issues and human factors and is detailed at http://windows.lbl.gov/AEP/database.htm (Arasteh et. al. 2000).

Both house vintages (new and existing) have been modeled in this study. However, additional assumptions have been made for inputs that are user-defined or multiple-choice in *RESFEN 3.1*, such as the building type, floor area, foundation type, window size, orientation, and shading conditions. The prototypical house modeled for this analysis is a one-story house of wood-frame construction , 2000 square feet, with 15% of the floor area in windows, evenly distributed on all four orientations, and a typical shading condition represented by a combination of drapes, overhang, and shade from adjoining buildings. Table 2 summarizes the modeling assumptions used throughout this study. The assumptions shown in italics are those specified for this study, while those in regular font are fixed by *RESFEN 3.1*.

Climate and Data Aggregation

The parametric analysis of window U-factor and SHGC combinations in the prototypical houses of two vintages were completed for 51 cities in the United States. The results were then grouped into the ENERGY STAR zone in which they belonged. In our prior paper, the cities chosen for California were mainly coastal cities, which affected the regression fit for the South/Central zone in which the California cities are located. In this current analysis, a larger set of California cities have been chosen to better represent the state's wide climatic variation (see Appendix 1 for details).

To account for the disparity in housing starts or renovation activity in the areas represented by the 51 base case cities, the *DOE-2* results for the individual cities were weighted by population as a surrogate for building activity in calculating the average trade-off equations for each of the ENERGY STAR climate zones. The population represented by each city was estimated by assigning all the US counties to one of the 51 cities based on geographical proximity and climate similarity, and then summing the county populations as reported in the 2000 Census. The resulting population weights are shown in Table A-2.

Evaluation Based on Total Energy

A performance-based rating which allows trade-offs must determine which parameter is used as the basis for trade-offs. Choices include:

- total annual energy
- heating and cooling energy individually
- total annual energy cost

Table 2. *RESFEN 3.1 Operating* Assumptions

Parameter	*RESFEN 3.1* Assumption
Floor Area	*2000 ft² (186 m²) One-Story*
House Type	▪ New Construction ▪ Existing Construction
Foundation	*Foundation based on location, can be either Basement, Slab-on-Grade, or Crawlspace*
Insulation	Envelope insulation levels are based on location. ▪ New: 1993 Model Energy Code ▪ Exist.: (see Ritschard, et al. 1992)
Infiltration (Effective Leakage Area)	▪ New: 0.77 ft^2 (715 cm^2, approx. 0.58 air-changes/hr) ▪ Exist.: 1.00 ft^2 (930 cm^2, approx. 0.70 air-changes/hr)
Structural Mass	3.5 lb/ft^2 (17.1 kg/m^2) of floor area, in accordance with the MEC and AEP Subcom. Sep. 1998 recommendation.
Internal Mass Furniture	8.0 lb/ft^2 (39.1 kg/m^2) of floor area, in accordance with the MEC and AEP Subcom. Sep. 1998 recommendation.
Solar Gain Reduction	▪ *Drapes (summer 0.80, winter 0.90);* ▪ *1 ft. (0.3 m) overhang;* ▪ *67% transmitting same-height obstruction 20 ft (6.1m) away to represent adjacent bldgs;* ▪ *addition solar heat gain reduction by 0.1 due to insect screens, trees, dirt, building and*

	window self-shading, etc.
Window Area	*15% of floor area*
Window Type	*Variable*
Window Distribution	*Equally distributed on all four orientations*
HVAC System	Furnace & A/C
HVAC System Sizing	For each climate, system sizes are fixed for all window options by doing a *DOE-2* auto-sizing run for the same house with the most representative window for that specific climate.
HVAC Efficiency	▪ New : AFUE 0.78, SEER 10.0 ▪ Exist.: AFUE 0.70, SEER 8.0
Duct Losses	10% fixed (both heating and cooling)
Part-Load Performance	(see Henderson 1998)
Thermostat Settings	Living Space: Heat 70°F, Cool 78°F Basement: Heat 62°F, Cool 85°F
Night Setback	65°F 11 PM – 6 AM
Internal Loads	Sensible: 59.9 kBtu/day Latent: 12.2 kBtu/day
Natural Ventilation	Enthalpic – Sherman-Grimsrud (78°F/ 72°F based on 4 days' load history)
Weather Data	TMY2

In this analysis, total annual energy was chosen as the trade-off parameter. Total annual energy (expressed as source or primary energy and not site energy)[3] is the metric that best relates to natural resources used and pollution impacts, and on average correlates well with annual energy cost.

Iterative Search Procedure

Trade-offs are combinations of U-factor and SHGC that result in the same total energy use as the base case prescriptive ENERGY STAR window. To facilitate finding these U-factor/SHGC combinations, several DOS batch procedures have been developed to automate this process using iterative *DOE-2* calculations. These procedures all work in a similar fashion – the total energy use for the base case prescriptive ENERGY STAR window is first calculated using *DOE-2*; then the window U-factor is changed and the change in total energy use per change in SHGC calculated through sequential *DOE-2* simulations; comparing this change due to SHGC to the difference in total energy use from the base case, a new SHGC is calculated and *DOE-2* simulations repeated until one of three conditions is met: (1) the difference in total energy use is less than 0.02%, (2) the change in total energy use from the previous run is less than 0.04%, or (3) 16 iterations have been done. The first case indicates that a trade-off solution has been found, while the latter two cases indicate that a trade-off solution cannot be found, but the SHGC producing the minimum energy use for that U-factor has been identified.

The initial version of this iterative technique calculated the trade-off for a single building of a specified vintage in a specified location. Later versions combined housing vintages, and then different city/vintage combinations within a single lumped iteration, i.e., they used *DOE-2* to calculate the total energy use for each city/vintage combination, summed these energy uses weighted by population to produce the total energy use within an ENERGY STAR climate zone, and then did iterative *DOE-2* simulations to determine the SHGC trade-off that maintained the same total energy use within the climate zone. These lumped iterations are

[3] Source or primary energy takes into account the energy input necessary to deliver the end service. The main impact of this is that the inefficiencies of electricity generation and transmission (which make electricity delivered to the house roughly 30% efficient) are included. A factor of 3.22 is used to convert site electricity to primary/source energy (DOE Core Databook.)

necessary because the individual city and vintage trade-offs do not tell the sensitivity of total energy use to changes in SHGC, and thus cannot be averaged to derive the zone-wide trade-offs.

Trade-off Constraints - Issues for Consideration

Although equivalent annual primary energy consumption is the major basis for examining performance trade-offs, windows have many performance attributes and several must be considered when the trade-offs are evaluated. The following is a discussion of factors in addition to annual energy consumption that will influence the range of trade-offs that could be allowed. Other performance issues that will influence window selection such as comfort and view might be considered as constraints on some of the calculated equivalent energy values. We briefly review these issues below and then apply them as constraints to the energy results in each zone.

Issue: DOE Public Policy Concerns

DOE uses three main policy mechanisms - research and development, voluntary education, and mandatory codes and standards - to save energy and improve energy performance of building equipment and components. Traditionally, voluntary education programs such as ENERGY STAR promote products that are significantly higher than minimally compliant or regulated levels of efficiency. However, the current market situation for windows is somewhat atypical in several respects. In many locations, the ENERGY STAR level and mandatory code requirements are equivalent, and while there are more efficient products available in the market, these have not reached the critical mass needed to warrant the support of a mass market program such as ENERGY STAR Windows. Currently, DOE is conducting R&D to reduce the costs of these high-performance products and address other market barriers so that these can become the next generation of products with wide spread market appeal.

Thus, when DOE sets levels for ENERGY STAR Windows, the overall market trend and R&D goals act as key inputs, which are best categorized as in the interest of "public policy." For example, in the later discussion regarding a trade-off option for the Northern Zone, it would be unlikely for DOE to adopt a procedure that would provide ENERGY STAR labels for products with U-factors above the code requirement of 0.35, when DOE's long-term R&D goal, as articulated in meetings with industry at numerous Window R&D Roadmap events is to achieve U-factors as low at 0.1.

Another key consideration of DOE is to set public policies that are in the interest of the general public, and take appropriate measures to achieve this overall goal. For example, DOE initiated this entire analysis of a performance-based rating system because of concerns regarding key points articulated by the aluminum industry, such as consumer choice, improved durability, and greater structural integrity. Standing back from the specific issues regarding the ENERGY STAR levels and performance-based rating options, it is apparent there are many aluminum window products in the market place that are significantly lower in energy performance compared to other frame materials. Thus, when industry comments suggest that progressive aluminum manufacturers can achieve a U-factor of 0.42, this would appear to be beneficial to "public policy" because such a trend would represent a dramatic improvement in product performance and investment in higher performing products. At the same, such an effort may only be effectively viable over the short to mid term as DOE has articulated a long-term vision to achieve U-factors of 0.1 to 0.2

Issue: Always Meet or Beat Energy Code

The ENERGY STAR program has as one of its central premises, the requirement that it exceed (or at a minimum meet) locally based energy code requirements. The recent revisions to the ENERGY STAR program were developed in part to reflect upgrades and proposed code changes to residential codes (http://www.energycodes.gov). A move by ENERGY STAR to performance-based ratings might result, in some instances, in products whose individual window properties that do not meet code.

DOE received several comments regarding the current requirements in codes that allow for flexibility on a whole house basis to allow for components such as windows with lower energy performance characteristics to be used in a system that has an overall improvement in energy efficiency. These homes include other measures such as high performance walls or HVAC equipment to produce overall energy efficiency improvements. The key point is that such a precedent exists in the current code so the prescriptive requirements for windows should not prevent a performance-based rating system from going forward. However, it would add complexity to a fairly simple program.

DOE will need to make a final decision regarding this policy decision, i.e., whether energy code requirements should be a constraint on any ENERGY STAR performance-based trade-offs, including due consideration of comment from stakeholders. The ENERGY STAR Window Program has been used by jurisdictions to set building codes but this has not been the driving purpose for the program. Technology and markets change as well as codes. In the longer term we expect manufacturers to offer new cost effective products with even lower U values that may be well below then current code requirements. In that situation there would once again be an option for tradeoffs, as illustrated later in this report.

Issue: Maximum U-factor and SHGC values for Peak Electric Demand

While the primary reason for establishing U-factor and SHGC criteria are to minimize energy use, these parameters also can relate to reduced equipment sizes and lower electrical peak demand.

Maximum SHGC values serve to limit the contribution of windows to peak summer cooling loads. Maximum U-factors provide additional help in controlling summer peak heat gains. In the case of electrically heated homes in winter peaking areas, maximum U-factor requirements also serve to reduce peak winter loads.

A series of *DOE-2* simulations were done to study the impact on peak heating and cooling loads under the trade-off procedures described in this report. The primary concerns are on the impacts of increased SHGC on peak cooling loads in the Southern Zone and of increased U-factors on peak heating loads in the Northern Zone.

In the Southern Zone, a trade-off of lower SHGC for higher U-factor will result in a small reduction in the cooling peak (0.04- 0.06 kW or 1-2%) at the cost of a slight increase in heating peak (1-2 kBtu's or 4%). If the trade-off is of a lower U-factor for a higher SHGC, then there will be a 1-2 kBtu or 4-5% reduction in the heating peak at a cost of a slight increase in the cooling peak (0.03 -0.05 kW or 1-2%).

Under the potential trade-off procedure for future high-performance windows in the Northern Zone, a 40% increase in the U-factor from 0.25 to 0.35 will result in a 1.5-3.0 KBtu or 3-5% increase in the peak heating load, and a 0.50-0.75 kW or 5-25% increase in the peak cooling load. The large percent increases in cooling loads are due to the small cooling loads in the northern zone.

Overall, under the limited range of allowable trade-offs of SHGC for U-factor or vice-versa, the impacts on heating or cooling peaks are minor and do not appear to be a major determinant for the performance trade-off approach.

Issue: Comfort and Condensation Resistance

Changes in U-factor will change interior window glass temperatures which in turn will influence thermal comfort and condensation. Thermal comfort is maximized by low U-factor windows in both winter and summer. Low SHGC windows increase comfort in the summer while in the winter, higher SHGC windows can often increase thermal comfort, e.g. sitting in sunlight in a chilly room. Condensation in winter is minimized by lowering the U-factor: the specifics depend on climate, the details of window design, and the operation of the house in terms of moisture generation, air infiltration, etc.

NFRC has recently developed a new rating for condensation resistance. While this rating is not part of the ENERGY STAR criteria, maximum allowable U-factors can be used as a simple surrogate for controlling indoor condensation.

Small variations in U-factors and/or SHGCs from the base requirements will not adversely impact peak, comfort, and condensation. However, larger variations may have detrimental effects. For example, in the South/Central zone, a low U-factor, high SHGC window may have equal energy savings to the base 0.4/0.4 criteria; however SHGCs significantly higher than 0.4 may not be desirable (no matter what the compensating heating savings) due to impacts on summer peak and comfort. Therefore, maximum allowable values on U and SHGC have been proposed in this paper for the performance-based trade-off system (see Table 3).

Issue: Minimum Visible Transmittance and SHGC

The option of getting credit for SHGCs lower than 0.4 may encourage some manufacturers to promote low SHGC reflective glass as ENERGY STAR products. For a variety of reasons reflective glass and highly absorbing tinted glass are not normally used in the residential market and it seems unwise for ENERGY STAR to encourage or appear to encourage their use by specifying alternatives that can only be met with such low transmission products. Ultimately, consumer acceptance will dictate whether products are viable or not, and manufacturers will not sell windows with an ENERGY STAR label if consumers will not purchase them for other market reasons. . There are local requirements which not only permit but may require low transmittance glazings. For example some coastal areas in Florida have very low maximum allowable VT (Visible Transmittance) for environmental reasons, e.g., to avoid drawing newly hatched turtles to artificial lighting in settlements near their habitats along the Gulf of Mexico [4] Mediating between these conflicting requirements, this paper proposes a minimum SHGC and VT requirement on all qualifying products, except in locations with maximum allowable TV requirements.. The minimum might be defined in several different ways, in terms of an absolute minimum VT value or in terms of its relationship to SHGC, e.g. VT > 1.1 x SHGC. The appearance of the window e.g. reflective glass is one aspect of this decision as are the actual glass properties. Note that the appearance of the window is a combination of the glass properties themselves and the opaque elements of window sash, frame and dividers. The NFRC total window VT can differ by almost 30% from the VT for the glass alone. A double hung window with dividers and relatively clear glass and thick frame might have the same VT as a window with reflective glass and a minimal frame.

After considering these issues and examining a range of products that appear to be widely sold and accepted in southern climates we suggest a value of 30% as the minimum allowable VT for purposes of this study. Note that this whole window value will translate into a center glass VT of about 35-40% for a typical window and an NFRC SHGC of about 0.25 - 0.30 for typical residential products. We invite additional comment and feedback on manufacturers' experience with sales of low SHGC and low VT in southern climates.

[4] e-mail communication from Arlene Stewart of the Efficient Windows Collaborative in Florida, Sept. 22, 2004.

Candidate Trade-off Equations

The following sections discuss possible trade-offs between SHGC and U-factor for each ENERGY STAR climate zone, based on the results from the iterative *DOE-2* procedures described earlier in this report. In calculating the trade-offs for different cities, we found that the trade-off curves fall into three general conditions depending primarily on the ratio of heating to cooling in a location. In a heating-dominant location, the lines of equal energy use consistently curve up for increasing SHGC, as shown in Figure 2. In a cooling-dominant location, however, the lines of equal energy use consistently curve down for increasing SHGC, as shown in Figure 3.

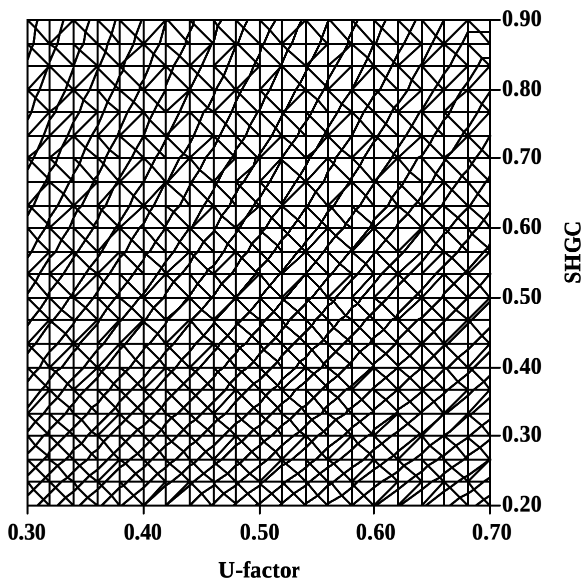


Figure 2. Lines of constant total energy use in Denver
(contour lines at every MBtu total energy use)

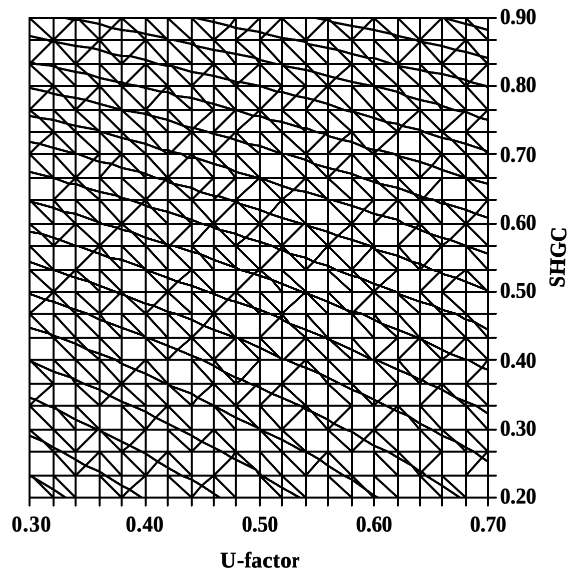


Figure 3. Lines of constant total energy use in Lake Charles
(contour lines at every MBtu total energy use)

In climates with significant amounts of heating and cooling, however, the situation becomes more complex. Since changes in SHGC affect heating and cooling energy use in opposing ways, the net impact on total energy use becomes muted. As shown in Figures 4 and 5, the contour lines are often vertical, indicating that changes in SHGC do not affect total energy use, and hence, provide no trade-off for increases in U-factor.

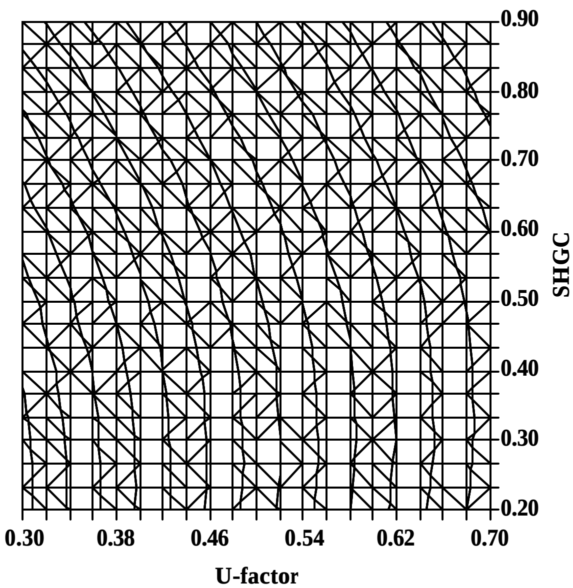


Figure 4. Lines of constant total energy use in a Nashville

(contour lines at every MBtu total energy use)

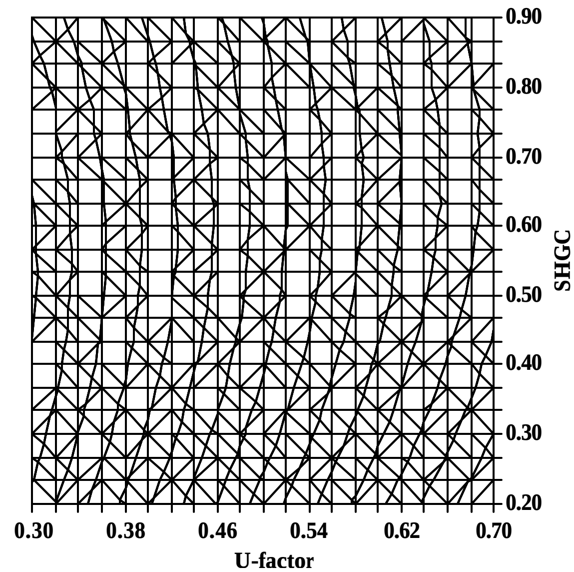


Figure 5. Lines of constant total energy use in Oklahoma City)

(contour lines at every MBtu total energy use)

The most complex situations occur in mild California climates. There, heating and cooling energy use are very sensitive to the amount of solar heat gain. Since heating is most sensitive at low SHGCs and cooling energy use at high SHGCs, in many locations there exist optimum SHGCs yielding the lowest total energy use. As shown in Figures 6 and 7, there are also instances where there are two trade-off solutions, one at the low SHGC and the other at high SHGC. Invariably, though, these trade-offs are for decreased U-factor and not particularly meaningful.

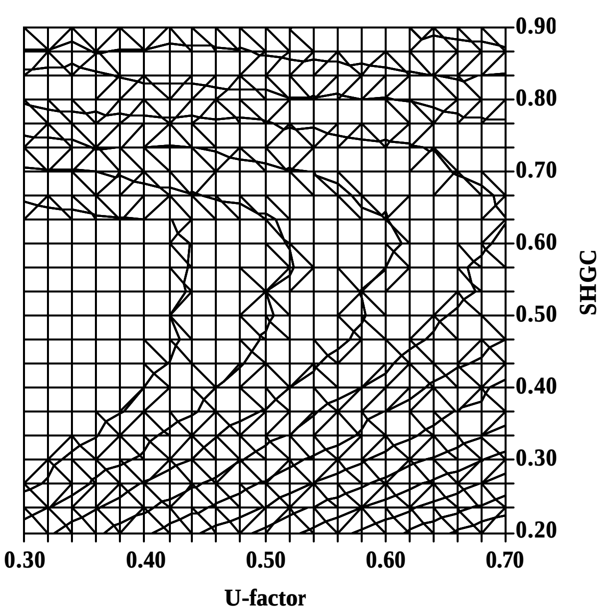


Figure 6. Lines of constant total energy use in a San Diego

(contour lines at every MBtu total energy use)

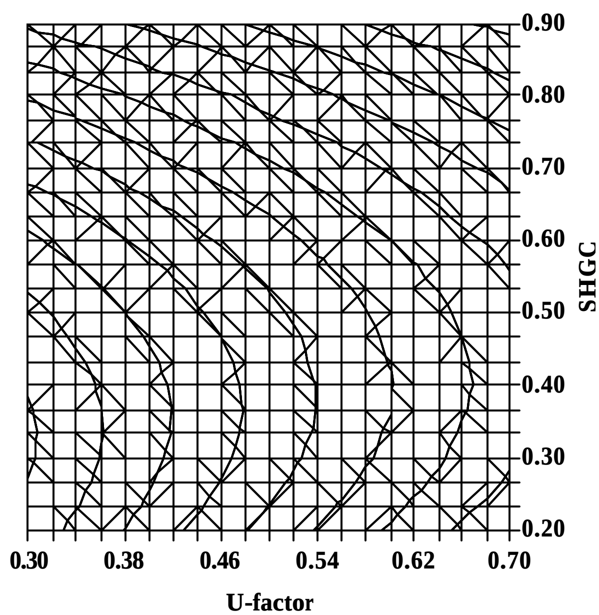


Figure 7. Lines of constant total energy use in Riverside

(contour lines at every MBtu total energy use)

Southern Zone

Analysis has been done for six cities within the Southern Zone (Honolulu, Miami, Lake Charles, Brownsville, Jacksonville, and San Antonio – see map on Figure 8). The ENERGY STAR prescriptive requirements in the Southern Zone are a U-factor less than 0.65 and a SHGC less than 0.40. Since the zone is dominated by cooling, SHGC has the primary impact and changes in U-factor do not substantially change SHGC. Alternatively, selecting an SHGC lower than the required 0.40 value can compensate for an increase in the U-factor above 0.65. In Table 3, iterative *DOE-2* simulations have been used to determine the trade-offs between U-factor and SHGC that result in unchanged total energy consumption. The last two columns of Table 3 show two options for zone-wide trade-off. The first is obtained by iterating over the population-weighted total energy use for all six locations; the second by considering only the four cities with heating loads (San Antonio, Jacksonville, Lake Charles, and Brownsville). This second option has been suggested by

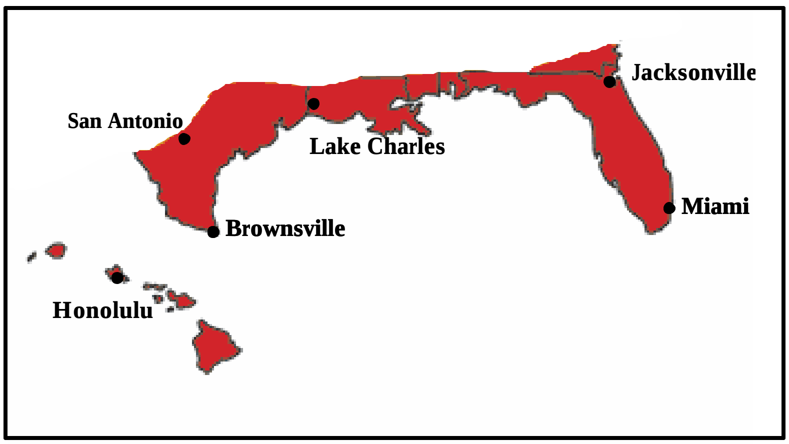


Figure 8. Cities analyzed for ENERGY STAR Window Southern Zone

one reviewer as a more conservative trade-off that would reduce total energy use in all cities, rather than balancing savings in some cities, e.g., Miami and Honolulu, against energy increases in other cities, e.g., Jacksonville and Lake Charles, as in the first option. Both options are intended to be zone-wide trade-offs applicable to any location in the Southern Zone.

Table 3 shows there are consistent trade-offs between reduced SHGC and increased U-factor. However, the upper limit for U-factor increases has been capped at 0.80 in order to still meet IRC energy codes. Trade-offs can also be developed for lower U-factors and higher SHGCs, but these are not suggested here because SHGC values higher than 0.40 would also not meet energy codes.

The trade-offs from Table 3 are also displayed graphically in Figure 9 so that the behavior and trends can be better understood. Brownsville, Jacksonville, San Antonio and Lake Charles all have the same characteristic shape in the relationship between U-factor and SHGC, while Miami and Honolulu show no dependence on U-factor because the heating loads in those two cities are virtually non-existent. The ratio of heating to cooling energies for each city is shown in Figure 10.

Two options for zone-wide trade-offs are shown on the two right-hand columns of Table 3. The first set of zone-wide trade-offs in Column 7 (labeled "Southern") are based on keeping constant the population-weighted total energy use for all six cities. These trade-offs allow relatively small decreases in SHGC to compensate for substantial increases in U-factor. For example, a reduction in SHGC from 0.40 to 0.37 would allow the U-factor to rise from 0.65 to 0.75. The reason for these large trade-offs is that Honolulu and Miami have almost no heating energy use and no energy penalty for increases in window U-factor. Thus, a zone-wide trade-off that includes these two cities would include a large credit for any reduction in SHGC, under the scenario of maintaining equal energy use in the entire zone, these large cooling energy savings are balanced against energy increases in the other four cities.

A more conservative zone-wide trade-off has been created by excluding Miami and Honolulu and requiring that equal total energy use be maintained as well in the remaining four cities (Lake Charles, Brownsville, San Antonio, and Jacksonville). This second set of zone-wide trade-offs is shown in Column 8 (labeled "Southern excl. Hono and Miami). These trade-offs are much smaller, for example requiring a SHGC reduction from 0.40 to 0.33 to compensate for the same rise in U-factor from 0.65 to 0.75. This option is also meant to be zone-wide. It simply makes the trade-off more stringent and provides energy reductions in virtually all cities in the Southern Zone.

Despite the technical viability of the tradeoff process, reviewers questioned the need for a tradeoff in this zone. Over the range of U-value considered, an insulating glass unit is required. For typical glass thicknesses in conventional residential windows the SHGC requirement will almost always be met with the use of a spectrally selective low-E coating. A cursory review of product data in the NFRC product directory, and reinforced by comments from consultants who serve the southern market, suggests that use of such a coating in an insulating glass unit, even with a suboptimal air space will readily meet the current U value requirement, with no need to pursue a tradeoff strategy. We invite additional comment on product lines that are marketed in this region. So while the tradeoff developed here might be technically feasible in the southern zone we see no compelling practical reason to suggest it at this time.

Table 3. Trade-offs for cities in the Southern Zone

U-factor	**SHGC Trade-off**							
	Jacksonville	Miami	Honolulu	Lake Charles	Brownsville	San Antonio	**Southern**	**Southern, excl. Hono & Miami**
0.65	0.40	0.40	0.40	0.40	0.40	0.40	**0.40**	**0.40**
0.66	0.39	0.40	0.40	0.39	0.40	0.39	**0.40**	**0.39**
0.67	0.39	0.40	0.40	0.38	0.40	0.39	**0.39**	**0.39**
0.68	0.38	0.40	0.40	0.37	0.39	0.38	**0.39**	**0.38**
0.69	0.38	0.40	0.40	0.37	0.39	0.37	**0.39**	**0.37**
0.70	0.37	0.40	0.40	0.36	0.39	0.36	**0.39**	**0.37**
0.71	0.36	0.40	0.41	0.35	0.39	0.36	**0.38**	**0.36**
0.72	0.36	0.40	0.41	0.34	0.39	0.35	**0.38**	**0.35**
0.73	0.35	0.40	0.41	0.33	0.39	0.34	**0.38**	**0.35**
0.74	0.34	0.40	0.41	0.32	0.38	0.33	**0.38**	**0.34**
0.75	0.34	0.40	0.41	0.31	0.38	0.32	**0.37**	**0.33**

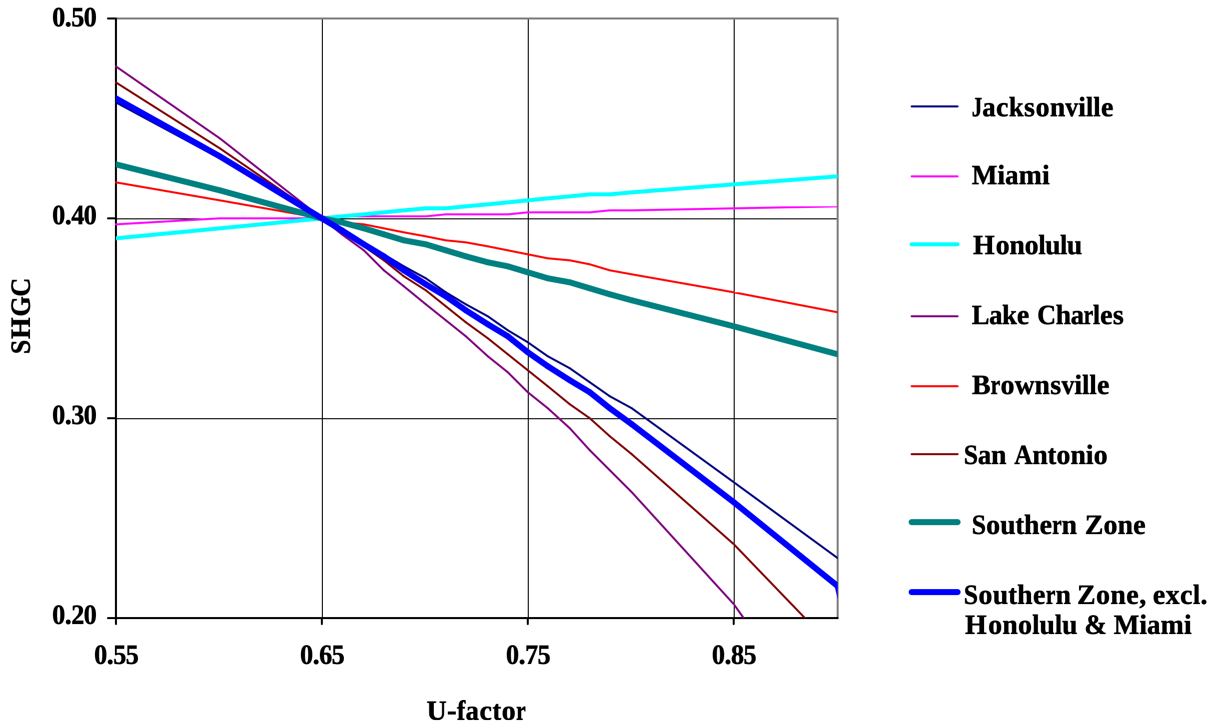


Figure 9. Southern Zone Trade-off Curves

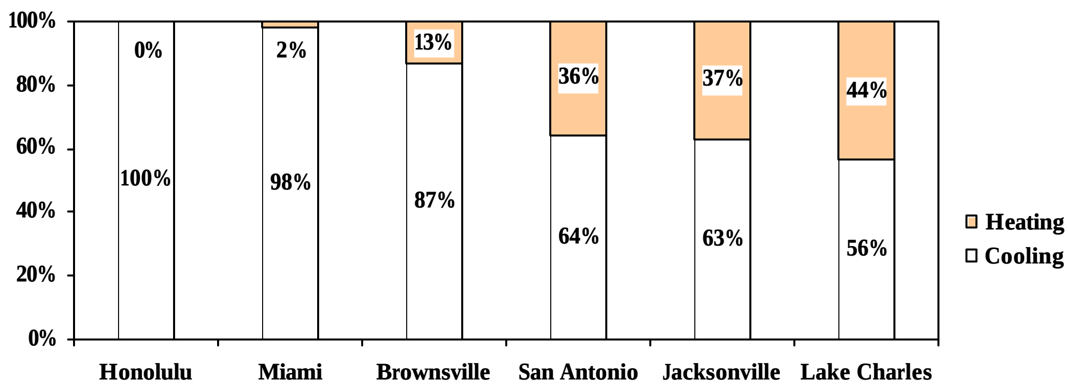


Figure 10. Heating and Cooling Percentages for Cities in the Southern Zone

South/Central Zone

Analysis has been done for 17 cities within the South/Central Zone (Birmingham, Phoenix, Oakland, Sunnyvale, San Diego, El Toro, Pasadena, Riverside, Red Bluff, Sacramento, Atlanta, Las Vegas, Oklahoma City, Charleston, Memphis, El Paso, and Fort Worth - see map in Figure 11). The ENERGY STAR prescriptive requirements in the South/Central Zone are a U-factor less than 0.40 and a SHGC less than 0.40. The analysis finds that contradictory trade-offs existed between different cities in the region. Furthermore, for many cities, particularly those in California, there is no possible trade-off in SHGC for increases in U-factor. Consequently, when all 17 cities were considered together weighted by population, zone-wide trade-offs were found only for decreases in U-factor (see Table 4 and Figure 12).

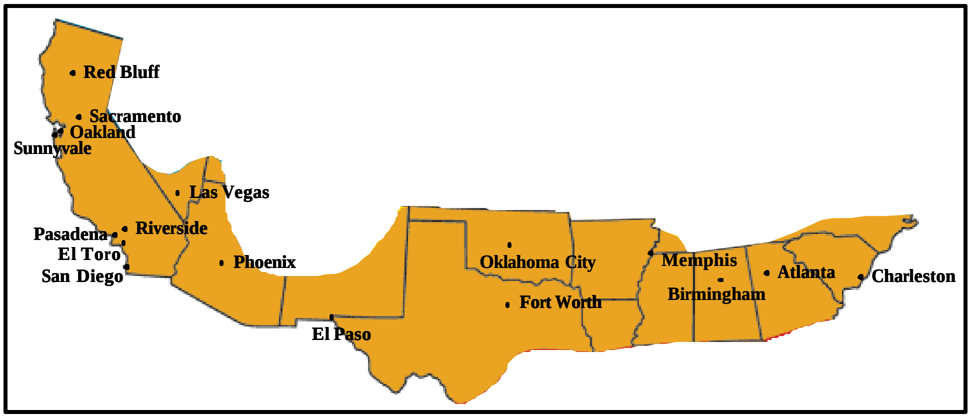


Figure 11. Cities analyzed in ENERGY STAR Windows South/Central Zone

In Table 4, iterative *DOE-2* simulations have been used to determine the trade-offs between U-factor and SHGC that result in unchanged total energy consumption. The last two columns of Table 4 show two options for zone-wide trade-off. The first is obtained by iterating over the population-weighted total energy use for all 17 locations; the second by excluding the eight California cities and iterating over the population-weighted total energy use for the remaining 9 locations. The trade-offs for the 17 cities and the first options are plotted in Figure 12. Table 4 indicates that 7 of the cities (5 in California) show no trade-offs, and 3 of the remaining 10 cities show partial trade-offs for increases in U-factor from the base case 0.40.

Table 4. Trade-offs for cities in the South/Central Zone

U-factor	SHGC Trade-off									
	Birmingham	Phoenix	Oakland	Sunnyvale	San Diego A	San Diego B	El Toro	Pasadena	Riverside	Red Bluff
0.30	0.70	0.45	0.31	0.30	0.28	0.72	0.23	0.15	0.06	0.75
0.32	0.66	0.44	0.33	0.32	0.30	0.71	0.25	0.18	0.10	0.70
0.34	0.62	0.43	0.35	0.34	0.33	0.71	0.28	0.21	0.13	0.65
0.36	0.58	0.42	0.37	0.36	0.35	0.70	0.32	0.25	0.17	0.59
0.38	0.51	0.41	0.38	0.38	0.38	0.67	0.36	0.29	0.22	0.52
0.40	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.64**	**0.40**	**0.40**	**0.40**	**0.40**
0.41	NS	0.39	0.41	0.41	0.41	0.64	NS	NS	NS	NS
0.42	NS	0.39	0.42	0.42	0.45	0.64	NS	NS	NS	NS
0.43	NS	0.38	0.43	0.43	0.47	0.64	NS	NS	NS	NS
0.44	NS	0.38	0.43	0.44	0.51	0.60	NS	NS	NS	NS
0.45	NS	0.37	0.44	0.45	0.53	NS	NS	NS	NS	NS

U-factor	SHGC Trade-off								
	Sacramento	Atlanta	Las Vegas	Oklahoma City	Charleston	Memphis	El Paso	Ft. Worth	**South/Central All Cities**	**South/Central non-Calif**
0.30	0.08	0.89	0.60	0.03	0.59	0.77	0.61	0.58	**0.02**	**0.63**
0.32	0.12	0.84	0.57	0.09	0.56	0.71	0.58	0.55	**0.06**	**0.59**
0.34	0.16	0.78	0.54	0.15	0.53	0.66	0.55	0.52	**0.11**	**0.55**
0.36	0.22	0.72	0.50	0.22	0.49	0.60	0.51	0.48	**0.16**	**0.51**
0.38	0.29	0.63	0.46	0.30	0.45	0.52	0.46	0.45	**0.23**	**0.46**
0.40	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**
0.41	NS	NS	0.36	0.46	0.37	0.28	0.36	0.38	**NS**	**0.36**
0.42	NS	NS	0.32	0.56	0.34	NS	0.26	0.35	**NS**	**0.31**
0.43	NS	NS	0.26	NS	0.29	NS	NS	0.32	**NS**	**0.24**
0.44	NS	NS	NS	NS	0.21	NS	NS	0.28	**NS**	**NS**
0.45	NS	NS	NS	NS	NS	NS	NS	0.23	**NS**	**NS**

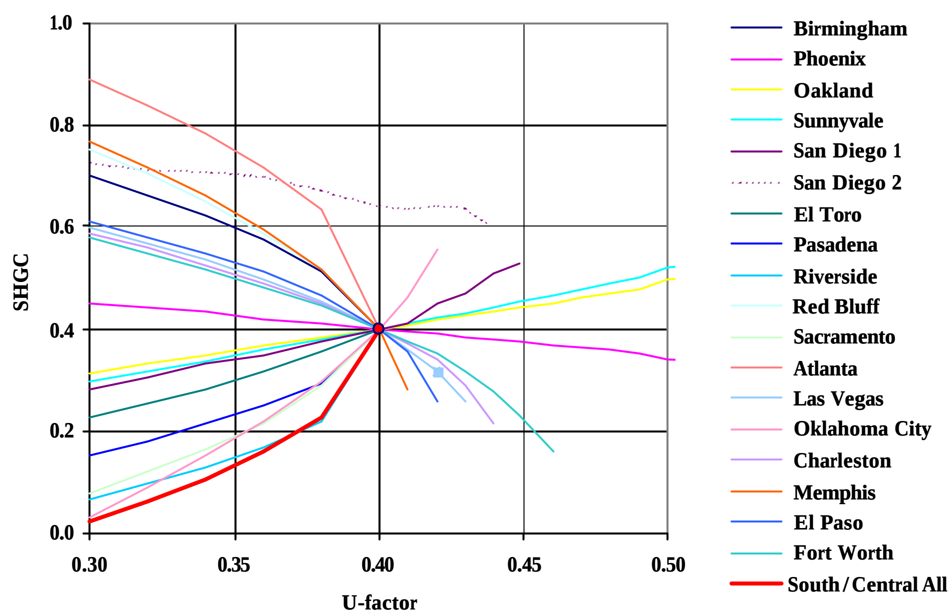


Figure 12. South/Central Zone Trade-off Curves

There is the interesting case of San Diego, shown in Table 4 and Figure 12 as “San Diego A” and “San Diego B” (see also Figure 6), where there are two solutions for the trade-off. As a result, even at the base case U-factor of 0.40, it is possible to relax the SHGC to 0.64 and achieve the same energy performance as at SHGC 0.40.

The large variation in the slopes of the trade-off curves is related to the large variation of heating/cooling ratios within the cities in the South/Central Zone. Figure 13 shows that the heating/cooling ratios in the South/Central zone range from 89% cooling in Phoenix to 99% heating in Oakland (see Figure 13). Because of the conflicting trade-offs among the cities and the large number of no solutions for increases

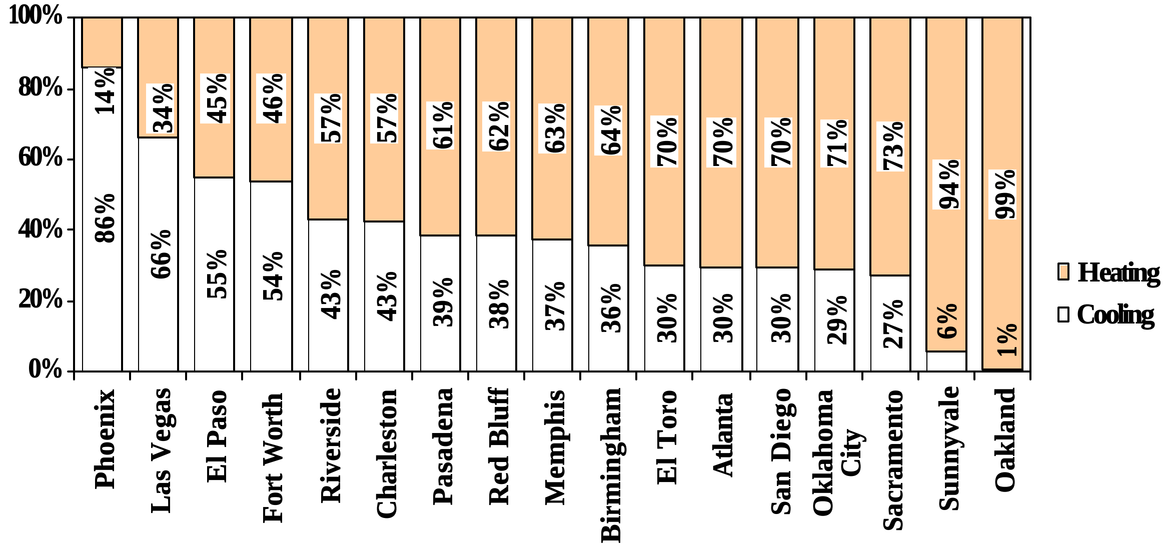


Figure 13. Heating/Cooling Ratios in cities in the South/Central Zone

in U-factor, the zone-wide population-weighted trade-off including all 17 cities is very unrealistic. It “permits” meaningless trade-offs between very low SHGC and decreases in U-factor, and no trade-offs for increases in U-factor beyond the base case value of 0.40. Based on such results, an earlier draft of this report concluded in January 2004 that it was not possible to produce a technically defensible zone-wide trade-off equation for the South/Central Zone.

Subsequent analysis noted that most of the contradictory trade-offs and no solution cases occur in the eight California locations. If these locations are left out of the zone-wide aggregation, the resulting trade-offs are reasonably consistent (see last Column of Table 4 and Figure 14).

With the exception of Oklahoma City, which is heating-dominant and hence has a trade-off curve with an increasing slope, the remaining 9 cities are all cooling-dominant and have trade-off curves with decreasing slopes. Of these, one (Atlanta) has no solutions, and the rest partial trade-off solutions for increased U-factors. The last column in Table 4 and the thick line in Figure 14 show the zone-wide trade-off for the South/Central Zone excluding the California locations. This trade-off permits a modest increase in U-factor up to 0.42 for a decrease in SHGC from 0.40 down to 0.31. Since these trade-offs have been calculated by iterative *DOE-2* simulations that keep the population-weighted total energy use in the 9 cities constant, the cumulative market impact on total energy use should be zero. Windows with SHGC of .31 or less are not common but are listed by a number of manufacturers in the NFRC certified products directory. In prior industry meetings with DOE and in comments regarding these performance-based tradeoffs, members of the aluminum frame industry confirmed that the .42 U value suggested here was achievable as a viable, marketable product.

A suggestion has been made by one reviewer that the U-factor requirement simply be relaxed from 0.40 to 0.42 without an associated SHGC reduction. As shown in the assessment of market impacts from various options later in this report, such a change would increase home energy use by an average of 4 Therms per year or 1% of total energy use. Furthermore, this would represent a clear change in the current ENERGY STAR program, which DOE has stated on numerous occasions is not the intent for developing the performance-based rating system.

In summary, due to the differences in climate and heating/cooling ratios, there is no single viable solution for the entire zone. The only justifiable trade-off from the point of equal energy use is one that excludes locations in California. The arguments for this option are: (1) it is the only technically valid trade-off option that maintains the objective of equal energy use, and (2) the exclusion of California is the most straightforward and simplest to administer, compared to any other possible geographical or climate differentiation. It does add some modest administrative complexity to the program which is limited by the simple exclusion of California. While there are not many products on the market today that meet the .31 SHGC requirement these could be readily manufactured based on existing technologies in the marketplace.

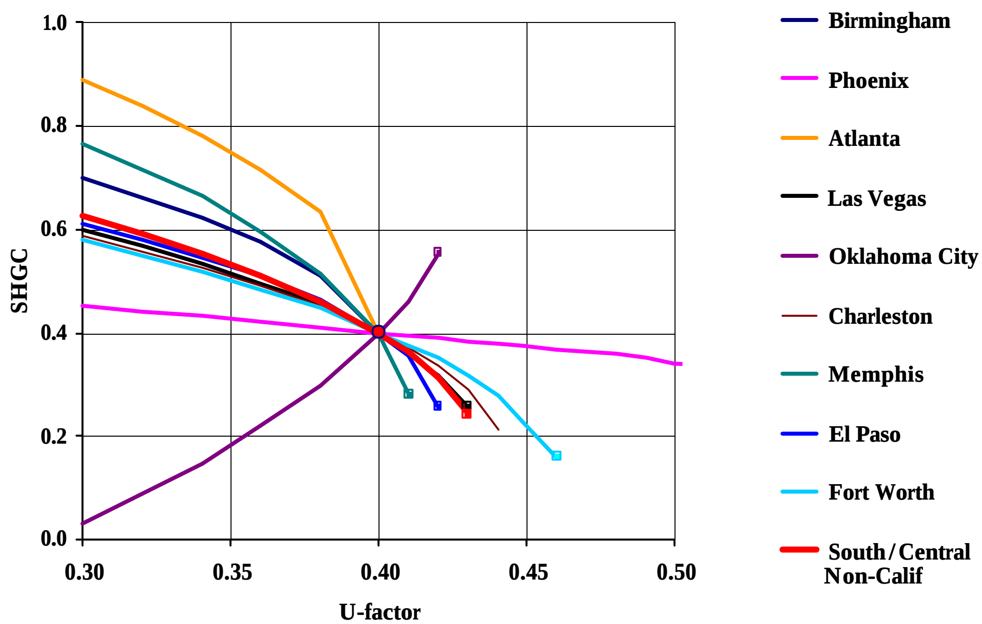


Figure 14. South/Central Zone Trade-off Curves excluding California climates

North/Central Zone

Analysis was done for 5 cities within the North/Central Zone (Washington, Kansas City, Raleigh, Albuquerque, and Nashville - see map in Figure 15). The ENERGY STAR prescriptive requirements in the South/Central Zone are a U-factor less than 0.40 and a SHGC less than 0.55.

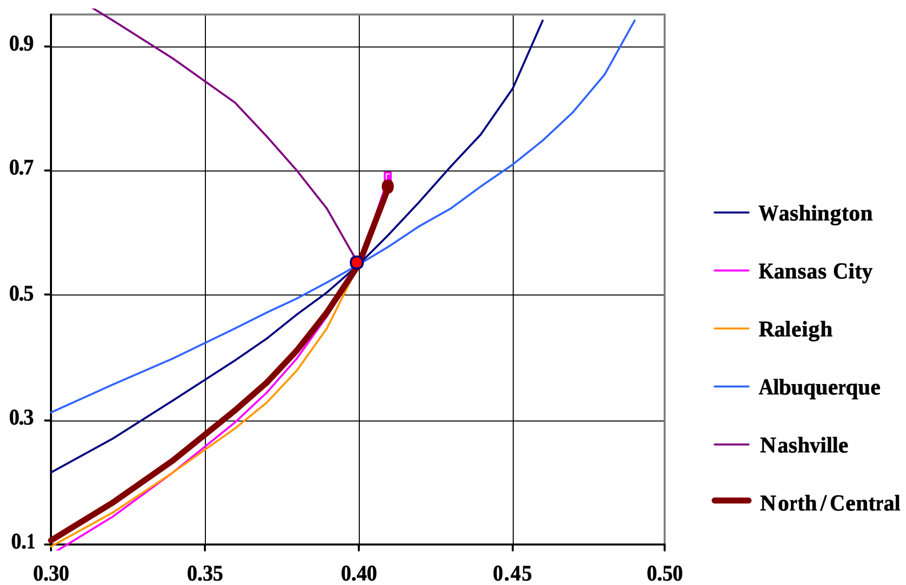
Figure 15. Cities analyzed for ENERGY STAR Window North/Central Zone

The calculated city-by-city and zone-wide trade-off curves for the North/Central Zone are shown in Table 5 and Figure 16. Similar to the South/Central Zone, Table 5 shows that the North/Central Zone is a mix of cities with no solutions (Raleigh), partial solutions (Kansas City and Nashville), or with slight negative trade-offs (large increases in SHGC to compensate for small increases in U-factors) in Washington and Albuquerque. The slopes of the trade-off curves depend primarily on the ratio of heating to cooling in the simulated buildings, as shown in Figure 17.

The zone-wide trade-off curve based on the population-weighted total energy use of all five cities is shown on the right-hand column of Table 5 and the thickened line in Figure 16. There is a meaningless trade-off of lower SHGC for lowered U-factor, and a small trade-off of 0.67 SHGC for a 0.01 increase in U-factor to 0.41. Such a small and limited trade-off is not considered worthwhile.

Table 5. Trade-offs for cities in the North/Central Zone

U-factor	**SHGC Trade-off**					
	Washington	Kansas City	Raleigh	Albuquerque	Nashville	**North/Central**
0.30	0.22	0.08	0.10	0.31	1.00	**0.11**
0.32	0.27	0.15	0.15	0.36	0.94	**0.17**
0.34	0.33	0.21	0.21	0.40	0.88	**0.24**
0.36	0.40	0.29	0.29	0.45	0.81	**0.31**
0.37	0.43	0.34	0.33	0.47	0.75	**0.36**
0.38	0.47	0.40	0.38	0.50	0.70	**0.41**
0.39	0.50	0.47	0.45	0.52	0.64	**0.47**
0.40	**0.55**	**0.55**	**0.55**	**0.55**	**0.55**	**0.55**
0.41	0.60	0.69	0.58	0.67	NS	**NS**
0.42	0.65	0.61	NS	NS	NS	**NS**
0.43	0.71	0.64	NS	NS	NS	**NS**
0.44	0.76	0.67	NS	NS	NS	**NS**
0.45	0.83	0.71	NS	NS	NS	**NS**
NS	NS	NS	NS	NS	NS	**NS**
NS	NS	NS	NS	NS	NS	**NS**
NS	NS	NS	NS	NS	NS	**NS**



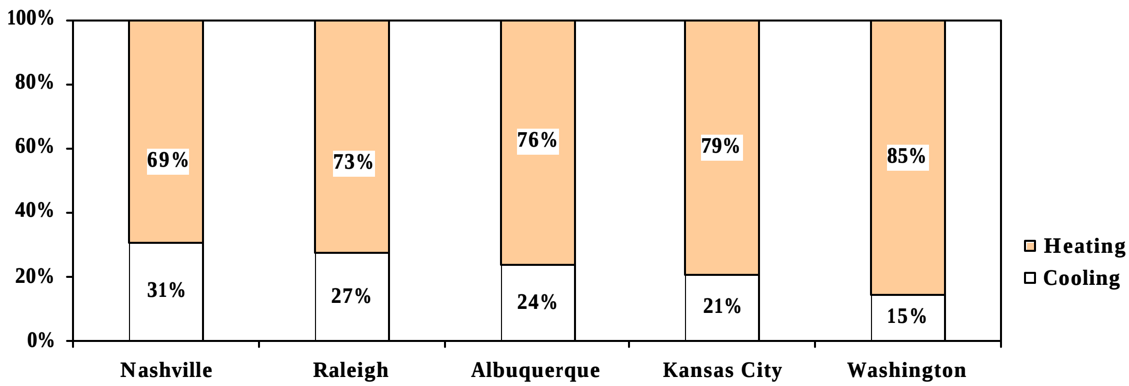


Figure 16. North/Central Zone Trade-off Curves
Figure 17. Heating and Cooling Ratios for cities in the North/Central zone

Northern Zone

Analysis was done for 23 cities within the North/Central Zone (Anchorage, Denver, Boise, Chicago, Boston, Portland ME, Minneapolis, Great Falls, Bismarck, Omaha, Reno, Buffalo, New York, Dayton, Medford, Portland OR, Philadelphia, Pittsburgh, Salt Lake City, Burlington, Seattle, Madison, and Cheyenne - see map in Figure 18). The ENERGY STAR® prescriptive requirement in the Northern Zone is a U-factor less than 0.35 with no SHGC requirement.

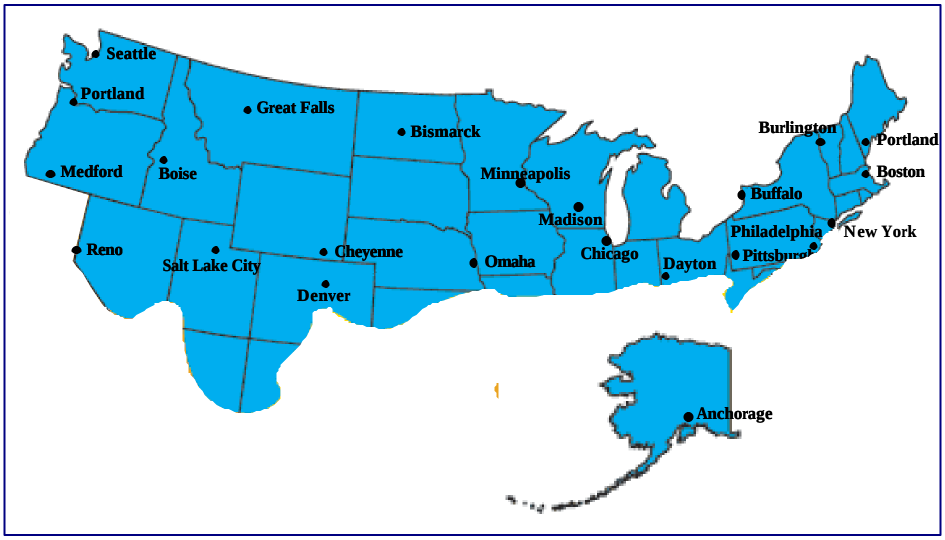


Figure 18. Cities analyzed for ENERGYSTAR® Window Northern Zone

Therefore in order to establish a base energy consumption for trade-offs we must define a nominal base case SHGC. There have been several suggestions for how to select this value, considering both what is allowable as well as what is typically sold into these markets. Considering the various arguments and the wide range of proposed plausible alternatives (0.27 - 0.55) for this analysis we have selected 0.40. In this heating-dominated zone, trade-offs will be based on increasing SHGC because the increased solar gain will help offset the winter heating load, which will allow the U-factor to increase. By comparison the associated increase in summer cooling energy is a relatively small impact.

Table 6 shows the equivalent SHGC associated with different variations of U-factor from the base case of 0.35. Figure 19 shows that all the cities in the zone are consistent and relatively "well-behaved" with respect to each other. Although the equivalent annual energy criterion is met there are several concerns with these trade-offs. First many states in the Northern zone have or are moving toward building codes in which a 0.35 U-factor is a requirement for new construction or major renovations requiring building permits. The only conditions under which a higher U-factor might be allowable would be when a performance-based compliance path is chosen for the overall building, or in the case of small retrofit or replacement projects that do not require code compliance. Furthermore there are several other factors that argue against raising the allowable U-factor much beyond the 0.35 limit. First, peak heating load is determined by overall building heat loss to which windows contribute. Relaxing the U-factor will therefore increase peak heating loads. Higher U-factors will reduce interior glass temperatures, reducing thermal comfort and increasing the probability of condensation.

Therefore, although we were able to derive technically valid solutions for trade-off alternatives with equal energy, because of the code requirements limiting U-factors to 0.35 and below, the allowable U-factor should not go higher than the maximum code value and therefore there is not a viable trade-off possible.

Table 6. Trade-offs for cities in the Northern Zone

U-factor	SHGC Trade-off											
	Anchor age	Denver	Boise	Chicago	Boston	Portland ME	Minnea polis	Great Falls	Bis marck	Omaha	Reno	Buffalo
0.27	0.22	0.26	0.22	0.18	0.24	0.27	0.20	0.23	0.22	0.15	0.27	0.20
0.29	0.26	0.29	0.26	0.23	0.28	0.30	0.25	0.27	0.26	0.21	0.30	0.24
0.31	0.31	0.33	0.31	0.29	0.32	0.33	0.30	0.31	0.31	0.27	0.33	0.29
0.33	0.35	0.36	0.35	0.34	0.36	0.37	0.35	0.36	0.35	0.33	0.37	0.35
0.35	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**
0.36	0.42	0.42	0.42	0.43	0.42	0.42	0.43	0.42	0.42	0.44	0.42	0.43
0.37	0.45	0.44	0.45	0.46	0.44	0.43	0.46	0.45	0.45	0.48	0.43	0.46
0.38	0.47	0.46	0.48	0.50	0.46	0.45	0.48	0.47	0.48	0.53	0.45	0.48
0.39	0.49	0.48	0.50	0.53	0.48	0.47	0.51	0.49	0.50	0.58	0.47	0.52
0.40	0.51	0.50	0.53	0.57	0.51	0.49	0.54	0.52	0.53	0.63	0.49	0.55
U-factor	**SHGC Trade-off**											
	New York	Dayton	Med ford	Port land OR	Phila delphia	Pitts burgh	Salt Lake C	Burling ton	Seattle	Madi son	Che yenne	**North ern**
0.27	0.20	0.20	0.17	0.23	0.19	0.18	0.20	0.23	0.27	0.22	0.27	**0.21**
0.29	0.25	0.24	0.22	0.27	0.24	0.23	0.24	0.27	0.30	0.26	0.31	**0.25**
0.31	0.30	0.29	0.27	0.31	0.29	0.28	0.29	0.31	0.33	0.30	0.34	**0.30**
0.33	0.35	0.35	0.33	0.35	0.34	0.34	0.34	0.36	0.36	0.35	0.37	**0.35**
0.35	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**
0.36	0.42	0.43	0.44	0.43	0.43	0.43	0.43	0.42	0.42	0.43	0.42	**0.43**
0.37	0.45	0.46	0.48	0.45	0.46	0.47	0.46	0.44	0.44	0.45	0.43	**0.45**
0.38	0.48	0.49	0.52	0.48	0.50	0.50	0.49	0.47	0.45	0.48	0.45	**0.48**
0.39	0.51	0.52	0.57	0.50	0.53	0.54	0.53	0.49	0.47	0.50	0.47	**0.51**
0.40	0.54	0.55	0.63	0.52	0.56	0.57	0.57	0.51	0.49	0.53	0.48	**0.54**

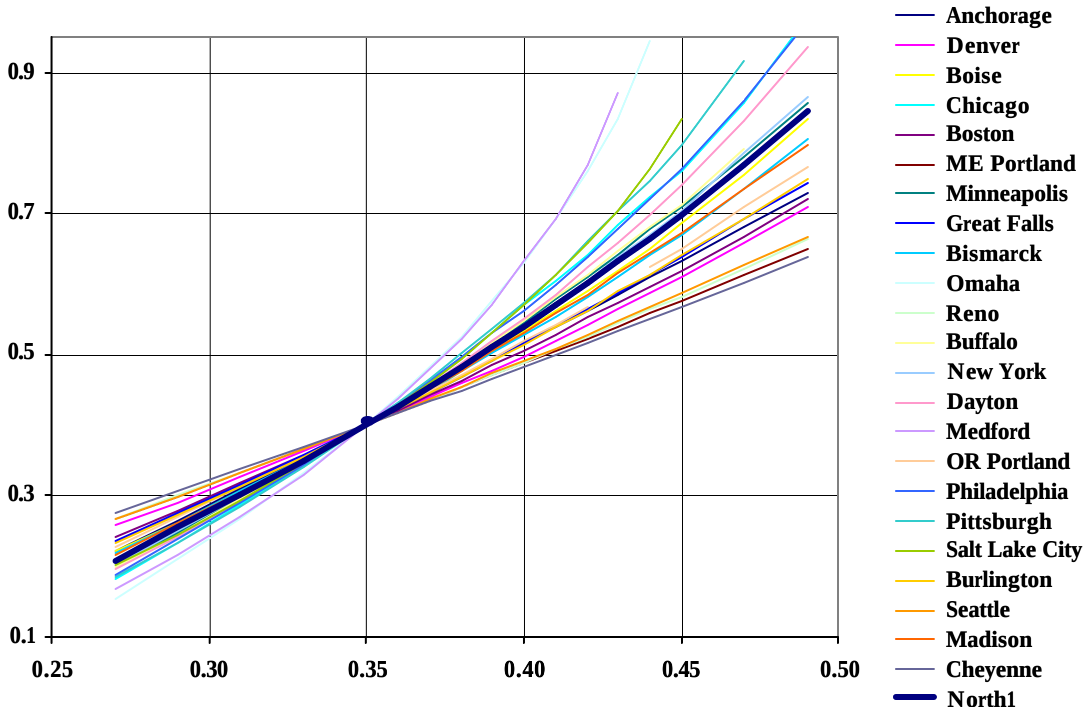


Figure 19. Northern Zone Trade-off Curves

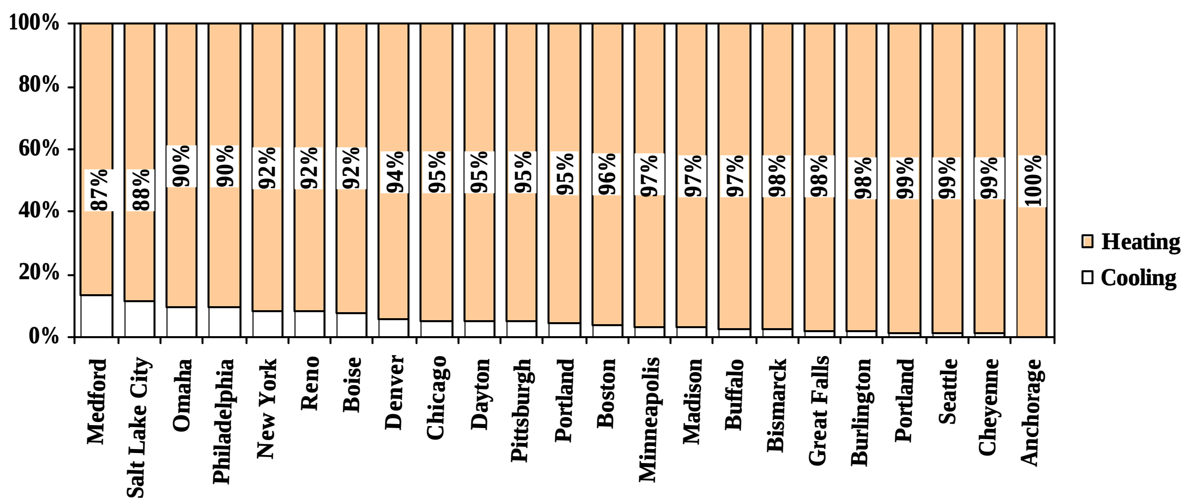


Figure 20. Heating and Cooling Ratios of Cities in the Northern Zone

Northern Zone - Future High Performance Windows

In the current trade-off scenarios, because ENERGY STAR criteria will follow building code values, in many cases the potential trade-offs cannot be implemented as they would exceed constraints from the energy codes. The DOE long term 2020 vision for Zero Energy Buildings will require windows with U-factors in the range of 0.1-0.2 with dynamic control of solar gain. At that point, the ENERGY STAR representing the best on the market might require dynamic windows, thus requiring a new definition for U-factor and SHGC. However, in the more immediate future, we would expect that technology will provide new, cost-effective options for more thermally efficient windows, but that the building codes will not move as quickly to mandate those lower U-factors. New ENERGY STAR criteria might respond to these market leaders and thus provide additional opportunity for trade-offs that do not currently exist. To provide an idea for how this might work we consider the following case: imagine a new round of technological and cost improvements that makes a U-0.25 window readily available in the marketplace. Assume that codes remain at U- 0.35 but that ENERGY STAR responds by targeting a U-factor of 0.25 and a SHGC of 0.40 for market-leading windows in the Northern zone. It would then be possible to generate trade-offs for U-factors between the ENERGY STAR value, U-0.25 and the Code requirement of U-0.35. Table 7 below illustrates the SHGC associated with each 0.01 increment in U-factor required to maintain constant overall energy use. Similar approaches can be taken with using other criteria as a new ENERGY STAR starting point. The same qualifiers exist as in the previous discussion regarding the impacts of increased U-factor on comfort, peak load, condensation, but since the "worst" window in this trade-off is a U-0.35 window, which is widely, accepted today, it seems there would not be a serious problem with non-energy performance constraints.

Table 7. Future high performance window trade-offs for cities in the Northern Zone

U-factor	**SHGC Trade-off**											
	Anchorage	Denver	Boise	Chicago	Boston	Portland ME	Minneapolis	Great Falls	Bismarck	Omaha	Reno	Buffalo
0.21	0.30	0.32	0.30	0.28	0.31	0.33	0.29	0.31	0.30	0.25	0.32	0.29
0.23	0.35	0.36	0.35	0.34	0.35	0.36	0.34	0.35	0.35	0.32	0.36	0.34
0.25	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**
0.26	0.43	0.42	0.43	0.43	0.42	0.42	0.43	0.42	0.43	0.44	0.42	0.43
0.27	0.45	0.44	0.46	0.47	0.44	0.44	0.46	0.45	0.45	0.49	0.44	0.46
0.28	0.48	0.46	0.49	0.51	0.47	0.46	0.49	0.47	0.48	0.54	0.46	0.50
0.29	0.50	0.49	0.52	0.55	0.49	0.48	0.53	0.50	0.51	0.60	0.48	0.53
0.30	0.53	0.51	0.55	0.59	0.51	0.49	0.56	0.52	0.54	0.67	0.50	0.57
0.31	0.55	0.53	0.58	0.63	0.54	0.51	0.59	0.55	0.57	0.74	0.52	0.60
0.32	0.58	0.56	0.61	0.67	0.56	0.53	0.63	0.58	0.60	0.83	0.54	0.64
0.33	0.60	0.58	0.65	0.71	0.59	0.55	0.67	0.60	0.63	0.97	0.56	0.68
0.34	0.63	0.61	0.68	0.76	0.61	0.57	0.70	0.63	0.67	1.00	0.59	0.71
0.35	0.66	0.64	0.73	0.81	0.64	0.59	0.74	0.66	0.70	1.00	0.61	0.75
U-factor	**SHGC Trade-off**											
	New York	Dayton	Medford	Portland OR	Philadelphia	Pittsburgh	Salt Lake C	Burlington	Seattle	Madison	Cheyenne	**Northern**
0.21	0.29	0.28	0.25	0.30	0.28	0.27	0.28	0.31	0.32	0.30	0.33	**0.29**
0.23	0.34	0.34	0.32	0.35	0.33	0.33	0.34	0.35	0.36	0.35	0.37	**0.34**
0.25	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**
0.26	0.43	0.43	0.44	0.43	0.43	0.44	0.44	0.42	0.42	0.43	0.42	**0.43**
0.27	0.46	0.46	0.49	0.45	0.47	0.47	0.47	0.45	0.44	0.46	0.43	**0.46**
0.28	0.49	0.50	0.55	0.47	0.50	0.51	0.51	0.47	0.46	0.48	0.45	**0.49**
0.29	0.52	0.53	0.61	0.50	0.54	0.55	0.56	0.50	0.48	0.51	0.47	**0.52**
0.30	0.56	0.57	0.68	0.53	0.58	0.60	0.60	0.53	0.50	0.54	0.49	**0.55**
0.31	0.59	0.61	0.79	0.56	0.63	0.65	0.65	0.55	0.52	0.57	0.51	**0.59**
0.32	0.63	0.65	0.96	0.59	0.67	0.70	0.71	0.58	0.54	0.60	0.52	**0.62**
0.33	0.66	0.70	1.00	0.62	0.72	0.75	0.79	0.61	0.56	0.63	0.54	**0.66**
0.34	0.70	0.74	1.00	0.65	0.76	0.80	0.94	0.64	0.58	0.67	0.56	**0.70**
0.35	0.75	0.79	1.00	0.68	0.82	0.86	1.00	0.67	0.60	0.70	0.58	**0.73**

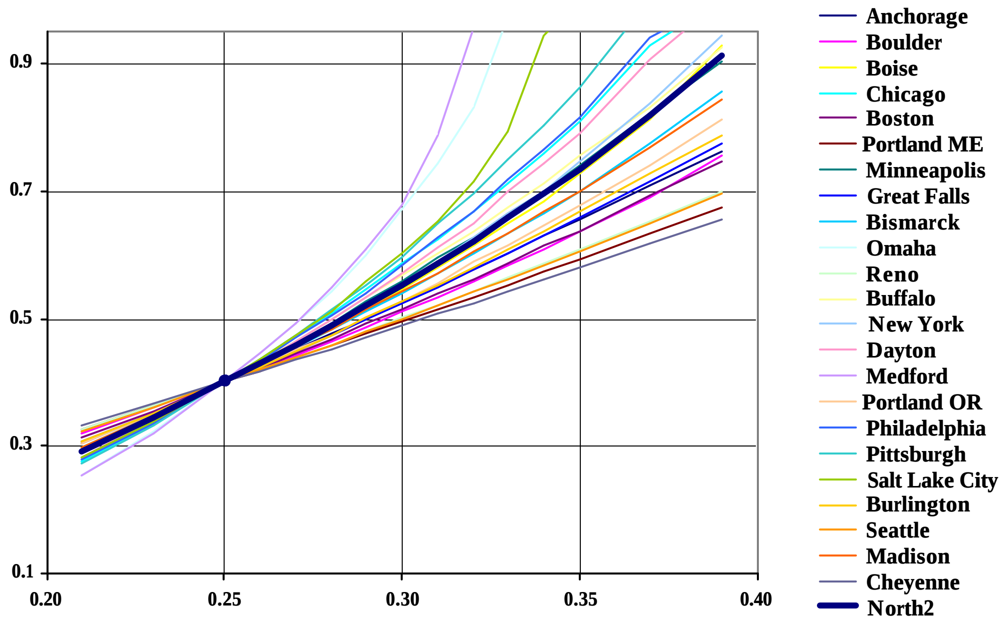


Figure 21. Northern Zone future high-performance window trade-off curves

Acknowledgements

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Appendix 1: Assessment of Energy Impact of Proposed Trade-off Curves

This study concludes that zone-wide trade-off curves are technically feasible only for the Southern and South/Central zones with some adjustments. We also demonstrated a technically viable solution for future high-performance windows in the Northern zone. In this section the potential impacts of this trade-off on the aggregate energy use in these three zones are assessed by comparing the aggregate total energy use of all cities of each zone calculated by *DOE-2* for a representative window trade-off option and the prescriptive ENERGY STAR window. To address the concern raised by several reviewers of the January draft of this report about an "apples to oranges" comparison with the impact analysis done by Barbour and Arasteh (2002) of the ENERGY STAR program, this assessment is done in two ways: (1) using the procedures and assumptions described in this report, and (2) using the procedures previously developed by Barbour and Arasteh in the 2002 study.

There are numerous differences between these two procedures in estimating the total energy use of windows in the US residential stock. These include: (1) the current study is based on a 2000 ft^2 prototype building, while Barbour and Arasteh is based on a 1540 ft^2 prototype building, (2) the current study uses population weights to account for differing amounts of housing and retrofit activity represented by each base city, while Barbour and Arasteh 2002 did a straight average of the 48 cities in the data base, (3) the current study calculates building energy use for two vintages of houses in 51 cities using *DOE-2*, while Barbour and Arasteh calculated them for one vintage in 48 cities using regression equations developed in 1998 from a data base of *DOE-2* runs (see Arasteh et al. 2000), (4) the current study uses a fuel source multiplier of 3.0, whereas Barbour and Arasteh 2002 used a multiplier of 3.32, and (5) the current study estimated the total energy use in each climate zone by multiplying the DOE-2 results by the estimated size of the building market, whereas Barbour and Arasteh normalized the calculated energy savings from different window measures to the national residential energy consumption reported by RECS. The last difference is probably the most important, since in this normalization procedure, Barbour and Arasteh 2002 accounted for the occurrence of electric heating, which after accounting for the fuel source multiplier, increased the aggregate heating energy use by as much as 30% in the warmer climates. In this study, however, heating is always assumed to be provided by natural gas, resulting in lower total heating energy use in each climate zone. Since trade-offs often have opposing effects on heating and cooling energy use, the increased heating energy use assumed by Barbour and Arasteh 2002 can affect the calculated trade-offs.

Appendix 1A: Assessment of Market Impact Based on the Aggregation Method used in this Study

We assessed the potential energy impacts of each strategy discussed above, even where significant issues were noted with a particular strategy. These energy impacts are reviewed in this section both in terms of aggregates for entire zone as well as for individual cities.

To assess the aggregate market impact of the trade-off curves, the following assumptions about the market size for ENERGY STAR windows were adapted from Barbour and Arasteh 2002: (1) since windows have an average lifetime of 40 years, 2.5% of the existing housing stock are considered, (2) 100% of the new housing stock is considered. Consequently, the window market for existing and new housing is roughly similar in size which is also consistent with recent annual market sales surveys.

In the Southern Zone, it is assumed that 10% of both the new and existing vintages in each city will use the trade-off option of a U-factor/SHGC combination of 0.72/0.38 (proposed curve no. 1) or 0.72/0.35 (proposed curve no. 2) in lieu of the prescriptive criteria of 0.65/0.40.

Similarly, in the South/Central Zone, it is assumed that 10% of both the new and existing vintages in each city will use the trade-off option of a U-factor/SHGC combination of 0.42/0.31 (proposed curve no. 2 excluding California locations) in lieu of the prescriptive criteria of 0.40/0.40. However, the simple allowance of the U-factor to be increased to 0.42 as suggested by one reviewer is assumed to be used by 50% of all houses, since there would be no reason for any manufacturer to exceed that requirement.

To assess the likely energy impact of the potential trade-off for high-performance windows in the future, it is also assumed that 10% of both the new and existing vintages in each city will use the trade-off option of a U-factor/SHGC combination of 0.30/0.55 in lieu of the hypothetical prescriptive criteria of 0.25/0.40.

DOE-2 simulations have been done for the different window conditions in all cities in the three zones, and the results aggregated with the population weights described in Appendix C. The results are shown in Table 8.

Table 8. Energy impact of representative trade-offs for windows in the Southern and South/Central zones and for hypothetical high-performance windows in the Northern zone

Zone	Window U-factor and SHGC	Total energy use (trillion Btu's)	Difference in total energy use (trillion Btu's)	Percent difference in total energy use (%)	Average total energy use per affected house (MBtu)	Percent diff. in average total energy use per affected house (%)
Southern	0.65/0.40 (base case)	23.20			56.97	
Southern	0.72/0.38 (trade-off)	23.19	0.00	0.00	56.96	0.03
Southern	0.72/0.35 (trade-off)	23.16	0.03	0.15	56.12	1.49
South/Central	0.40/0.40 (base case)	50.97			50.80	
South/Central	0.42/0.40 (allowance)	51.20	(0.23)	(0.44)	51.25	(0.88)
South/Central	0.42/0.31 (trade-off excl. Calif. locations)	50.98	(0.00)	(0.00)	50.81	(0.02)
Northern	0.35/0.40 (base case)	165.70			109.05	
Northern High Perf.	0.25/0.40 (hypothetical base case)	156.77	8.93	5.39	103.17	5.39
Northern High Perf.	0.30/0.55 (hypothetical trade-off)	156.78	(0.00)*	0.00	103.20	(0.02)*

* relative to hypothetical Northern hi-performance base case

In the Southern zone, the first trade-off option (0.72/0.38) results in neutral energy use, while the second more conservative trade-off option (0.72/0.35) results in an average energy reduction of 0.85 MBtu or 1.5% per house.

In the South-Central zone, a simple allowance of the U-factor to 0.42 will lead to an average energy increase of 0.45 MBtu or nearly 1% per house in the zone. With the proposed trade-off option of 0.42/0.31 in the non-California locations, there is no energy impact and the average total energy use per house in the zone remains unchanged (an insignificant 0.02% increase). If California locations are included, there is no possible trade-off for any increase in U-factor.

For future high-performance windows in the Northern zone with a base case of 0.25/0.40, a hypothetical trade-off option of 0.30/0.55 also results in no energy impact and the same average total energy use in the zone.

The impact of these trade-offs on individual cities are shown in Figures 22, 23, and 24 respectively.

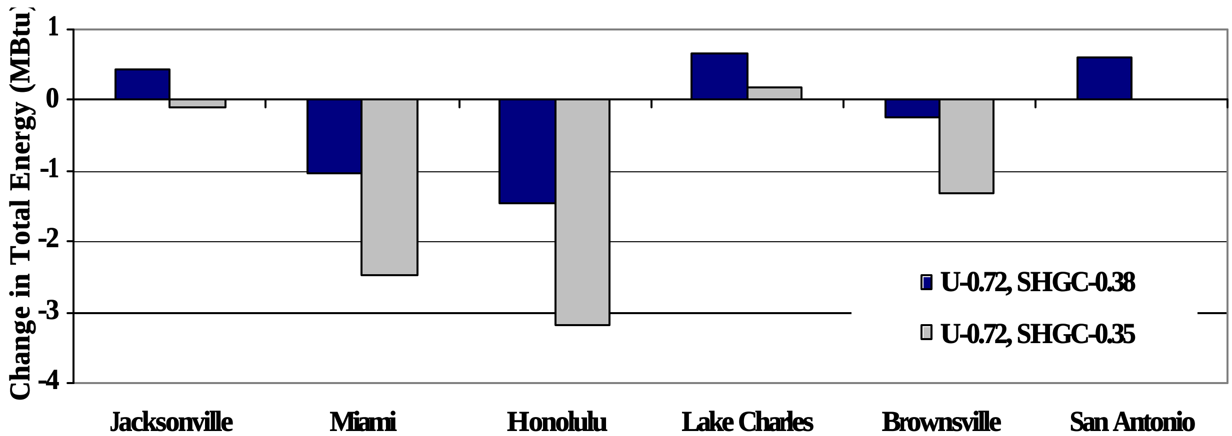

Figure 22. Change inTotal Energy Use in Southern Cities for Two Trade-off Options

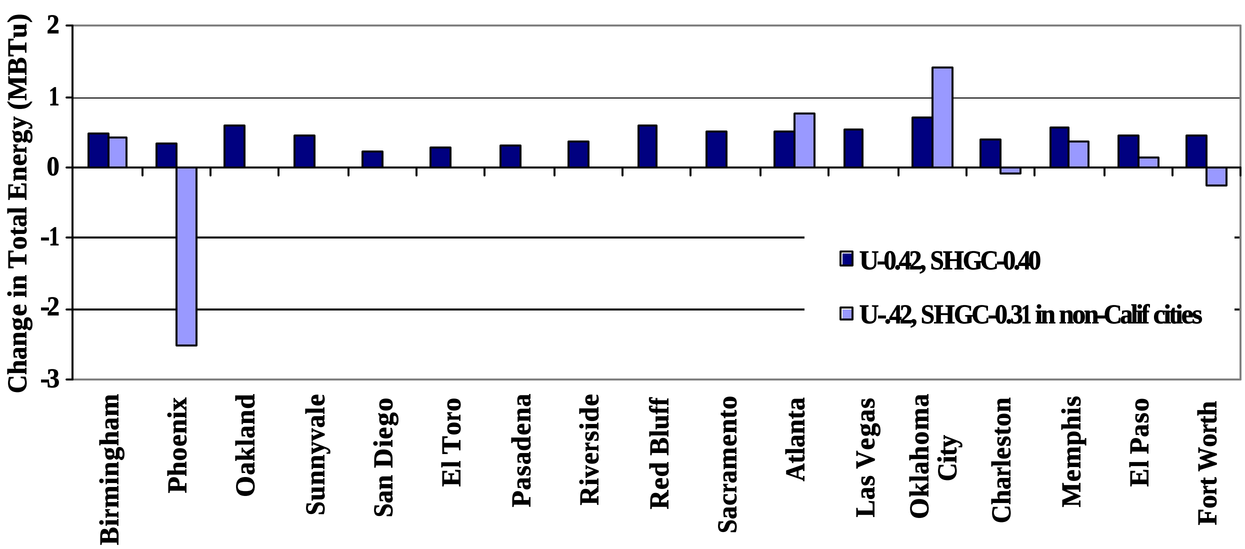

Figure 23. Change in Total Energy Use in South/Central Cities for Two Trade-off Options

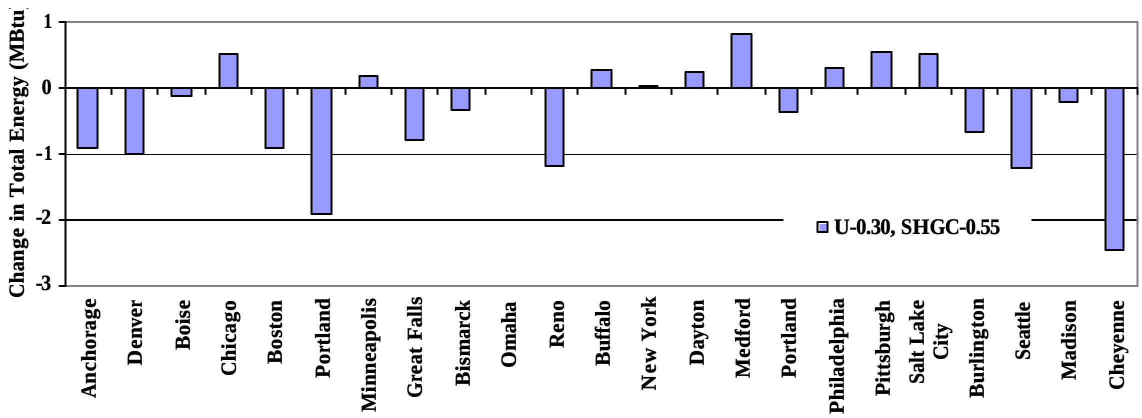

Figure 24. Change in Total Energy Use in Northern Cities for Hypothetical Trade-Off Option

Appendix 1B: Assessment of Market Impact Based on the Aggregation Method in the 2002 Study by Barbour and Arasteh

The Barbour and Arasteh study (2002) produced an Excel spreadsheet that evaluated the energy impacts of the ENERGY STAR windows program on the entire US residential building stock. To maintain consistency in the market assessment of the proposed trade-off options, the same spreadsheet has been used, with additional Worksheets added for the trade-off options analyzed in this report. Since the Barbour and Arasteh study normalized the calculated energy uses to the total regional and national energy use reported in the Residential Energy Consumption Survey (RECS), it is not possible to deduce the average energy uses per house. However, it is possible to roughly estimate the percent differences per region or house for the four ENERGY STAR climate zones. These results are shown in Table 9.

Table 9. Energy impact of representative trade-offs for windows in the Southern and South/Central zones and for hypothetical high-performance windows in the Northern zone based on market impact assessment in 2002 study by Barbour and Arasteh

Zone	Window U-factor and SHGC	Total energy use (trillion Btu's)	Difference in total energy use (trillion Btu's)	Percent diff. in total energy use (%)	Percent diff. in energy use for affected house (%)
Southern	0.65/0.40 (base case)	21.48			
Southern	0.72/0.38 (trade-off)	21.51	(0.03)	(0.13)	(1.35)
Southern	0.72/0.35 (trade-off)	21.49	(0.01)	(0.07)	(0.68)
South/Central	0.40/0.40 (base case)	35.77			
South/Central	0.42/0.40 (allowance)	36.00	(0.23)	(0.64)	(1.27)
South/Central	0.42/0.31 (trade-off excl. Calif. locations)	35.81	(0.04)	(0.11)	(1.13)
Northern	0.35/0.40 (base case)	130.59			
Northern High Perf.	0.25/0.40 (hypothetical base case)	125.99	4.60	3.65	3.65
Northern High Perf.	0.30/0.55 (hypothetical trade-off)	126.05	(0.06)*	(0.05)*	(0.48)*

* relative to hypothetical Northern hi-performance base case

In comparing Tables 8 and 9, the Barbour and Arasteh 2002 study is generally less favorable to the trade-off options in the Southern and South/Central zones. For example, whereas Table 8 shows that the U-

0.72/SHGC-0.38 trade-off option for the Southern zone and the U-0.42/SHGC-0.30 trade-off option excluding California locations for the South/Central zone as energy neutral, Table 9 shows them to increase the average total energy use by 1.3% and 1.1%, respectively. Even the more conservative U-0.72/SHGC-0.35 trade-off option for the Southern zone, which Table 8 shows as reducing energy use by 1.5%, is shown in Table 9 as increasing it by 0.7%.

As noted earlier, there are numerous differences in methodology between the Barbour and Arasteh 2002 study and the current one. However, the most critical difference causing these differing assessments of the trade-off options is that Barbour and Arasteh attributes a portion of the heating energy use to electric heating based on RECS consumption data, whereas the current study assumes that all heating is provided by natural gas. Since this electric heating is multiplied in Barbour and Arasteh 2002 by a fuel source multiplier of 3.32, the resultant heating energy use is increased by 2.5 times (3.32/(100/75), 100 being the efficiency of electric heating, and 75 that for gas heating). According to the spreadsheet used in Barbour and Arasteh 2002, RECS shows the following breakdown of fuel type for heating and cooling in the four ENERGY STAR Climate Zones (see Table 10).

Table 10. Estimated Energy Consumption by Fuel Type in ENERGY STAR Climate Zones Based on RECS

	Heating				Cooling	Total
	Gas	Electric	Oil	All	Electric	Energy
Southern	0.16	0.12	-	0.28	0.44	0.72
South/Central	0.45	0.26	0.04	0.75	0.42	1.17
North/Central	0.39	0.20	0.13	0.73	0.10	0.82
Northern	2.76	0.71	0.84	4.31	0.39	4.70
Total				6.08	1.34	7.42

In the Southern zone, 43% of the heating energy use is attributed to electric heating, while in the South/Central zone, 35% is attributed to electric heating. Since electric heating is roughly 2.5 times more fuel intensive, this means that the Barbour and Arasteh study is assuming 35% more heating energy use in the Southern zone, and 26% more in the South/Central zone, than the current study. The trade-off options described in this report balances, in part; increased heating energy use against reduced cooling energy use as the SHGC is varied. Because the Barbour and Arasteh study estimates substantially more heating energy use in these two zones, it also estimates that the trade-off options will increase total energy use rather than be energy neutral as estimated in the current analysis.

Appendix 2. California Weather Data Changes

In the previous scoping study (Arasteh et al. 2003); the following California cities were modeled:

Table A.1

Name	Weather File
CA Fresno	FRCATMY2.bin
CA Los Angeles	LACATMY2.bin
CA Red Bluff	CTZ11C.bin
CA San Diego	SDCATMY2.bin
CA San Francisco	SFCATMY2.bin

In the analysis discussed in this paper, those cities were replaced with the following cities and weather files, in order to try to mitigate the coastal climate bias in the first analysis. These weather files are those used by the California Energy Commission in their energy standards.

Table A.2

Name	Weather File
CTZ03-Oakland	CTZ03C.bin
CTZ04-Sunnyvale	CTZ04C.bin
CTZ07-San Diego	CTZ07C.bin
CTZ08-El Toro	CTZ08C.bin
CTZ09-Pasadena	CTZ09C.bin
CTZ10-Riverside	CTZ10C.bin
CTZ11-RedBluff	CTZ11C.bin
CTZ12-Sacramento	CTZ12C.bin

Appendix 2B. List of locations and weather data used in *DOE-2* analysis

Zone 1 – Southern

The following cities were simulated for the Southern Zone.

Table B.1

Name	Weather File
FL Jacksonville	JAFLTMY2.bin
FL Miami	MIFLTMY2.bin
HI Honolulu	HOHITMY2.bin
LA Lake Charles	LCLATMY2.bin
TX Brownsville	BRTXTMY2.bin
TX San Antonio	SATXTMY2.bin

Zone 2 – South/Central

The following cities were simulated for the South/Central Zone.

Table B.2

Name	Weather File
AL Birmingham	BIALTMY2.bin
AZ Phoenix	PHAZTMY2.bin
CA Oakland	CTZ03C.bin
CA Sunnyvale	CTZ04C.bin
CA San Diego	CTZ07C.bin
CA El Toro	CTZ08C.bin
CA Pasadena	CTZ09C.bin
CA Riverside	CTZ10C.bin
CA RedBluff	CTZ11C.bin

CA Sacramento	CTZ12C.bin
GA Atlanta	ATGATMY2.bin
NV Las Vegas	LVNVTMY2.bin
OK Oklahoma City	OCOKTMY2.bin
SC Charleston	CHSCTMY2.bin
TN Memphis	METNTMY2.bin
TX El Paso	EPTXTMY2.bin
TX Fort Worth	FWTXTMY2.bin

This ENERGY STAR zone includes all of Oklahoma even though some portions of Oklahoma have HDD > 3500 (including Oklahoma City). As shown in Figure 14, the trade-off curve for Oklahoma City is heating-dominant and differs from those of the other non-California locations.

Zone 3 – North/Central

The following cities were simulated for the North/Central Zone

Table B.3

City Name	Weather File
DC Washington	STVATMY2.bin
MO Kansas City	KCMOTMY2.bin
NC Raleigh	RANCTMY2.bin
NM Albuquerque	ALNMTMY2.bin
TN Nashville	NATNTMY2.bin

Zone 4 – Northern

The following cities were simulated for the Northern Zone:

Table B.4

City Name	Weather File
AK Anchorage	ANAKTMY2.bin
CO Denver	BOCOTMY2.bin
ID Boise	BOIDTMY2.bin
IL Chicago	CHILTMY2.bin
MA Boston	BOMATMY2.bin
ME Portland	POMETMY2.bin
MN Minneapolis	MIMNTMY2.bin
MT Great Falls	GFMTTMY2.bin
ND Bismark	BINDTMY2.bin
NE Omaha	OMNETMY2.bin
NV Reno	RENVTMY2.bin
NY Buffalo	BUNYTMY2.bin
NY New York	NYNYTMY2.bin
OH Dayton	DAOHTMY2.bin
OR Medford	MEORTMY2.bin
OR Portland	POORTMY2.bin
PA Philadelphia	PHPATMY2.bin
PA Pittsburgh	PIPATMY2.bin
UT Salt Lake City	SLUTTMY2.bin
VT Burlington	BUVTTMY2.bin
WA Seattle	SEWATMY2.bin
WI Madison	MAWITMY2.bin
WY Cheyenne	CHWYTMY2.bin

Appendix 3. Population weights for base case locations

To account for the disparity in housing starts or renovation activity in the areas represented by the 51 base case cities, the regression results for the individual cities were weighted by population as a surrogate for building activity in calculating the four region-wide trade-off equations. The population represented by each city was estimated by assigning all the counties to one of the 52 cities based on geographical proximity and climate similarity, and then summing the county populations as reported in the 2000 Census.

The population weights are shown in Table C.1.

Table C.1 Population represented by each base city

Base City	2000 pop	% of nation	Base City	2000 pop	% of nation
FL Jacksonville	7125.1	2.53	NM Albuquerque	999.0	0.35
FL Miami	9285.8	3.30	TN Nashville	12388.4	4.40
HI Honolulu	1211.5	0.43	AK Anchorage	626.9	0.22
LA Lake Charles	9884.6	3.51	CO Denver	4301.3	1.53
TX Brownsville	1761.0	0.63	ID Boise	3370.1	1.20
AL Birmingham	5522.1	1.96	IL Chicago	17827.6	6.33
AZ Phoenix	4834.7	1.72	MA Boston	7650.3	2.72
CA Oakland	4898.2	1.74	ME Portland	903.7	0.32
CA Sunnyvale	3347.0	1.19	MN Minneapolis	5463.5	1.94
CA San Diego	2813.8	1.00	MT Great Falls	997.4	0.35
CA El Toro	2846.3	1.01	ND Bismarck	846.8	0.30
CA Pasadena	10671.9	3.79	NE Omaha	5479.1	1.95
CA Riverside	3254.8	1.16	NV Reno	602.1	0.21
CA Red Bluff	539.4	0.19	NY Buffalo	4806.9	1.71
CA Sacramento	5325.9	1.89	NY New York	19140.7	6.80
GA Atlanta	7757.9	2.76	OH Dayton	5856.5	2.08
NV Las Vegas	1673.6	0.59	OR Medford	764.3	0.27
OK Oklahoma City	3913.7	1.39	OR Portland	2657.5	0.94
SC Charleston	7419.9	2.64	PA Philadelphia	8994.7	3.20
TN Memphis	4583.2	1.63	PA Pittsburgh	9917.5	3.52
TX El Paso	1963.0	0.70	UT Salt Lake City	2718.2	0.97
TX Fort Worth	9306.3	3.31	VT Burlington	3695.7	1.31
TX San Antonio	3465.2	1.23	WA Seattle	3817.7	1.36
DC Washington	16882.6	6.00	WI Madison	11312.1	4.02
MO Kansas City	9227.1	3.28	WY Cheyenne	431.6	0.15
NC Raleigh	6337.8	2.25	**National Total**	**281421.9**	**100.00**