***** DRAFT FOR COMMENT *****

Analysis Results for Performance Based Ratings for the ENERGY STAR® Windows Program

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Executive Summary

A set of prescriptive thermal performance criteria for four distinct US geographical zones are now in use by the Energy Star Windows program. DOE and the window industry are interested in determining 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 it 1) can equal or exceed the nominal energy savings of the existing criteria, 2) has no other adverse market impacts, and 3) provides consistent and understandable results leading to enhancement of the value of the overall program.

LBNL has undertaken a short-term but intensive technical study to determine if these criteria can be met. Initial conclusions with engineering backup are provided in this paper to stimulate broader industry discussion. We summarize our separate conclusions for each of the four Energy Star geographical zones.

South Zone: The technical basis for performance-based alternatives was developed for the southern zone, utilizing lower SHGC to compensate for increased U. It appears that this tradeoff approach could be implemented without other significant adverse impacts.

South Central Zone: This zone encompasses a wide range of climates. In some climates an increased U can be compensated for by a decreased SHGC; in some climates an increased U can be compensated for by a increased SHGC, and in some climates all alternative parameters will always result in increased energy consumption, thus defeating the purpose of this approach. Although a mathematical tradeoff solution was derived that on average will result in equal or lower energy for the entire zone, in some cities within the zone the energy use will always increase. If a different set of tradeoffs was allowed for different cities within the zone this problem might be resolved. But we believe such a solution is not likely to be readily accepted. Accordingly because of the way that the zone boundaries are currently defined it appears that it is not possible to define a single set of zone-wide tradeoffs that accomplishes the desired goals.

North Central Zone: As with the South Central Zone this zone encompasses a wide range of climates within which the energy impacts of changing U and SHGC vary widely. Therefore although we were able to derive a set of performance tradeoffs for the entire zone using the regression equations the resultant technical solution in many of the cities are not likely to be accepted for reasons similar to those explained above for the South Central zone.

North Zone: The technical basis for performance-based alternatives were developed for the northern zone, utilizing increased SHGC to compensate for increased U. But since the increased U would not meet code minimum thermal requirements, we conclude that alternative criteria are not feasible in the North Zone.

This technical analysis provides input into the DOE process for considering whether a performance-based tradeoff system is feasible and if so, to assist in selecting the tradeoff criteria to be used. This technical analysis will be updated as needed in response to technical input from reviewers.

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 the Solar Heat Gain Coefficient (SHGC) for each ENERGY STAR zone (except for the North 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. Key performance requirements for each of the four zones are listed below in Table 1.

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

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 ENERGY STAR® Windows Program [2]. In that paper, the key performance issues were discussed, and several options for the performance-based tradeoffs 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

[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 tradeoffs are presented only for windows; ultimately, alternative tradeoffs will have to be prepared for skylights and doors separately.

alternative criteria. The primary tool used for the energy analysis was RESFEN, based on DOE-2, a tool which has been used by the industry for many years and considered by NFRC for use in a national energy rating system. In parallel with the LBNL evaluation of alternative criteria an NFRC task group is reviewing the modeling assumptions used in the RESFEN program to determine if they believe any changes in these assumptions should be made. Because of critical time factors LBNL was asked by DOE to proceed in a parallel effort to develop candidate performance-based numbers using the current version of RESFEN while the NFRC group reconsidered the RESFEN assumptions.

This paper expands on Option 2 (tables for tradeoffs) and Option 3 (regression equations for tradeoffs) described in the LBNL 2003 paper. Both options are evaluated using regression equations to predict energy consumption for each of the four ENERGY STAR zones.. In the first paper, the performance tradeoffs represented by an example regression equation showed that combinations of window properties which do not strictly meet both U and SHGC prescriptive requirements for a given zone may result in levels of annual energy performance equivalent to products which meet 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

The RESFEN computer program was used to generate a series of energy consumption results for a range of different window types in different cities throughout the United States for both new and existing residential buildings. The resulting data was then used to generate regressions equations that would predict heating and cooling energy consumptions and annual totals based on a range of input values of U-factor and SHGC. The regressions for the first paper were developed for each city. In this current analysis the regression equations were developed based on the ENERGY STAR zones, which aggregates the data from all the cities in one zone into a single equation. This introduces a number of analytical issues that are addressed later in this paper.

Analysis Tool

RESFEN, a building energy analysis software tool developed by LBNL using the DOE2 simulation engine, was used to generate the heating and cooling energy consumption results which were then used in the tradeoff regression equations.

Modeling Assumptions

The modeling assumptions used for this regression analysis are from the current version of RESFEN 3.1. Some parameters are fixed with climate while others vary with climate. This set of assumptions covers both technical issues and human factors and is detailed at http://windows.lbl.gov/AEP/database.htm (Arasteh et. al. 2000).

These modeling assumptions are currently under review by an NFRC Task Group. NFRC expects to make recommendations to DOE in March regarding whether they believe any of the modeling assumptions should be changed.

The current modeling assumptions include different thermal performance and equipment criteria for typical new and existing construction. Both types of construction were modeled for the current regressions. The house modeled for this analysis was a 1 story, wood-frame construction , 2000 square feet, with 15% of the floor area in windows, evenly distributed on all four orientations, with the RESFEN "typical" shading setting.

Building Parametrics

A large set of simulations was completed as the basis for the regression analysis. The following parametrics for key building and window features were simulated to create the database for the regressions:

- 36 windows were modeled representing a wide range of commonly available, existing products as well as high performance products not yet widely sold
- new and existing construction, each with associated thermal and HVAC properties for different climates

Climate and Data Aggregation

The building and window parametrics were completed for 52 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 different set of cities were chosen for California to better represent the state's wide climatic variation (see Appendix 1 for complete details).

Evaluation Based on Total Energy

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

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

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.

Regression Analysis

The objective of the regression analysis is to extract a simple mathematical relationship between building energy use and the key window thermal parameters of interest, U factor and SHGC. Mathematical regressions on large databases have been used historically in cases similar to this in the development of codes and performance models: an equation is developed which has as input the primary variables (U, SHGC in this case) and which has as output, the desired parameter (e.g. total energy). In the regressions developed for each of the 52 climates (for the August 1, 2003 analysis), the mathematical correlations agreed closely with the original DOE2 data since each represented a somewhat homogeneous data set from simulations for a single climate. However, in this current analysis, where the individual city data is aggregated together by zone, the regression results will differ from the city based results, sometimes significantly because the regression is forced to capture a much wider variation in performance data. Climate aggregation may turn out to a more significant factor than most modeling assumptions, introducing differences that may be greater than the differences between new and existing construction, for example. In the work reported here we use some results directly from the regression results and others that include direct DOE-2 modeling in order to better understand some of the complex modeling interactions and as a check on the regression approach.

[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.)

Zone Based Regression Equations

The RESFEN simulation results for the 52 locations have been distilled into a regression expression which is a function of U-factor andSHGC, and which predicts heating and cooling energy consumption. The total energy consumption (Eq 2 below) can then be used to determine if a particular combination of U and SHGC allows the window to qualify for the ENERGY STAR rating, meaning that it has equal or lower energy consumption compared to as a window which just meets the requirements.

Heating and Cooling Energy Consumption Regression Equation:

The regression equation generated from the fits of the window parameters for calculating the heating and cooling energy consumption is quadratic in all terms and takes the following form:

$$Y = A + (B_1 * U) + (B_2 * S) + (C_{11} * U^2) + (C_{12} * U * S) + (C_{22} * S^2) \qquad \text{(Eq 1)}$$

Where:

Y is either heating or cooling energy consumption (heating is in MBtu, and cooling is in kWh)

Constants are listed in Appendix 1, Table 19 for heating and cooling by ENERGY STAR zone

Total Energy Consumption:

$$E = H + (0.011 * C) \qquad \text{(Eq 2)}$$

Where:

E = the primary energy use in MBTU

H = the heating energy use in MBTU

C = the point of use electrical use in KWH

0.011 = the heat rate of 11,000 BTU per KWH which represents the primary energy needed to produce 1 KWH of electrical energy.

Tradeoff Equation:

In addition to being able to determine the total energy consumption, it is also useful to be able to determine the trade-offs between the U-factor and the SHGC which give a fixed energy consumption. This can be determined from the equation for energy by treating the energy use as a given and solving for either U or S (SHGC). For example if we assume that we have varied U and would like to know S the equation becomes:

$$C_{22}S^2 + (B_2 + C_{12}U)S + (A + B_1U + C_{11}U^2 - E) = 0, \qquad \text{(Eq 3)}$$

If we let:

$K = C_{22}$,
$L = (B_2 + C_{12}U)$
$M = (A + B_1U + C_{11}U^2 - E)$

Where:
S = SHGC
U = U-factor
Constants are listed in Appendix 1, Table 19 for heating and cooling by ENERGY STAR zone

then the two solutions to this equation are:

$$S = (-L \pm [L^2 - 4KM]^{1/2})/(2K) \qquad \text{(Eq 4)}$$

The solution that is of interest is the one that is closest to the original value of S.

Note that in some cases there will not be any solution to this equation. In this case trade-offs are only possible if the total energy is higher. This is a critical result which occurs in a number of cities making it impossible to find an alternative solution for that specific city.

Tradeoff Constraints -- Issues for Consideration

Although equivalent annual primary energy consumption is the major basis for examining performance tradeoffs, windows have many performance attributes and several must be considered when the tradeoffs are evaluated. The following is a discussion of factors in addition to annual energy consumption that will influence the range of tradeoffs that could be allowed. Other performance issues that will influence window selection such as comfort and view and 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: 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 products whose individual window properties that do not meet code in some circumstances.

This issue is potentially applicable in all zones. Therefore, regional energy code requirements may need to be a filter on any ENERGY STAR performance based tradeoffs with a requirement that U and SHGC not be relaxed beyond code requirements. In the longer term, if Energy Star criteria drop below code values then there would once again be an opportunity to benefit from that flexibility..

Issue: Maximum U 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 tradeoff procedures described in this report. The primary concerns are on the impacts of increased SHGC on peak cooling loads in the South Zone and of increased U-factors on peak heating loads in the North Zone.

In the South Zone, a tradeoff 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 tradeoff 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 tradeoff 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 U: 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 tradeoff 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 an ENERGY STAR products. For a variety of reasons reflective glass and highly absorbing tinted glass has not been normally used in the residential market and it seem unwise for Energy Star to encourage or appear to encourage its use by specifying alternatives that can only be met with such low transmission products. For this reason, a minimum SHGC and VT (visible transmittance) requirement on all qualifying products is proposed in this paper . 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 have selected 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 Tv in southern climates.

Example Tradeoffs Using Regression Equations and Constraints

The following section discusses possible tradeoffs between SHGC and U-factor for each ENERGY STAR zone, based on the regression equation presented in this paper.

South Zone

Energy Star requirements in the South Zone are U-factor < 0.65 and SHGC < 0.4, Since the zone is dominated by cooling, SHGC has the primary impact and changes in U-factor will not substantially change SHGC. Alternatively, selecting an SHGC that is lower than the required 0.4 value might allow an increase in U-factor while maintaining constant annual energy use. In Table 2 below, the regression equation was used to establish a base case energy consumption for U-factor = 0.65 and SHGC = 0.4, and then the equation was used to determine which the equivalent U-factor and SHGC combinations would result in unchanged energy consumption.

The table shows that lowering the SHGC can permit higher U-factors, with the upper limit of the U-factor tradeoff being set to 0.80 in order to still meet IRC energy codes. Tradeoffs could 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.

Table 2. South Zone Tradeoffs from Population-Weighted Regression

U-factor	SHGC Tradeoff
0.66	0.40
0.67	0.39
0.68	0.39
0.69	0.39
0.70	0.38
0.71	0.38
0.72	0.38
0.73	0.37
0.74	0.37
0.75	0.37
0.76	0.36
0.77	0.36
0.78	0.36
0.79	0.35
0.80	0.35

Results from Table 2 are regression equation predictions for the entire south zone weighted by the population of the cities for which the DOE-2 simulations were completed. To better understand the trends we also evaluated the city by city tradeoff results and compared them to the zone averages, all shown in Table 3. We also compared the results to direct DOE-2 calculations not using the regression approach, which is shown in Table 4. The DOE-2 simulations agree well with regression results giving us confidence in their use as the primary analytical tool. Results from Table 4 are also displayed graphically in Figure 1 so that the behavior and trends can be better understood. Jacksonville, Lake Charles and Brownsville all have the same characteristic shape in the relationship between U and SHGC with Miami showing no dependence on U since the heating loads are virtually non-existent. The specific breakdown of heating and cooling for each city is shown in Figure 2.

The average regression for the full zone shows that a reduction in SHGC from 0.40 to 0.35 compensates for the increased energy as U rises from 0.65 to 0.8. In Miami and Brownsville the average solution of SHGC =0.35 would result in lower energy consumption than the Energy Star base case; in Jacksonville and Lake Charles it would result in higher energy consumption but the 0.35 window in all climates would average out to the same energy as the Energy Star prescriptive approach.

Table 3. South Zone Tradeoffs from Population-Weighted Regression by City

	SHGC Tradeoff			
U-value	FL Jacksonville	FL Miami	LA Lake Charles	TX Brownsville
0.66	0.39	0.40	0.39	0.40
0.67	0.39	0.40	0.38	0.40
0.68	0.38	0.40	0.37	0.39
0.69	0.37	0.40	0.37	0.39
0.70	0.37	0.40	0.36	0.39
0.71	0.36	0.40	0.35	0.39
0.72	0.35	0.40	0.34	0.39
0.73	0.35	0.40	0.33	0.38
0.74	0.34	0.40	0.32	0.38
0.75	0.33	0.40	0.31	0.38
0.76	0.32	0.40	0.30	0.38
0.77	0.32	0.40	0.29	0.37
0.78	0.31	0.40	0.28	0.37
0.79	0.30	0.40	0.27	0.37
0.80	0.29	0.40	0.26	0.37

Table 4. South Zone Tradeoffs from DOE2 Runs

	SHGC Tradeoff			
U-value	FL Jacksonville	FL Miami	LA Lake_Charles	TX Brownsville
0.65	0.40	0.40	0.40	0.40
0.70	0.37	0.40	0.37	0.39
0.75	0.35	0.40	0.33	0.38
0.80	0.32	0.40	0.30	0.37

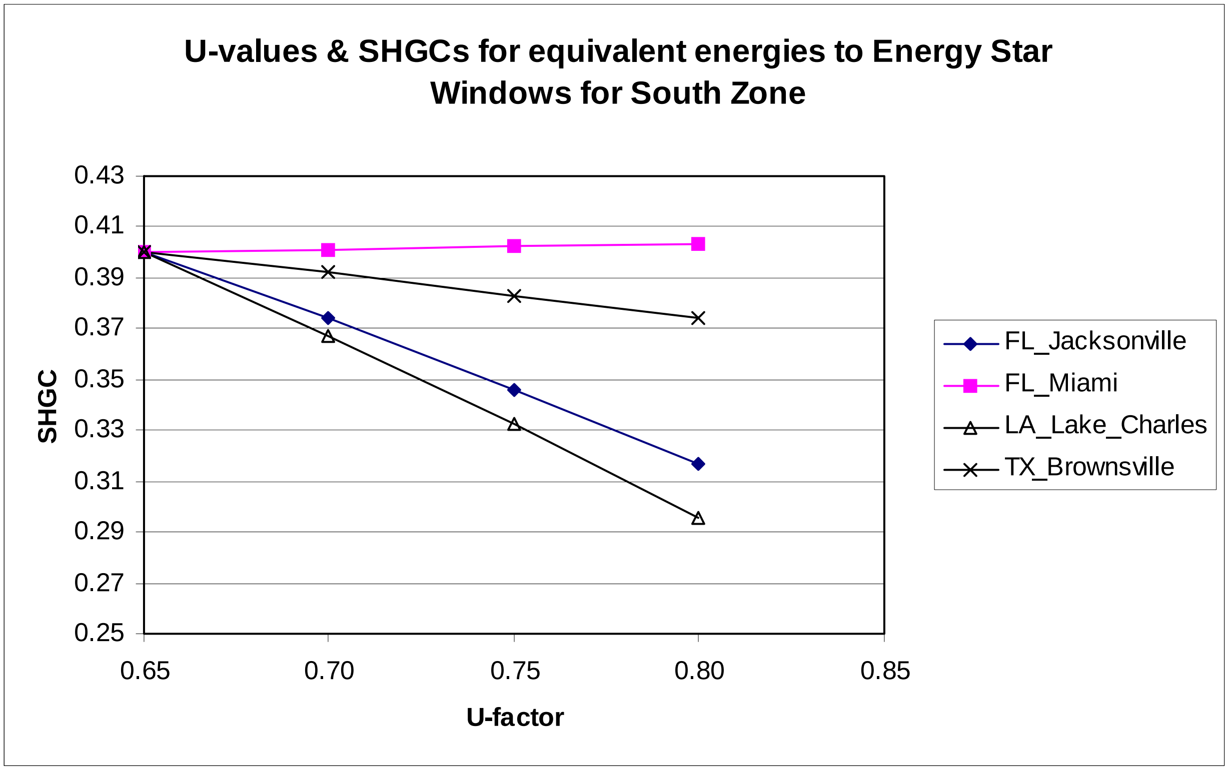

Figure 1. U-values and SHGCs for Equivalent Energies to Energy Star Windows for South Zone from DOE2 Runs

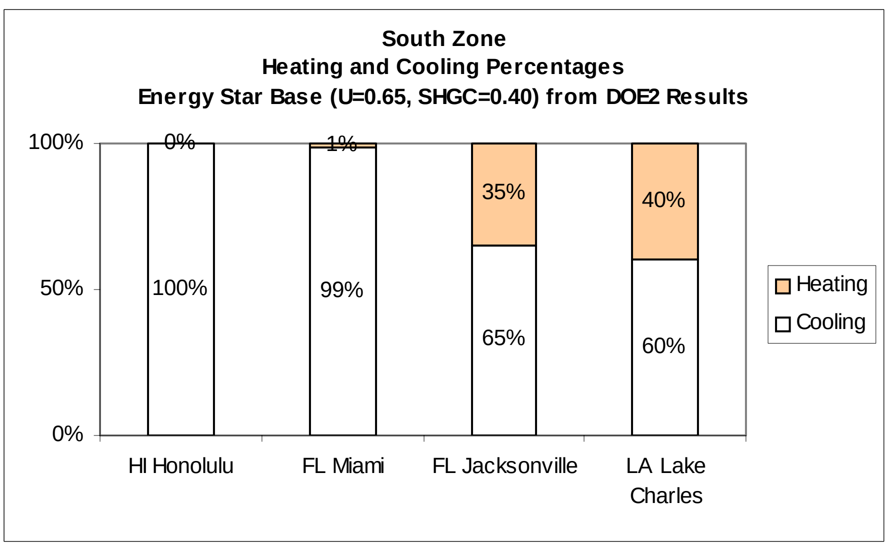

Figure 2. Heating and Cooling Percentage Comparison for South Zone

South Central Zone

The regression equation was used for the South Central Zone to establish a base case energy consumption, and then the equation was used to determine a series of U-factors and SHGC combinations that would result in the same unchanged base case energy consumption. The equation properly reproduced the contradictory tradeoffs that exist among the different cities in the region. In addition, there were several cities for which the equation could not find any tradeoff solution at all. Due to the large city-to-city differences in tradeoffs, the population-weighted regional solution was a very small tradeoff requiring large decreases in SHGC to compensate for any increase in U-factor (see Table 5). For example, a 0.02 U-factor increase from 0.40 to 0.42 would require a large reduction in SHGC from 0.40 to 0.28. Ignoring the plausibility of such a tradeoff, the city-by-city results show a more fundamental problem in that this tradeoff, while correct for the overall zone average, results in increased energy use compared to what the true tradeoff should be for a particular city (see Table 6).

To confirm and analyze these tradeoff results from the regression equation, Table 7 was regenerated using an iterative procedure using DOE-2 to identify the U-factor/SHGC combination that produces the equivalent energy use as the EnergyStar 0.40/0.40 criteria. Table 7 and Figure 3 presents the tradeoff curves from the DOE-2 iterative procedure. Although there are some differences in the specific SHGC values in individual cities, Table 7 revealed the same general patterns as Table 6 -- large differences and sometimes contradictory tradeoffs between the individual cities, and a number of cities where the iterative method also could not find solutions.

The reason for these results become clear when the DOE-2 runs were analyzed in more detail. Figure 4 shows the heating and cooling energy uses (in source units) for a wide range of SHGC at a constant U-factor of 0.40 for four cities that had no tradeoff solution. At first glance, the increases in cooling energies seem to be exactly balanced by the decreases in heating energies, resulting in no change in total energies as SHGC is increased from 0.20 to 0.60. Figure 5 shows the total energies of the four cities in more detail, revealing that the energies do vary slightly with SHGC, and have minima close to the 0.40 SHGC chosen as the EnergyStar criterion. In other words, in these three cities 0.40 is already very near the optimum SHGC, so that if the U-factor requirement is relaxed, there is no better SHGC that can be used to achieve the equivalent energy performance. This is shown graphically in Figure 5, where the dot represents the energy performance of the EnergyStar 0.40/0.40 base case, while the line represents the energy performance of a window with a U-factor to 0.41 through a range of SHGC. Even for such a tiny U-factor increase of 0.01, there is no way to achieve the same energy performance by altering the SHGC.

The cases of no tradeoff solution occur in those cities where these two conditions exist: (1) heating and cooling energies cancel each other, resulting in there being an optimum SHGC, and (2) the optimum SHGC is close to the 0.40 EnergyStar SHGC value (in cities that are either heating or cooling dominant, the total energy will vary substantially with SHGC, producing optimum SHGCs from the energy point of view at either 1.00 or 0.00). Leaving aside those cities with the above "no solution" condition ,the rest of the cities in the South Central Zone are a mix of heating-dominant (California coastal) or cooling-dominant (Phoenix) locations. As seen in Tables 6 and 7 and Figure 3, the former would have negative trade-offs (higher SHGCs to compensate for increased U-factor) while the latter would have positive trade-offs (lower SHGCs to compensate for increased U-factor).

Given this mix of conditions, the positive region-wide trade-off (see Table 4) must be regarded as largely a statistical artifact of the climate aggregation that would be wrong or misleading when applied to most of the individual cities. Based on this analysis of the results, we feel that the climate variations within the South Central Region are too complex to produce a technically defensible single trade-off equation.

Table 5. South Central Zone Tradeoffs from Population Weighted Regression

U-factor	SHGC Tradeoff
0.41	0.35
0.42	0.28
0.43	0.19

Table 6. South Central Zone Tradeoffs from Population-Weighted Regression by City

	SHGC Tradeoff																
U-factor	Birming-ham	Phoe-nix	Oak-land	Sunny-vale	San Diego	El Toro	Pasa-dena	River-side	Red Bluff	Sacra-mento	Atlan-ta	Las Vegas	Charles-ton	Mem-phis	El Paso	Fort Worth	San Antonio
0.41	0.34	0.39	0.41	0.41	0.42	NS	0.35	0.37	0.35	NS	NS	0.38	0.38	0.35	0.37	0.38	0.39
0.42	0.27	0.39	0.42	0.42	0.44	NS	0.29	0.34	0.29	NS	NS	0.35	0.35	0.28	0.34	0.36	0.39
0.43	0.15	0.38	0.43	0.44	0.47	NS	NS	0.31	0.22	NS	NS	0.33	0.33	0.21	0.31	0.34	0.38

Table 7. South Central Zone Tradeoffs from DOE2 Runs

	SHGC Tradeoff																
U-value	Birming-ham	Phoe-nix	Oak-land	Sunny-vale	San Diego	El Toro	Pasa-dena	River-side	Red Bluff	Sacra-mento	Atlan-ta	Las Vegas	Charles-ton	Mem-phis	El Paso	Fort Worth	San Antonio
0.42	NS	0.39	0.42	0.42	0.44	NS	NS	NS	0.30	NS	NS	0.36	NS	0.36	0.29	0.35	0.37
0.44	NS	0.38	0.43	0.45	0.51	NS	NS	NS	NS	NS	NS	0.31	NS	0.32	NS	NS	0.33
0.46	NS	0.37	0.45	0.47	NS	NS	NS	NS	NS	NS	NS	0.24	NS	0.26	NS	NS	0.28

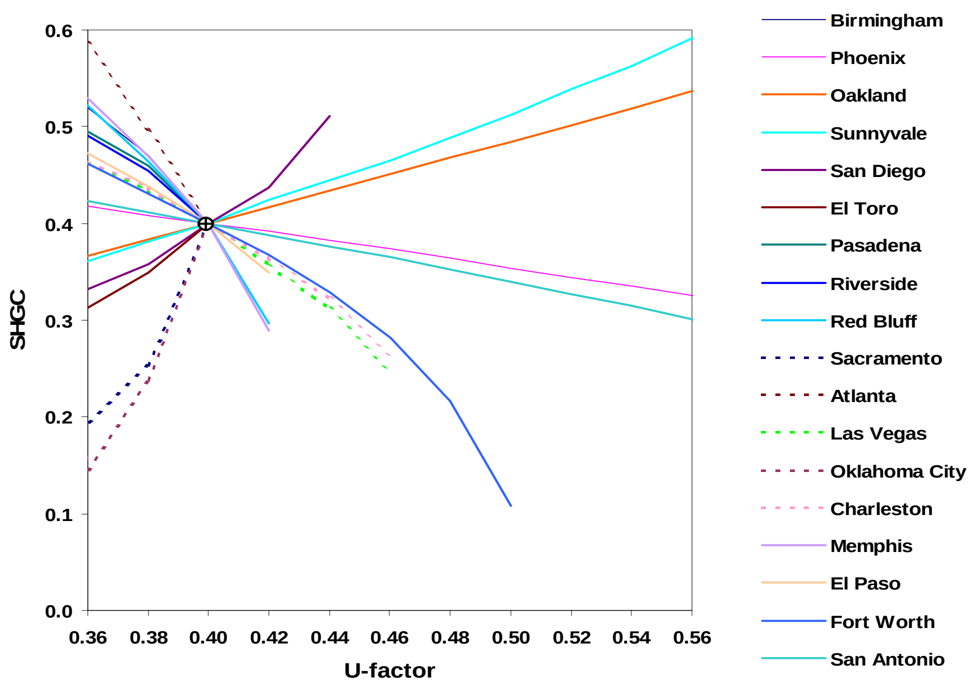

Figure 3. U-factors and SHGCs for Equivalent Energies to EnergyStar Windows Criteria for South Central Zone

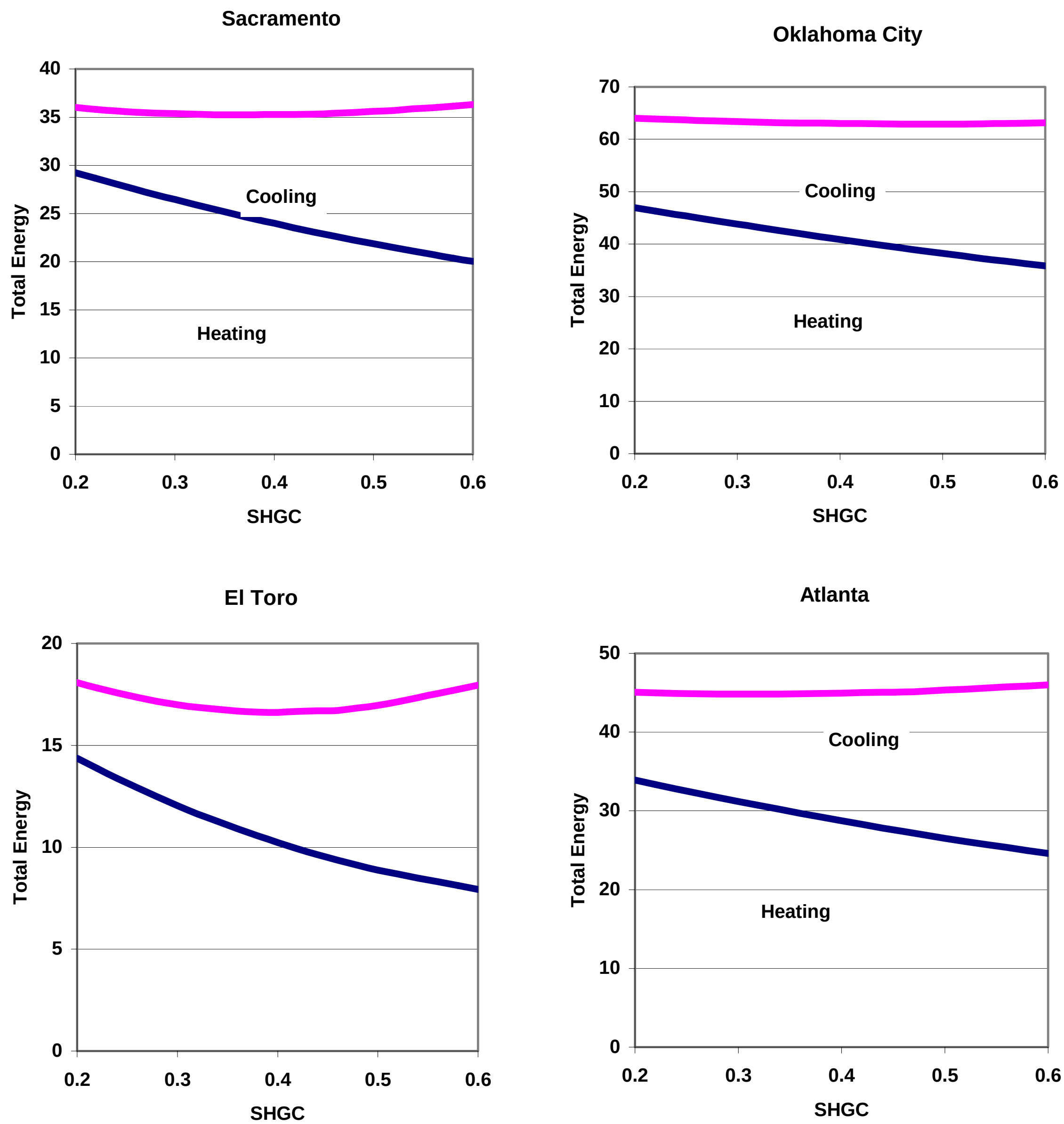

Figure 4. Heating and Cooling Energies in Four South Central Zone Cities with U-0.40 and SHGC varying from 0.20 to 0.60

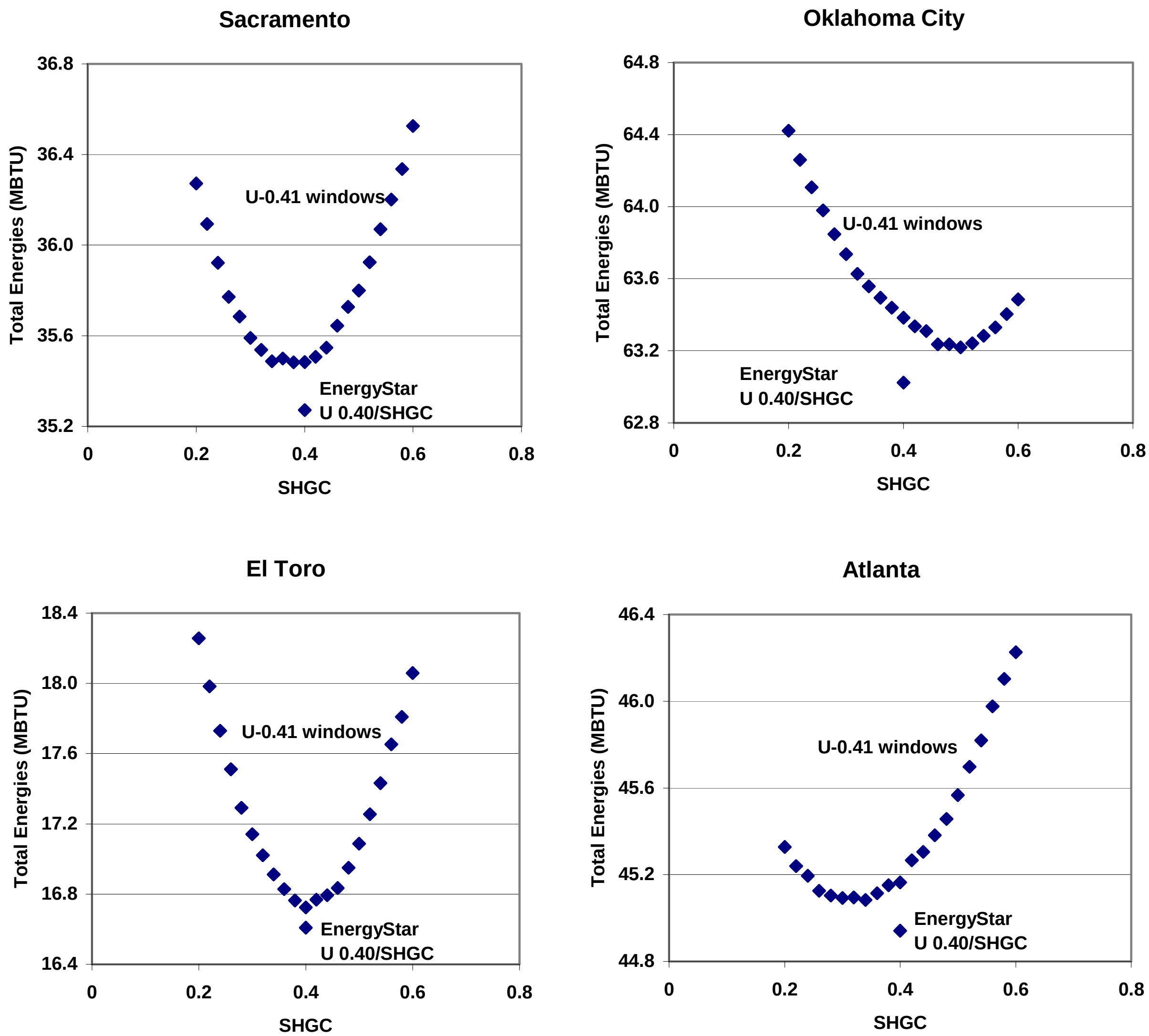

Figure 5. Total Energies in Four South Central Zone Cities with Windows of U-0.41 and SHGC varying from 0.20 to 0.60 compared to that of a base case EnergyStar window with U-0.40 and SHGC 0.40

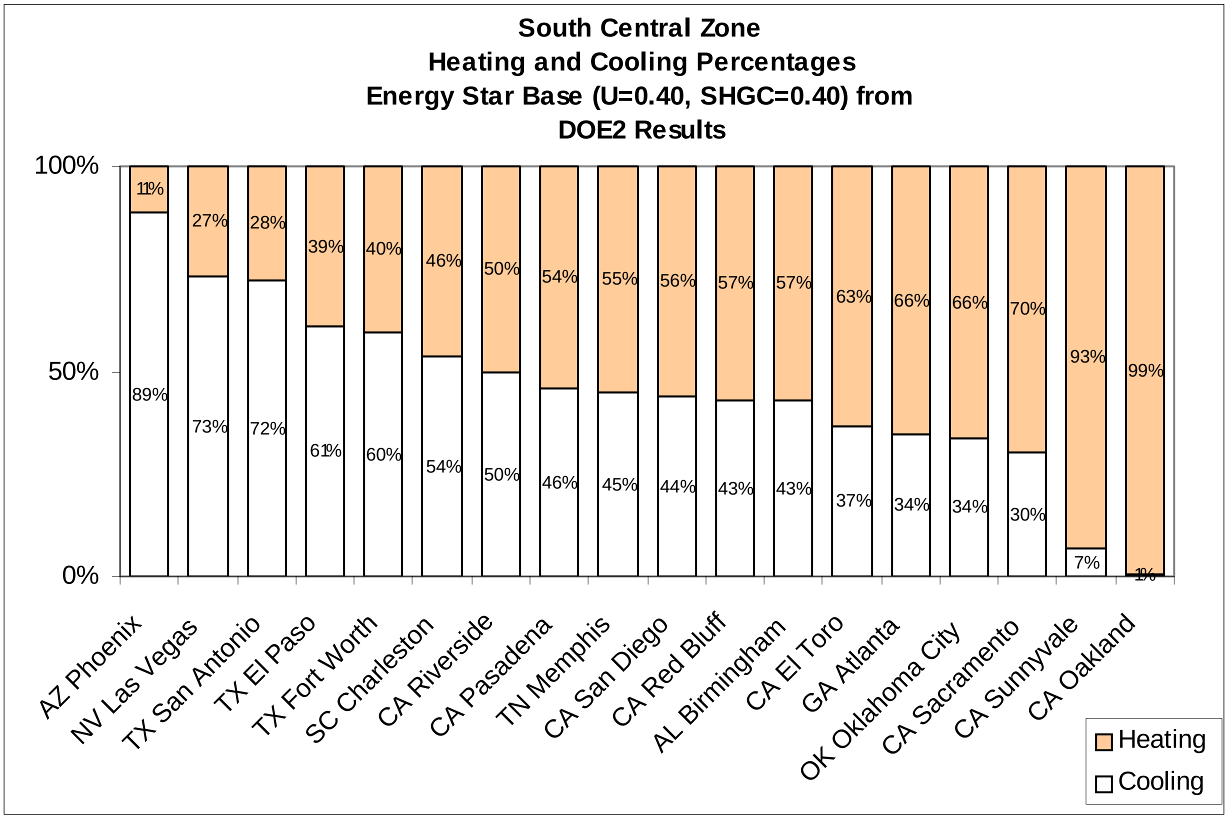

Figure 6. Heating and Cooling Percentage Comparison for South Central Zone

North Central Zone

Tradeoffs for the North Central Zone are shown in Table 8 using the regression equation for the entire zone as before. Small increases in U can be offset with relative large increases in SHGC. Tables 9 and 10 show backup data for the city by city tradeoffs using both the regression equation and direct DOE-2 simulation. The DOE-2 results in Table 10 show a mix of cities with no solutions (Raleigh and Nashville) or with slight negative trade-offs (large increases in SHGC to compensate for small increases in U-factors in Washington, Kansas City, and Albuquerque). Figure 9 shows the ratio of heating to cooling energy use (HCR) from DOE-2 for the South Central Zone and North Central Zone cities and reveals that HCR is a fairly good indicator of whether a city will have a positive trade-off, no solution, or negative trade-off. When the HCR is less than 0.30, i.e., cooling is more than 70% of the energy use, there is a positive trade-off (reduced SHGC to compensate for increased U-factor). When the HCR is greater than 0.7, i.e., heating is more than 70% of the energy use, there is a negative trade-off (increased SHGC to compensate for increased U-factor). When HCR is between 0.3 and 0.7, i.e., heating and cooling are comparable, there is generally no solution for any trade-off for increased U-factor, but of course there would remain trade-offs for reduced U-factor.

Table 8. North Central Zone Tradeoffs from Population Weighted Regression

U-factor	SHGC Tradeoff
0.41	0.60
0.42	0.65
0.43	0.69
0.44	0.73

Table 9. North Central Zone Tradeoffs from Population-Weighted Regression by City

	SHGC Tradeoff				
U-value	DC Washington	MO Kansas City	NC Raleigh	NM Albuquerque	TN Nashville
0.41	0.58	0.61	0.60	0.57	0.71
0.42	0.62	0.66	0.65	0.60	0.79
0.43	0.65	0.71	0.69	0.62	0.86
0.44	0.68	0.75	0.73	0.64	0.91

Table 10. North Central Zone Tradeoffs from DOE2 Runs

	SHGC Tradeoff				
U-value	Washington	Kansas City	Raleigh	Albuquerque	TN Nashville
0.41	0.63	NS	0.43	0.61	0.45
0.42	0.73	NS	NS	0.70	NS
0.43	NS	NS	NS	0.77	NS
0.44	NS	NS	NS	NS	NS

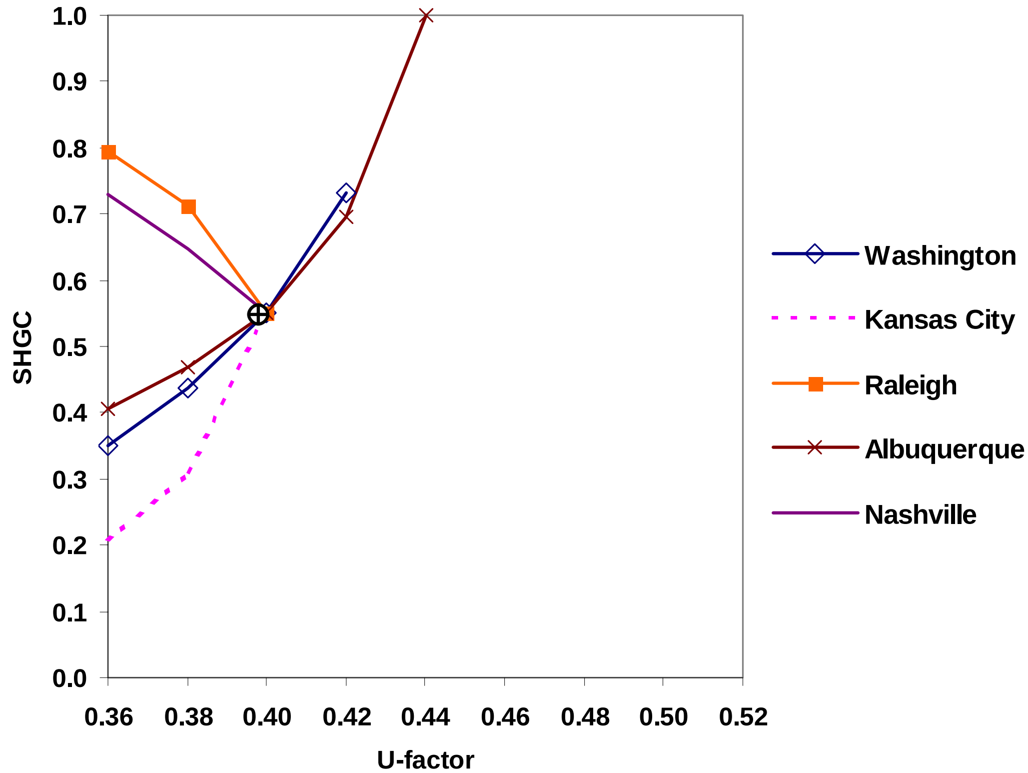

Fig. 7. U-factors and SHGCs for Equivalent Energies to EnergyStar Windows Criteria for Windows in North Central Zone

There was some concern about the apparent discrepancies between the regression-based tradeoffs in Table 8 and 9 and the DOE-2-based tradeoffs (or lack of) in Table 10. A closer look using DOE-2 simulations reveals that these discrepancies are more apparent than real. Taking Nashville as an example, Table 9 shows a negative tradeoff (increased SHGC) to compensate for U-factor increases, while Table 10 shows a positive trade (decreased SHGC) for only the first 0.01 increase in U-factor and no solution thereafter. Figure 10 compares DOE-2 energy results for the base case condition (U=.4, SHGC=.55) to energy use for two sets of U factor results (curves for U= .41 and U= .42) over a large range of SHGC. As with many locations in the South Central Zone, Nashville has a mix of heating and cooling that results in an optimum SHGC in the neighborhood of 0.30. Since the EnergyStar SHGC is set at 0.55, there is a slight potential for improving the SHGC to compensate for a 0.01 increase in U-factor to 0.41. However, when the U-factor is raised to 0.42, there is no SHGC that can maintain equivalent energy performance. The left hand curve expands the axis so that details can be seen. The right-hand plot on Figure 10 is the identical data displayed with a full range of energy use, and shows that the tradeoff curve is in reality very flat. Therefore, it is understandable that the regression equation would find solutions missing in the DOE-2 analysis, and produce different tradeoff values. In terms of predicted energy use, these differences in tradeoff values and solutions have a very small impact.

Because three of the cities have no solutions and the remaining two have small negative trade-offs, our recommendation for the North Central Zone is also that a trade-off equation is not technically defensible. In some sense the problem in this zone could be viewed as even more difficult than in the South Central Zone. Although the South Central Zone contained more variations in trade-off conditions, they are more geographically distinct (California Coastal versus Phoenix versus the rest). In the North Central Zone, the differences seem to run along degree-day lines running east-west, pitting Albuquerque-Kansas City-Washington versus Nashville-Raleigh).

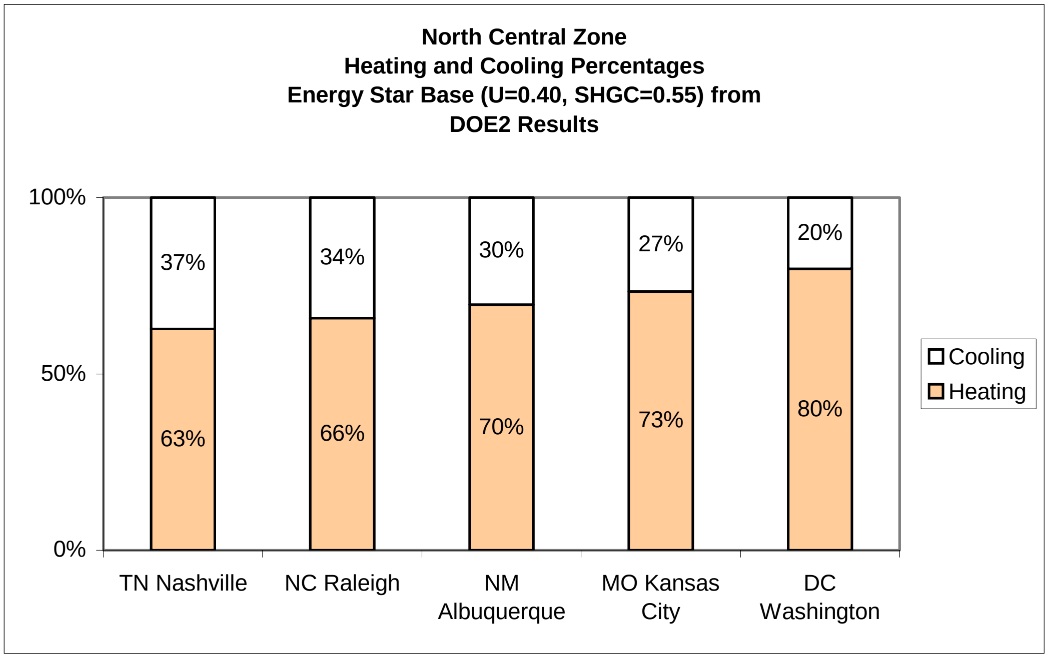

Figure 8. Heating and Cooling Percentage Comparison for North Central Zone

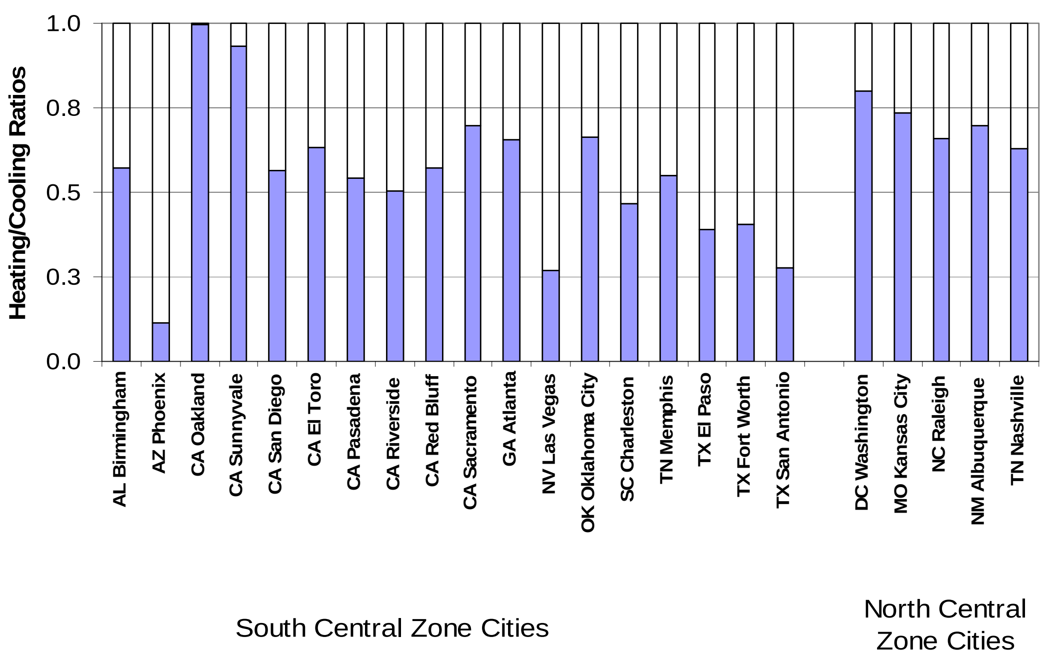

Figure 9. Heating and Cooling Ratios for cities in the South Central and North Central zones

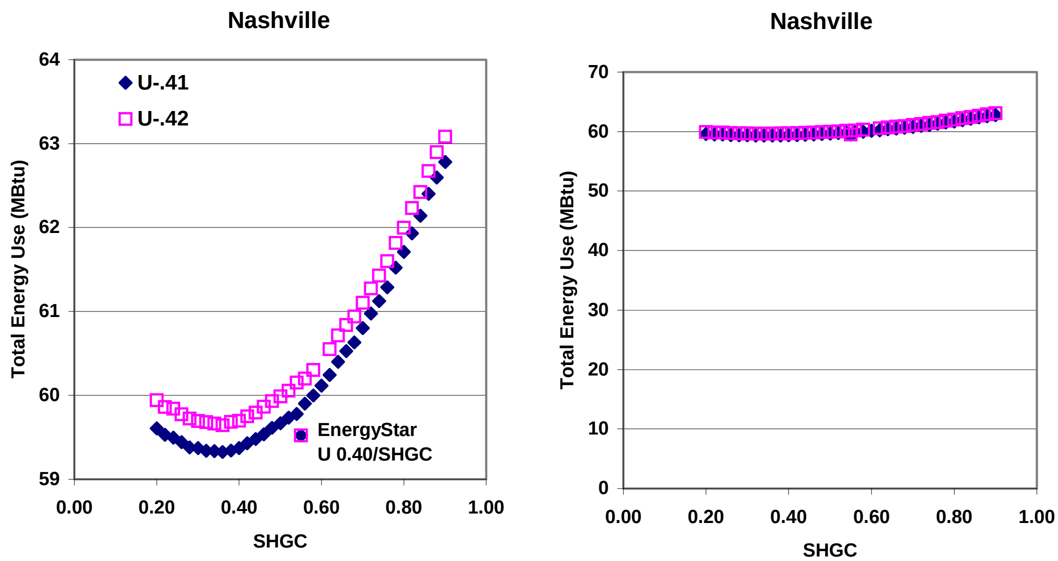

Figure 10. Heating and Cooling Percentage Comparison for North Central Zone: two views of the same data (note vertical scale differences with expanded scale on left for clarity)

North Zone

The North zone criteria as currently defined, has no SHGC requirement. Therefore in order to establish a base energy consumption for tradeoffs 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 0.4. (Using the equations in the appendix the reader can explore the impact of other selections.) In this heating-dominated zone, tradeoffs 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 11 shows the "equivalent SHGC" associated with five 0.01 increments in U-factor. Table 12 and Figure 11 show 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 allowing these tradeoffs. First many states in the Northern zone have or are moving toward building codes in which a 0.35 U is a requirement for new construction or major renovations requiring building permits. The only conditions under which a higher U 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 much beyond the 0.35 limit. First, peak heating load is determined by overall building heat loss to which windows contribute. Relaxing the U value will therefore increase peak heating loads. Higher U values will reduce interior glass temperatures, reducing thermal comfort and increasing the probability of condensation of frost.

Therefore although we were able to derive technically valid solutions for tradeoff alternatives with equal energy because of the code requirements limiting U to 0.35 and below we recommend that the U not go higher than the maximum code value and therefore no tradeoff is possible.

Table 11. North Zone Tradeoffs from Population Weighted Regression

U-factor	SHGC Tradeoff
0.36	0.43
0.37	0.46
0.38	0.49
0.39	0.51
0.40	0.54

Table 12. Tradeoff Values by City

	SHGC Tradeoff										
U-value	AK Anchor-age	CO Denver	ID Boise	IL Chic-ago	MA Boston	ME Portland	MN Minnea-polis	MT Great Falls	ND Bismark	NE Omaha	NV Reno
0.36	0.43	0.42	0.43	0.43	0.42	0.42	0.43	0.42	0.43	0.44	0.42
0.37	0.45	0.44	0.46	0.47	0.44	0.44	0.46	0.45	0.45	0.49	0.44
0.38	0.48	0.46	0.48	0.50	0.47	0.46	0.49	0.47	0.48	0.53	0.46
0.39	0.50	0.49	0.51	0.53	0.49	0.47	0.52	0.49	0.51	0.56	0.48
0.40	0.52	0.51	0.54	0.57	0.51	0.49	0.55	0.52	0.53	0.60	0.50

	SHGC Tradeoff											
U-value	NY Buf-falo	NY New York	OH Day-ton	OR Med-ford	OR Port-land	PA Phil-adel-phia	PA Pitts-burgh	UT Salt Lake City	VT Bur-ling-ton	WA Seattle	WI Madi-son	WY Chey-enne
0.36	0.43	0.43	0.43	0.45	0.43	0.43	0.44	0.44	0.42	0.42	0.43	0.42
0.37	0.46	0.46	0.46	0.50	0.45	0.47	0.47	0.47	0.45	0.44	0.45	0.43
0.38	0.49	0.49	0.49	0.54	0.48	0.50	0.50	0.50	0.47	0.46	0.48	0.45
0.39	0.52	0.51	0.52	0.58	0.50	0.53	0.54	0.54	0.50	0.48	0.51	0.47
0.40	0.55	0.54	0.55	0.61	0.52	0.56	0.57	0.57	0.52	0.49	0.53	0.49

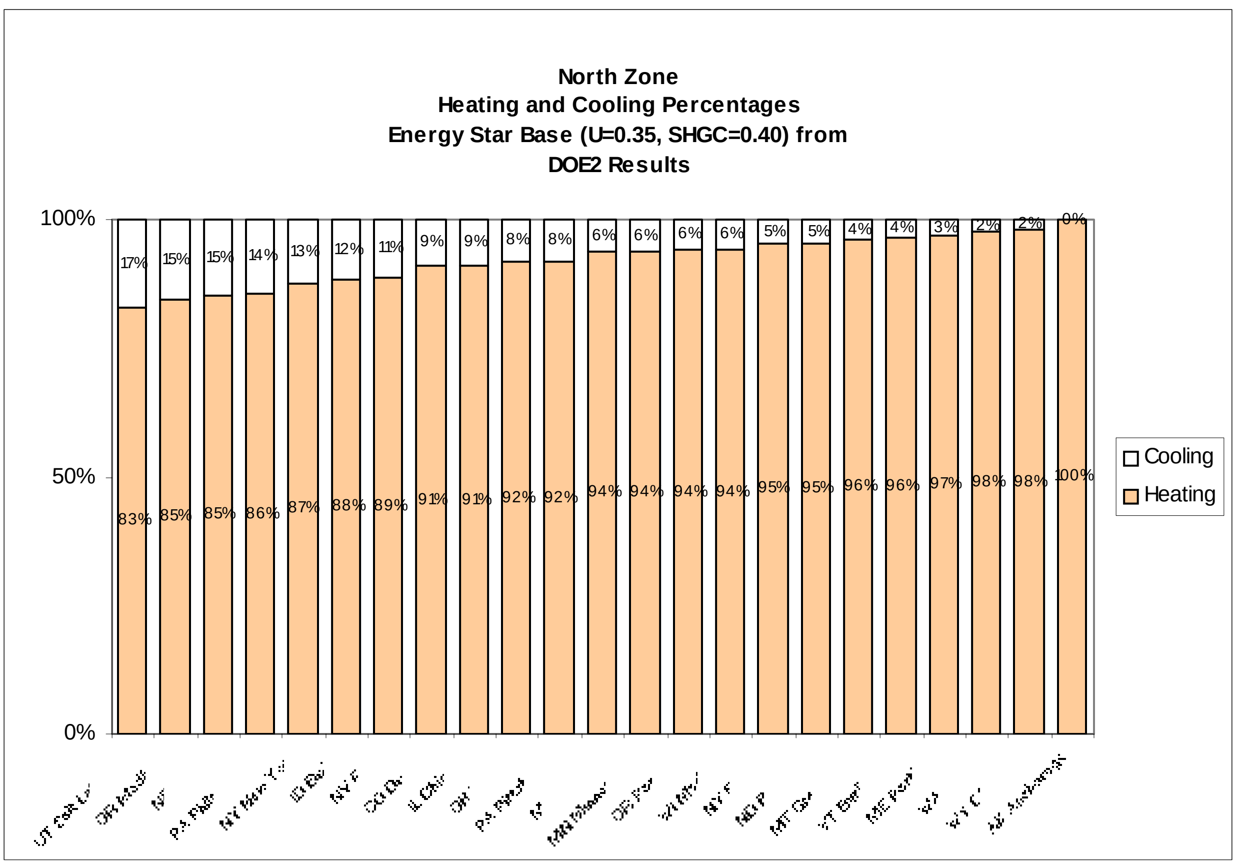

Figure 11. Heating and Cooling Percentage Comparison for North Zone

North Zone -- Future High Performance Windows

In the current tradeoff scenarios, because Energy Star values follow building code values, in many cases the potential tradeoffs can't be implemented because they would exceed constraints from the energy codes. The DOE long term 2020 vision for Zero Energy Buildings will require windows with U values in the range of 0.1 - 0.2 with dynamic control of solar gain. In the future therefore we would expect that technology will provide new, cost-effective options for more efficient windows, but that the building codes will not move as quickly to mandate those lower U values. New Energy Star criteria might respond to these market leaders and thus provide additional opportunity for tradeoffs 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 future. Assume that codes remain at U- 0.35 but that Energy Star responds by targeting U = 0.25 and SHGC = 0.4 for market-leading windows in the Northern zone. It would then be possible to generate tradeoffs for U values between the Energy Star value, 0.25 and the Code requirement of 0.35. Table 13 below illustrates the SHGC associated with each 0.01 increment in U 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 on comfort, peak load, condensation, but since the "worst" window in this tradeoff 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 13. Tradeoffs for North Zone

Base case set to U=0.25, SHGC=0.40	
U-factor	**SHGC Tradeoff**
0.26	0.43
0.27	0.46
0.28	0.49
0.29	0.51
0.30	0.54
0.31	0.57
0.32	0.59
0.33	0.62
0.34	0.65
0.35	0.67

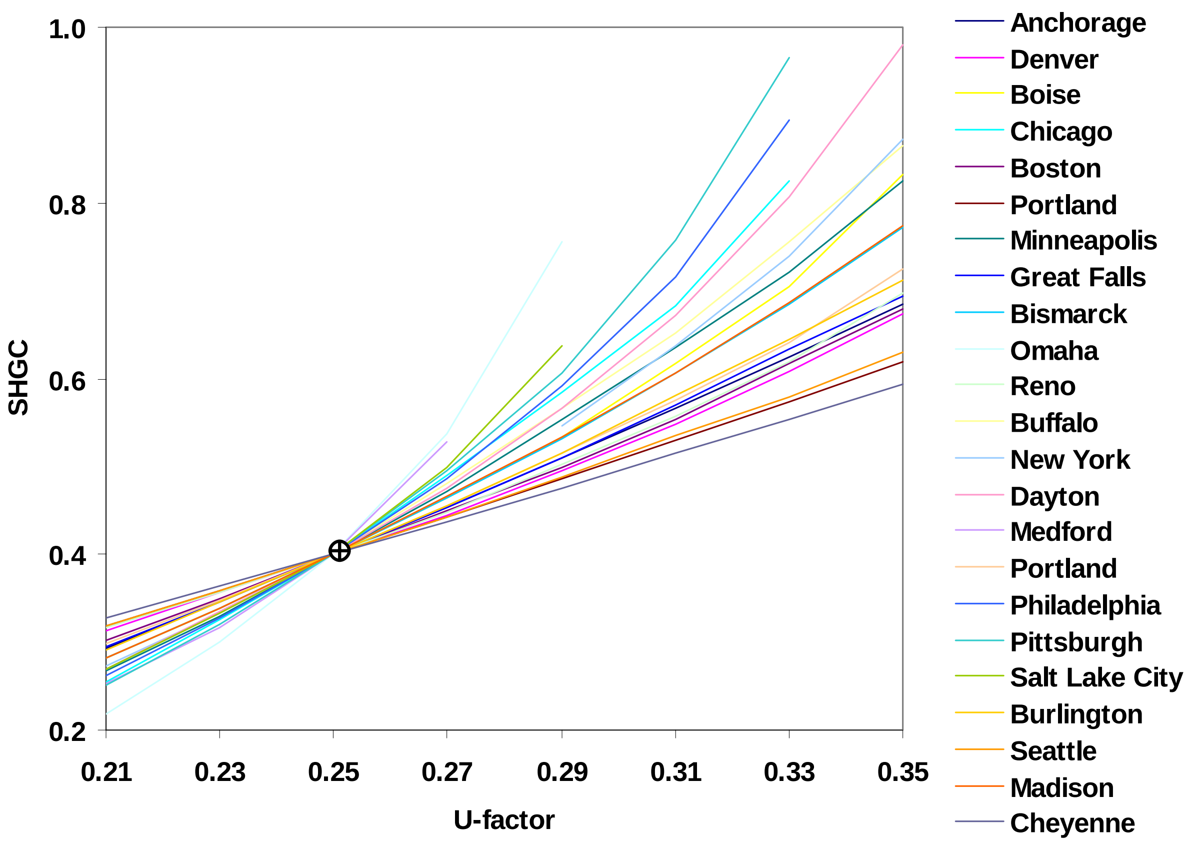

Figure 12. U-factors and SHGCs for Equivalent Energies to EnergyStar Windows Criteria for Future High-Performance Windows in Northern Zone

References

Arasteh, D., R.D. Mitchell, S. Selkowitz. August 1, 2003. *Performance Based Ratings for the ENERGY STAR® Windows Program: A discussion of issues and future possibilities*. Lawrence Berkeley National Laboratory. Berkeley CA.

Arasteh, D., J. Huang, R.D. Mitchell, R. Clear, and C. Kohler. *A Database of Window Annual Energy Use in Typical North American Single-Family Houses*. **ASHRAE Transactions**, V. 106, Pt. 1, 2000.

Sullivan, R. and F. Winkelmann. 1998. *Validation studies of the DOE2 Building Energy Simulaion Program*. LBNL Report 42241. Lawrence Berkeley National Laboratory. Berkeley CA.

Appendix 1: Regression Documentation

California Weather Data Changes

In the first paper, the following California cities were modeled:

Table 14

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 regression 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 15

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

Zone by Zone City Grouping

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 14

Table 16. Population represented by each base city

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

Zone 1 – South

The following cities were simulated for the regression in Zone 1

Table 17

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

Honolulu was simulated but the results were not included in the regression as there is so little energy consumption for that location that the results would be skewed by including it.

Zone 2 – South Central

The following cities were simulated for the regression in Zone 2:

Table 18

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
TX San Antonio	SATXTMY2.bin

This ENERGY STAR zone includes all of Oklahoma even though some portions of Oklahoma have HDD > 3500 (including Oklahoma City). Including Oklahoma City in the regression would thus have skewed the results and therefore that city was dropped from the regression development.

Zone 3 – North Central

The following cities were simulated for the regression in Zone 3:

Table 19

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 – North

The following cities were simulated for the regression in Zone 4:

Table 20

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

Detailed Regression Background

The zonal calculator gives the average energy use of a reference house in a given climate zone as a function of the two most important window thermal parameters: U = thermal conductivity of the window, and S = solar heat gain coefficient of the window. The reference house has 2000 square-feet of floor area, and 300 square-feet of window area, with 75 square-feet of window per orientation. Computer calculations of the energy use of the house were run for both new and existing construction. The window parameters were varied over the following ranges: $0.12 \leq U \leq 1.25$, $0.25 \leq S \leq 0.76$. The climate in the U.S. was broken into the four ENERGY STAR zones which were represented by weather tapes listed in Tables 10-13 above.

In general, changes in the window parameters, U and S, have a greater effect on energy use in climate where the base energy use is higher. Fits with multiplicative terms are more efficient (need fewer terms) than fits with additive terms when all the parameters are considered. However, when only the window parameters are allowed in the regression the additive and multiplicative fits are of similar quality. The additive fits are much easier to calculate, and are therefore what was used in the work described herein.

Heating and cooling were fit separately. This makes it easier to identify terms which were significant. Total energy was calculated by the formula: E = H + 0.011 C, where E is the primary energy use in MBTU, H is the heating energy use in MBTU, C is the point of use electrical use in KWH, and 0.011 is the heat rate of 11,000 BTU per KWH which represents the primary energy needed to produce 1 KWH of electrical energy.

Heating and Cooling Energy Consumption Regression Equation:

The regression equation generated from the fits of the window parameters for calculating the heating and cooling energy consumption is quadratic in all terms and takes the following form:

$$Y = A + (B_1 * U) + (B_2 * S) + (C_{11} * U^2) + (C_{12} * U * S) + (C_{22} * S^2) \qquad \text{(Eq 1)}$$

Where:

Y is either heating or cooling energy consumption (heating is in MBtu, and cooling is in kWh)

Constants A through C_{33} are listed in Table 2 for heating and cooling by ENERGY STAR zone

Total Energy Consumption:

$$E = H + (0.011 * C) \qquad \text{(Eq 2)}$$

Where:

E = the primary energy use in MBTU

H = the heating energy use in MBTU

C = the point of use electrical use in KWH

0.011 = the heat rate of 11,000 BTU per KWH which represents the primary energy needed to produce 1 KWH of electrical energy.

The inclusion of different climates, and conditions in the data vastly increases the noise and makes it difficult to determine which terms in the zonal fit above are actually significant. Figure 1 shows the problem for zone 1. There are 108 different sets of values of the three independent parameters, I, U, and

S. For each of these values there are 8 data points representing the 4 cities and 2 construction types. Figure 1 shows that the spread over these 8 points is larger than the spread due to the independent parameters in the fit. This added noise can make some parameters look statistically insignificant, even though they are in fact significant.

In order to test whether a particular coefficient was significant or not, the fits were first run with added terms for the weather (city), and the construction. Figure 2 shows what happens to the fit in figure 1 when the above terms are added. Terms in I, U, or S which were significant in this expanded fit were kept in the zonal fit.

The tables below give the parameters of the reduced fits. Note that zero values represent coefficients that were not statistically significant and were therefore set to zero.

Table 21. Regression Equation Constants by Zone

		Heating Coefficients			
		Zone 1	**Zone 2**	**Zone 3**	**Zone 4**
Intercept	**A**	13.1203188	30.1420994	81.5887762	113.313636
U	**B1**	11.6143433	24.6507646	46.5434131	62.1428159
S	**B2**	- 8.70906202	-20.9934575	-23.8194947	-26.0843127
U*U	**C11**	-2.9213995	-7.16856044	-13.0573747	-16.2353149
U*S	**C12**	1.4067757	4.6812333	12.477919	16.496118
S*S	**C22**	0	0	-10.74905	-15.49505
		Cooling Coefficients			
		Zone 1	**Zone 2**	**Zone 3**	**Zone 4**
Intercept	**A**	4692.10906	2432.23927	1896.63747	774.208782
U	**B1**	104.627702	131.037537	-44.7715538	-2.18945863
S	**B2**	3024.64394	1863.10944	2158.17733	852.361056
U*U	**C11**	190.12924	124.841109	106.55141	110.296745
U*S	**C12**	-702.9679	-454.4285	-164.8853	-325.9308
S*S	**C22**	926.29977	588.93543	0	613.078374
		Combined Heating and Cooling Coefficients			
E	**E**	61.2	52.0	95.6	110.6