Performance Criteria for Residential Zero Energy Windows

Dariush Arasteh, Howdy Goudey, Joe Huang, Christian Kohler, and Robin Mitchell
Windows and Daylighting Group
Lawrence Berkeley National Laboratory
Berkeley CA 94720

ABSTRACT

This paper shows that the energy requirements for today's typical efficient window products (i.e. ENERGY STAR™ products) are significant when compared to the needs of Zero Energy Homes (ZEHs). Through the use of whole house energy modeling, typical efficient products are evaluated in five US climates and compared against the requirements for ZEHs. Products which meet these needs are defined as a function of climate. In heating dominated climates, windows with U-factors of 0.10 Btu/hr-ft^2-F (0.57 W/m^2-K) will become energy neutral. In mixed heating/cooling climates a low U-factor is not as significant as the ability to modulate from high SHGCs (heating season) to low SHGCs (cooling season).

INTRODUCTION AND BACKGROUND

Approximately two quads ($2*10^{15}$ Btu, 2.1 EJ) of annual heating energy use in the United States are attributable to heat loss through windows, primarily in residential buildings. Even if all existing windows were replaced with currently available energy-efficient windows, the heating consumption attributable to windows would still be more than one quad (10^{15} Btu, 1.1 EJ) [Arasteh et. al. 2006]. Today's typical efficient product (U-factor[1] under 0.35 Btu/hr-ft^2-F (1.99 W/m^2-K) and a SHGC[2] between 0.3 and 0.5), when evaluated from the perspective of a Zero Energy Home (ZEH), is an energy liability. As shown in Apte et. al., 2003 windows in central and northern climates need to be much better insulators (U-factor of 0.10 Btu/hr-ft^2-F (0.57 W/m^2-K) and allow in solar heat gain for space heating, and/or they need to be dynamic in their range of solar heat gain (i.e. maximize solar gains in the winter but minimize them in the summer).

This paper expands on our prior study (Apte et. al.) by showing in detail the impacts of window performance properties (U, SHGC) on annual energy use for a typical house. Our goal is to define the properties necessary for windows to have zero impact on the energy use in a typical house (i.e. a Zero Energy Window). Our prior study considered the effects of nine specific windows on energy use. This study was designed to be more generic and allow the reader to understand where any specific window (with a known U and SHGC) sits in relation to zero energy use.

Highly insulating window development efforts often focus on the development of an insulating glass unit with center-of-glass U-factors of 0.10 Btu/hr-ft^2-F (0.57 W/m^2-K), a target which can be achieved with three layers of glass, two low-e coatings and a low-conductivity gas fill. Vacuum units and aerogel are other alternatives under R&D. Spacer and frame effects can be expected to degrade this performance; as

---

[1] U-factor is the composite thermal conductance of a window and is the inverse of the R-value, which is a measure of the window's thermal resistance. A lower U-factor means lower heat transfer for a given temperature difference and projected area. U-factors are expressed in Btu/(h-ft^2-F) [W/m^2-K].

[2] Solar Heat Gain Coefficient (SHGC) indicates the fraction of heat from incident solar radiation (sunlight) that flows through a window by means of optical transmission, as well as absorption and re-radiation and convection. SHGC is expressed as a number between 0 and 1. The lower a window's SHGC, the less solar heat the window transmits (i.e., the less heat the window will add to a building's interior).

such a total window U-factor of 0.12 Btu/hr-ft^2-F (0.68 W/m^2-K) is targeted as being a realistic long-term product for ZEHs.

While there is clear data from prior studies (Sullivan and Selkowitz 1987, Apte at. al. 2003) that lower U-factor windows are needed for ZEHs throughout the central and northern US, the question of an optimal SHGC, particularly in climates with some cooling load, deserves significant attention. As such, our analysis focuses on looking at the impacts of a typical window's SHGC as well as on the potentials from windows with dynamic SHGC (i.e. a SHGC which is reduced in the summer). This SHGC reduction can come from the use of a mechanized shading device or from an active glazing (i.e. an electrochromic glass; see for example www.sage-ec.com). A summer SHGC of 0.16 was picked as representative of a window with a reduced summer SHGC; such a value allows for the design of a window which can offer a reasonable view (visible transmittance of glass greater than 0.30) but will make a serious reduction in solar gains.

SIMULATION PROCESS

To understand the appropriate performance criteria for windows in ZEHs, we began by performing DOE-2 simulations of 2,500 unique combinations of window U-factors and Solar Heat Gain Coefficients (SHGCs) for each of five cities, representing a range of climate conditions in regions where at least moderate heating is required during the year (climate data tabulated below by city).

City	Heating Degree Days		Global Solar Average Daily Total Radiation	
	HDD_{65} (F)	HDD_{18} (C)	Btu/ft^2	Wh/m^2
Minneapolis MN	8002	4446	1257	3962
Salt Lake City UT	5636	3131	1475	4649
Washington DC	5233	2907	1300	4098
Riverside CA	2103	1168	1633	5149
Charleston SC	2209	1227	1462	4610

Fifty U-factors ranging from 0.02 to 1 Btu/h-ft^2-F (0.11 to 5.68 W/m^2-K)and fifty SHGC values ranging from 0.02 to 1 were used for the simulations. The 2,500 results for each city are the sum of annual heating (from a gas furnace) and cooling (from air conditioning). This total annual energy value is expressed in MBtu and [GJ] (using a multiplier of 3.22 for site to source efficiency as per the DOE Core Data Book). We choose to depict combined annual heating and cooling energy, because although most climates are dominated by either heating or cooling, the lesser factor can still be significant and should not be ignored, as concluded by Sullivan and Selkowitz (1987). The building used in the modeling was not intended to represent one specific house but rather to be representative of new tract construction. As such, some of the specifics (overhang length, window distribution by orientation, neighboring buildings and shading) are not likely to correlate to a specific house but are intended to represent the average impact for a large number of houses. Specifically, this representative house is a 2,000 ft^2 (186 m^2) (new construction) single-family residence with 300 ft^2 (28 m^2) of windows distributed equally on all four orientations (i.e., 75 ft^2 (7 m^2) of window area per exterior wall) and "typical" solar gain reduction (per RESFEN 3.1) [Mitchell, 1999]. Insulation values are climate dependent. A summary of the building's characteristics, including its shading assumptions is given in Appendix 1. This study looks at the energy impacts of windows in typical new construction where little or no attention is given to using passive features such as site characteristics and building design (orientation, landscaping, overhangs, building shape) to minimize energy use. This is done in order to provide insight on what types of windows should be the subject of R&D efforts. Such passive features are recognized as effective tools for energy-efficiency but are not the subject of this paper.

A secondary simulation study of the same five cities was conducted with unequal window area distribution. Four cases of energy use data were collected for each city, to provide information regarding the predominant glass area facing South, West, North or East. The distribution of the 300 ft^2 (28 m^2) glass area was 60% on the predominant side, 10% on the opposite wall, and 15% each on the adjoining walls.

It is important to note that in addition to location, window performance depends on a number of factors including orientation, shading levels, building shell characteristics, and occupancy patterns. For the most part, variations of these parameters were not studied since this project is aimed at defining generic product targets for use in typical houses. Window selection choices for specific houses would benefit from a more site specific analysis.

RESULTS AND DISCUSSION

The simulation results with equally distributed glass area are shown as three-dimensional contour plots for all five cities. Figures 1-5 show results for windows with SHGCs which are constant throughout the year. Figures 6-10 show results for the same five cities, with heating season SHGCs as shown on the plots' x-axis, but with cooling season SHGC's reduced to 0.16. This second set of data represents performance ranges for a sample dynamic window.

On each graph, six window products are plotted. The first five are representative of real products available today, and are taken from the typical windows defined by the Efficient Windows Collaborative website (www.efficientwindows.org). The sixth window is a hypothetical improved version of the fifth with lower U-factor (from frame improvements) and higher SHGC values (from an optimum selection of low-e coatings). These six windows are summarized in the table below. These windows are plotted for reference purposes as these graphs allow the user to visualize the impacts of any hypothetical window, as long as its U-factor and SHGC are known.

Window	U-factor		SHGC	EWC ID	Description
	Btu/hr-ft^2-F	W/m^2-K			
#1	0.84	4.77	0.64	17	Single clear, Wood/vinyl frame
#2	0.49	2.78	0.56	19	Double clear, wood/vinyl
#3	0.37	2.10	0.53	22	Double high gain low-e, Ar, wood/vinyl
#4	0.34	1.93	0.30	24	Double low gain low-e, Ar, wood/vinyl
#5	0.18	1.02	0.40	33	Triple, moderate gain low-e, Kr, insulated vinyl or fiberglass frame
#6	0.12	0.68	0.44		Improved triple, moderate gain low-e, Kr

In all of these plots, the intersection of any U-factor (from the y-axis) and any SHGC (from the x-axis) is the energy performance (total annual heating and cooling energy use in MBtu and GJ) of a residence with the aforementioned design using windows with those two characteristics. Windows #3 and #4 are in the performance range of products typically sold today to meet Energy Star criteria.

The performance threshold at which a window provides net energy gain for the building rather than net energy loss is demarcated by a line (not visible on Figures 4 and 5 as explained below). We established this baseline energy use line by simulating the aforementioned 2000 ft^2 (186 m^2) house with no heat flow through the windows, i.e., the SHGC and U-value properties of the windows were set to zero, representing perfect thermal resistance, with no solar transmittance. For zero-energy homes to become a reality, it is desirable that windows provide a net source of energy, to the extent that this is practical in various climates. Admitting solar heat gain during the heating season to reduce the need for furnace operation is the only means for improving upon the energy consumption calculated for the baseline windowless house. However, the solar gains associated with the windows during the cooling season must not outweigh the energy saved on heating and the thermal conductance of the windows must be low enough to reduce the thermal losses to less than the solar gains. Daylight admitted through windows minimally reduces the consumption of energy for lighting but is not considered here since most residential lighting needs are at night and this effect is minor.

Fixed SHGC case

We first consider the case of (conventional) static windows, or windows where the SHGCs do not change over time (Figures 1-5).

In the city with the largest heating loads, Minneapolis, it is clear that products typical of today's Energy Star level (#3,#4) are far from the zero energy use line. A product which represents today's best available technology (#5) (which exceeds the Energy Star standards) is significantly closer to the zero energy use line, but not quite there. Improving on this window's U-factor significantly, such as window #6, brings this product nearly to the zero energy use line.

Salt Lake City and Washington D.C. are the two remaining heating dominated climates, and the relative performance of the six window products is similar to Minneapolis. However, because the loads are not as high in these climates as they are in Minneapolis, the total MBtu savings from higher performance windows is not as large. Because the ratio of heating to cooling is not as high in these climates, the impact of higher SHGCs on reducing annual energy use is less; in other words, the slopes of the equal energy lines are less in Salt Lake City and even less in Washington D.C., compared to Minneapolis.

With the cooling dominated climates of Riverside CA and Charleston SC (Figures 4 and 5), all products are far from the zero energy lines. In Riverside and Charleston, the line demarcating net energy gain/loss, which would be at 22.5 MBtu (24.7 GJ) and 36.7 MBtu (38.7 GJ) respectively, is not visible, because the energy use predicted for all simulated window property points is higher than the baseline. In these climates, the significant impact of solar heat gain through windows during the substantial summer cooling season cannot be offset by the reduced heating use attributable to solar heat gain through windows during the much more modest heating season. Comparing Figure 5 to Figure 11, which shows heating energy only in Charleston, it is evident that nearly 2/3 of the annual energy load in Charleston is attributed to cooling load for typical window products. On Figures 4 and 5, the dashed line represents the SHGC for a given U-factor that will achieve minimum energy use. It is interesting to note that for these cooling dominated climates, as the window U-factor drops, the SHGC to achieve minimum energy use also drops. This is due primarily to the fact that lower U-factors mean than there is a diminished need for the benefits of solar gains.

Our house prototype is insulated to levels typical of a new house (Mitchell 1999); it is expected that these optimum SHGC would drop even further in more insulated houses and would rise for existing houses which are typically not insulated as well. Obviously, these "optimum" SHGC lines are not absolute; they are highly sensitive to the distribution of window area by orientation, total window area, and shading.

Dynamic SHGC case

Dynamic windows in residential buildings offer the potential for the windows to transmit solar radiation when it is useful (the heating season) and to minimize solar transmission during the cooling season. The potential for dynamic windows is explored in detail in Apte et al. 2003, which finds that windows with dynamic solar heat gain properties that vary according to season could also become energy gainers. Readers of Apte et al. 2003 will note that the variable SHGCs assigned to represent dynamic products have been updated in this paper based on a more current analysis of available dynamic technologies.

Figures 6-10 are companion graphs to Figures 1-5 except that the SHGC during the cooling season (when air conditioning is required) is reduced to 0.16. This low point of 0.16 was selected as representative of dynamic products under R&D as well as an operable shading device.

In the heating dominated climates of Minneapolis, Salt Lake City, and Washington D.C., the drop in SHGC during the summer season is reflected in the increased slope of the lines of equal annual energy use. The value of solar gains is not compromised to such a degree by summer cooling penalties. In all three climates, hypothetical window #6 becomes a net energy provider. Another alternative to a cold climate zero-energy window emerges – that of a 0.20 to 0.30 Btu/hr-ft^2-F (1.14 to 1.70 W/m^2-K) U-factor window with a high winter SHGC. Such a window with a 0.6 SHGC is a zero energy product in Minneapolis (U-factor=0.20 Btu/hr-ft^2-F (1.14 W/m^2-K)) and Washington DC (U-factor=0.30 Btu/hr-ft^2-F (1.70 W/m^2-K)).

In the cooling dominated climates of Riverside and Charleston, the impact of a dynamic window is more dramatic. The nature of the curves (i.e. the slopes) change significantly. Small design changes to window #3, coupled with the addition of dynamic features, make it (or similar products) a candidate for a zero energy window. Large decreases in U-factor do not bring about huge energy savings.

Non – Equal Orientations

Sullivan and Selkowitz (1987) point out that the optimal window properties depend on a complex interaction among factors such as climate characteristics and window orientation. To illustrate the impact of window orientation on annual energy consumption, results for Minneapolis, in which 60% of the 300 ft^2 (28 m^2) glass area faces south, are presented in Figure 12. When compared to Figure 1 (same climate but with equal orientation for all window areas), this figure shows that the proposed prototype easily becomes a source of energy gain under these circumstances, suggesting that careful attention to window orientation in architectural design increases the likelihood that high performance windows will contribute net energy gain to the building.

CONCLUSIONS AND FUTURE WORK

Today's typical energy-efficient residential window represents a significant advance over clear double glazed products. However, such windows will be a liability in a zero-energy home. Using building simulation procedures, we explain what performance improvements will lead to the development of Zero Energy Windows for typical new-construction tract US homes in northern and central climates. The aim of this study is to provide insight on what types of windows should be the subject of R&D efforts for such homes.

In heating dominated climates, a static, high-solar-gain, window with a U-factor of about 0.12 Btu/hr-ft^2-F (0.68 W/m^2-K) can nearly meet the net energy gain criteria desired for zero-energy homes, when no special attention is paid to window orientation. Solar gains in heating dominated climates typically offset conductive losses in the winter and can turn such windows into net energy producers in the winter; if cooling loads are not excessive, the positive gain in the winter can compensate for summer cooling loads. This same window can easily exceed the criteria of a Zero-Energy Window with careful orientation design.

In mixed climates with both heating and cooling, a low U-factor becomes less of an important factor but some added means of seasonal dynamic solar gain control (e.g., by manual or automated shades, or electrochromics) will be necessary for the prototypes in this study to avoid consuming more energy than they gain. Devices such as overhangs and awnings as well as deciduous trees and building design can help with seasonal solar control but were not included in this analysis. Such passive features are recognized as effective tools for energy-efficiency but are not the subject of this paper.

Another approach to a Zero Energy Window in northern climates is to focus on the development of dynamic windows with a high maximum SHGC (i.e. 0.6). This lessens the need to reduce window U-factors to below 0.2 Btu/hr-ft^2-F (1.14 W/m^2-K) for Zero Energy Windows, from an energy perspective.

However, another significant feature of ZEHs may be their use of downsized HVAC systems, which may require that peak load impacts (both winter and summer) be minimized. Such constraints may argue for low U-factor dynamic windows, even if this combination exceeds the requirements for zero energy impacts. This topic of windows for ZEHs and HVAC integration requires additional research.

While this study focuses on energy, peak demand issues will also be addressed positively with dynamic products.

Orientation issues and building construction and operating characteristics can have a significant impact on the energy implications of a specific window. However, given that manufacturers, code officials, and other promotional programs do not know what type of home a window is going in, design goals for high performance windows must be developed for typical applications.

Future work on this subject should examine this subject in the context of what HVAC and envelope characteristic Zero Energy Homes will have. This study assumed HVAC and envelope characteristics typical of today's construction.

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, Building Technologies Program of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

REFERENCES

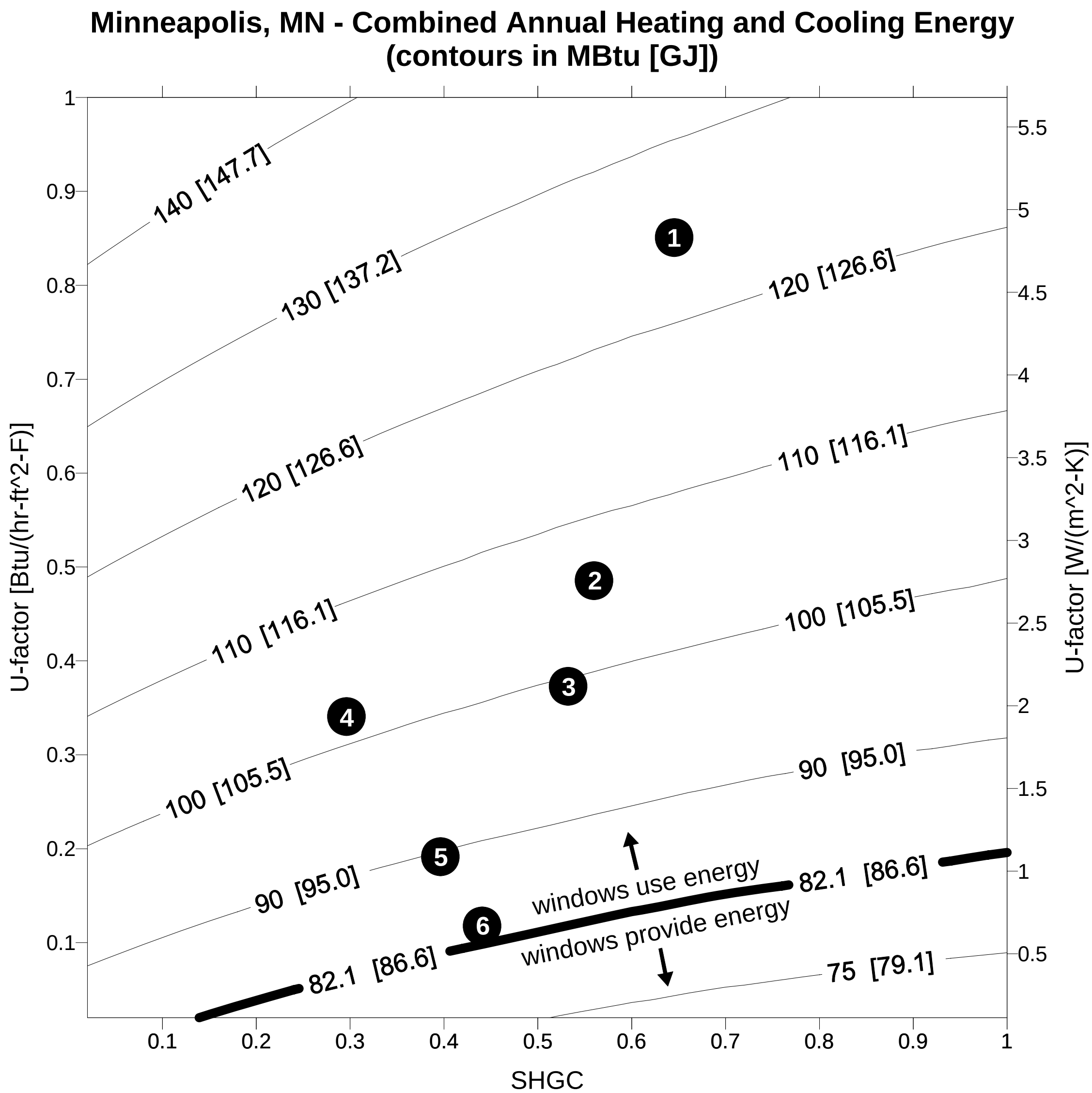
Arasteh, Dariush, Steve Selkowitz, Josh Apte, and Marc LaFrance. 2006. "Zero Energy Windows." Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove CA, August 2006. LBNL 60049

Apte, Josh, Dariush Arasteh, Yu Joe Huang. 2003. "Future Advanced Windows for Zero-Energy Homes." ASHRAE Transactions v. 109.

Mitchell, R., Huang, J., Arasteh, D., Sullivan, R., Phillip, S. 1999. RESFEN 3.1: A PC program for calculating the heating and cooling energy use of windows in residential buildings—Program Description. LBNL-40682 Rev.

Sullivan, R. and S. Selkowitz. 1987. "Residential Heating and Cooling Energy Cost Implications Associated with Window Type." ASHRAE Proceedings, January.

Sullivan, R. and S. Selkowitz. 1985. "Window Performance Analysis in a Single-Family Residence." Buildings III Conference, Clearwater Beach FL, December.



1 U=0.84 Btu/(hr-ft^2-F) [4.77 W/(m^2-K)], SHGC=0.64 - 124.3 MBtu [131.2 GJ] - single, clear, wood/vinyl

2 U=0.49 Btu/(hr-ft^2-F) [2.78 W/(m^2-K)], SHGC=0.56 - 106.2 MBtu [112.0 GJ] - double, clear, air, wood/vinyl

3 U=0.37 Btu/(hr-ft^2-F) [2.10 W/(m^2-K)], SHGC=0.53 - 99.3 MBtu [104.7 GJ] - double, high gain low-e, Ar, wood/vinyl

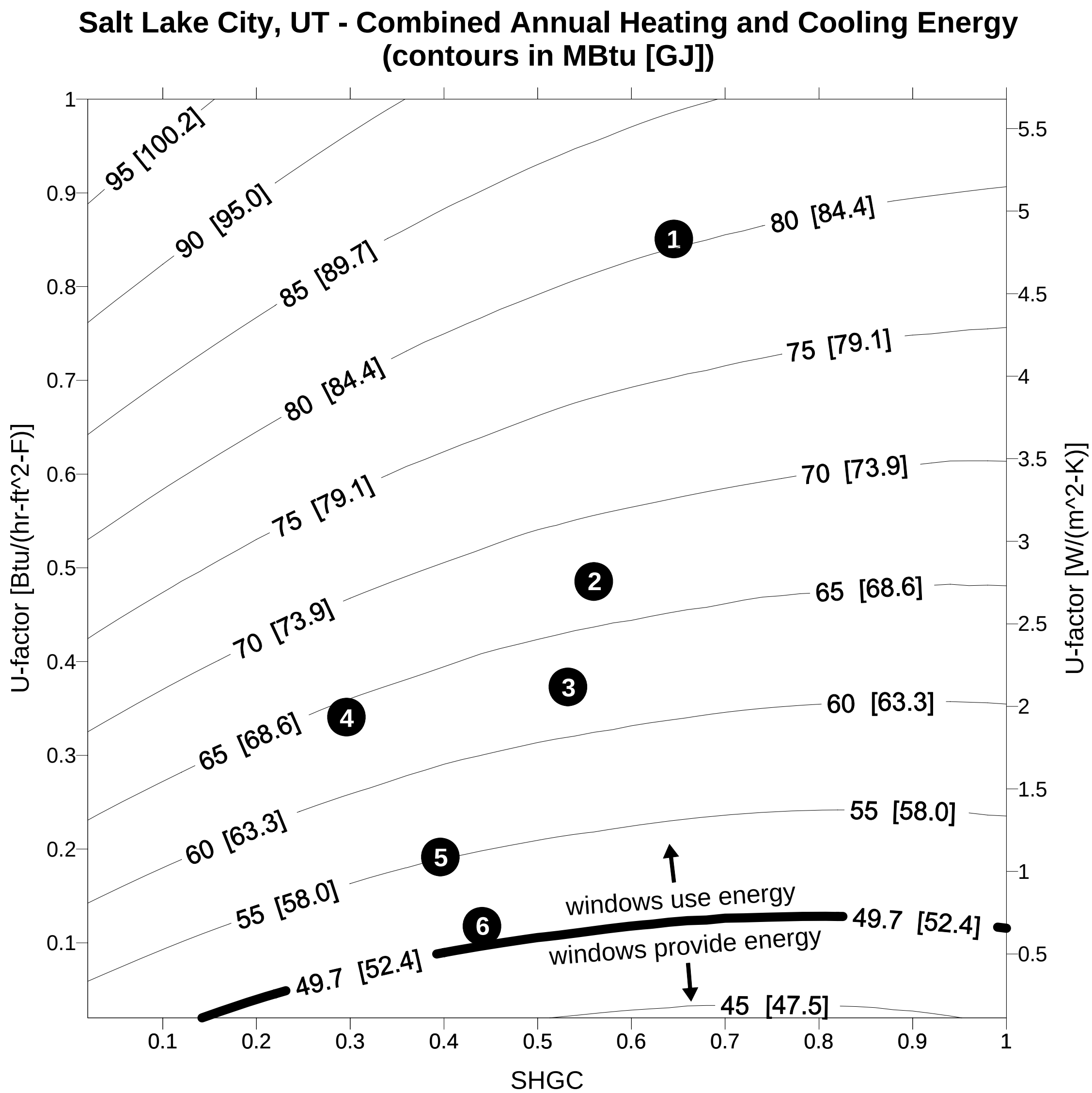
4 U=0.34 Btu/(hr-ft^2-F) [1.93 W/(m^2-K)], SHGC=0.30 - 101.9 MBtu [107.5 GJ] - double, low gain low-e, Ar, wood/vinyl

5 U=0.18 Btu/(hr-ft^2-F) [1.02 W/(m^2-K)], SHGC=0.40 - 88.7 MBtu [93.6 GJ] - triple, moderate gain low-e, Kr, insulated

6 U=0.12 Btu/(hr-ft^2-F) [0.68 W/(m^2-K)], SHGC=0.44 - 83.7 MBtu [88.3 GJ] - improved triple, moderate gain low-e, Kr

neutral energy impact of windows (energy consumption of building with no windows)

Figure 1 – Minneapolis, MN: Lines of equal annual source energy (combined heating and cooling, in MBtu and [GJ]) as a function of window U-factor and SHGC for a typical new house.



1 U=0.84 Btu/(hr-ft^2-F) [4.77 W/(m^2-K)], SHGC=0.64 - 80.0 MBtu [84.4 GJ] - single, clear, wood/vinyl

2 U=0.49 Btu/(hr-ft^2-F) [2.78 W/(m^2-K)], SHGC=0.56 - 67.3 MBtu [71.0 GJ] - double, clear, air, wood/vinyl

3 U=0.37 Btu/(hr-ft^2-F) [2.10 W/(m^2-K)], SHGC=0.53 - 62.3 MBtu [65.8 GJ] - double, high gain low-e, Ar, wood/vinyl

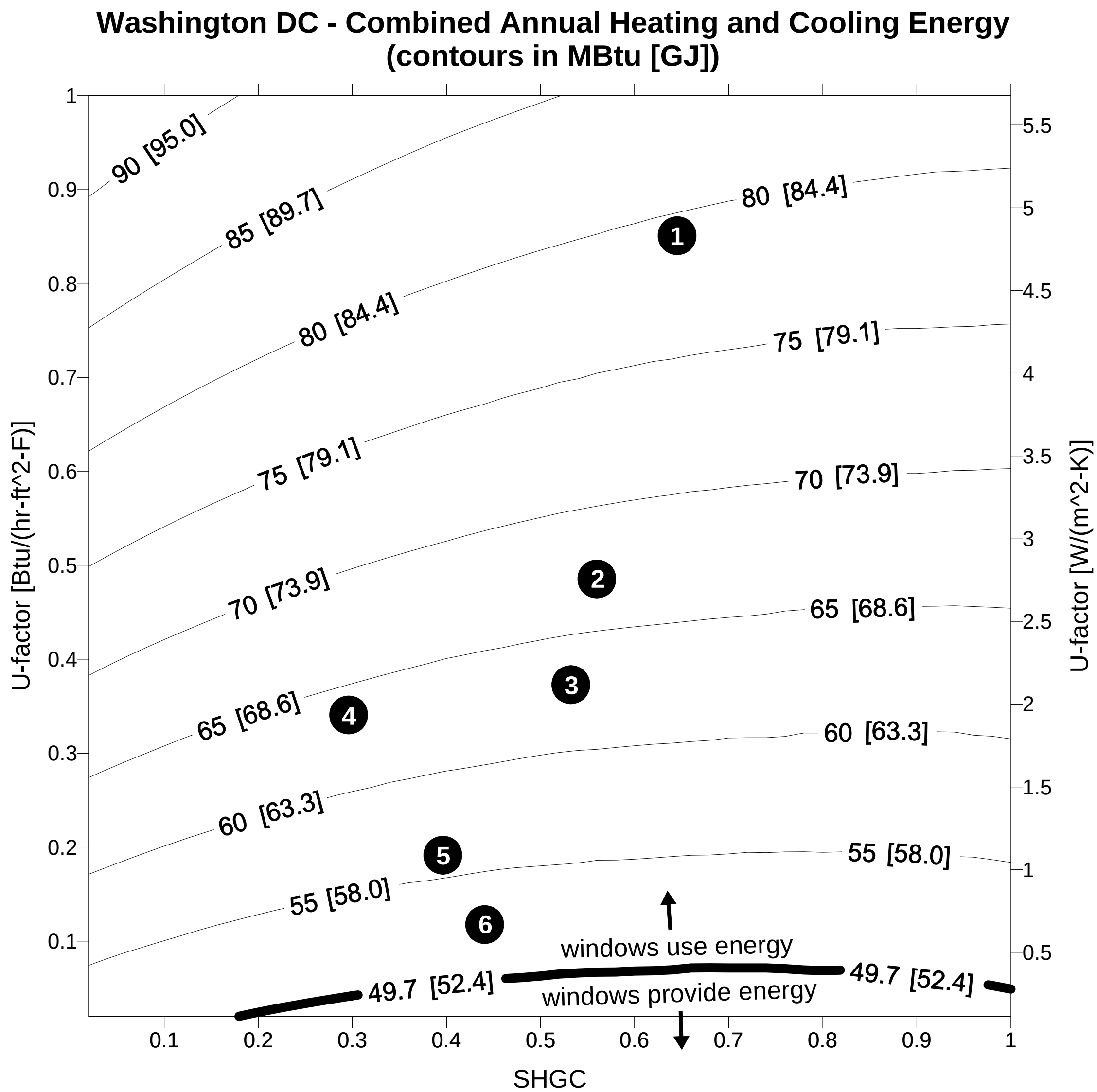
4 U=0.34 Btu/(hr-ft^2-F) [1.93 W/(m^2-K)], SHGC=0.30 - 64.0 MBtu [67.5 GJ] - double, low gain low-e, Ar, wood/vinyl

5 U=0.18 Btu/(hr-ft^2-F) [1.02 W/(m^2-K)], SHGC=0.40 - 54.5 MBtu [57.5 GJ] - triple, moderate gain low-e, Kr, insulated

6 U=0.12 Btu/(hr-ft^2-F) [0.68 W/(m^2-K)], SHGC=0.44 - 51.0 MBtu [53.8 GJ] - improved triple, moderate gain low-e, Kr

neutral energy impact of windows (energy consumption of building with no windows)

Figure 2 – Salt Lake City, UT: Lines of equal annual source energy (combined heating and cooling, in MBtu and [GJ]) as a function of window U-factor and SHGC for a typical new house.



1 U=0.84 Btu/(hr-ft^2-F) [4.77 W/(m^2-K)], SHGC=0.64 - 78.9 MBtu [83.3 GJ] - single, clear, wood/vinyl

2 U=0.49 Btu/(hr-ft^2-F) [2.78 W/(m^2-K)], SHGC=0.56 - 67.3 MBtu [71.0 GJ] - double, clear, air, wood/vinyl

3 U=0.37 Btu/(hr-ft^2-F) [2.10 W/(m^2-K)], SHGC=0.53 - 62.8 MBtu [66.3 GJ] - double, high gain low-e, Ar, wood/vinyl

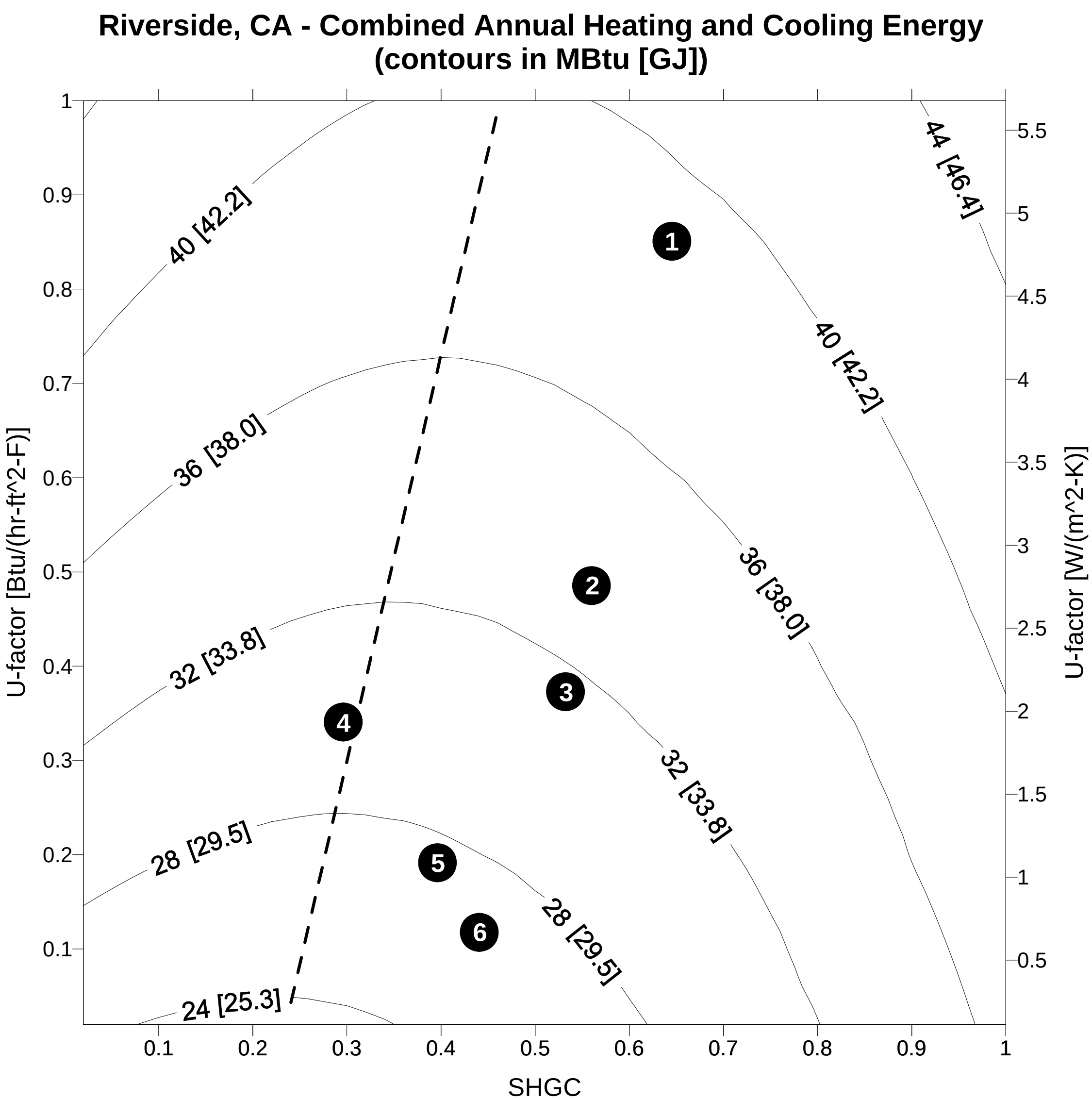
4 U=0.34 Btu/(hr-ft^2-F) [1.93 W/(m^2-K)], SHGC=0.30 - 63.5 MBtu [67.0 GJ] - double, low gain low-e, Ar, wood/vinyl

5 U=0.18 Btu/(hr-ft^2-F) [1.02 W/(m^2-K)], SHGC=0.40 - 55.6 MBtu [58.6 GJ] - triple, moderate gain low-e, Kr, insulated

6 U=0.12 Btu/(hr-ft^2-F) [0.68 W/(m^2-K)], SHGC=0.44 - 52.5 MBtu [55.4 GJ] - improved triple, moderate gain low-e, Kr

— neutral energy impact of windows (energy consumption of building with no windows)

Figure 3 – Washington DC: Lines of equal annual source energy (combined heating and cooling, in MBtu and [GJ]) as a function of window U-factor and SHGC for a typical new house.



1 U=0.84 Btu/(hr-ft^2-F) [4.77 W/(m^2-K)], SHGC=0.64 - 38.8 MBtu [40.9 GJ] - single, clear, wood/vinyl

2 U=0.49 Btu/(hr-ft^2-F) [2.78 W/(m^2-K)], SHGC=0.56 - 33.5 MBtu [35.3 GJ] - double, clear, air, wood/vinyl

3 U=0.37 Btu/(hr-ft^2-F) [2.10 W/(m^2-K)], SHGC=0.53 - 31.5 MBtu [33.2 GJ] - double, high gain low-e, Ar, wood/vinyl

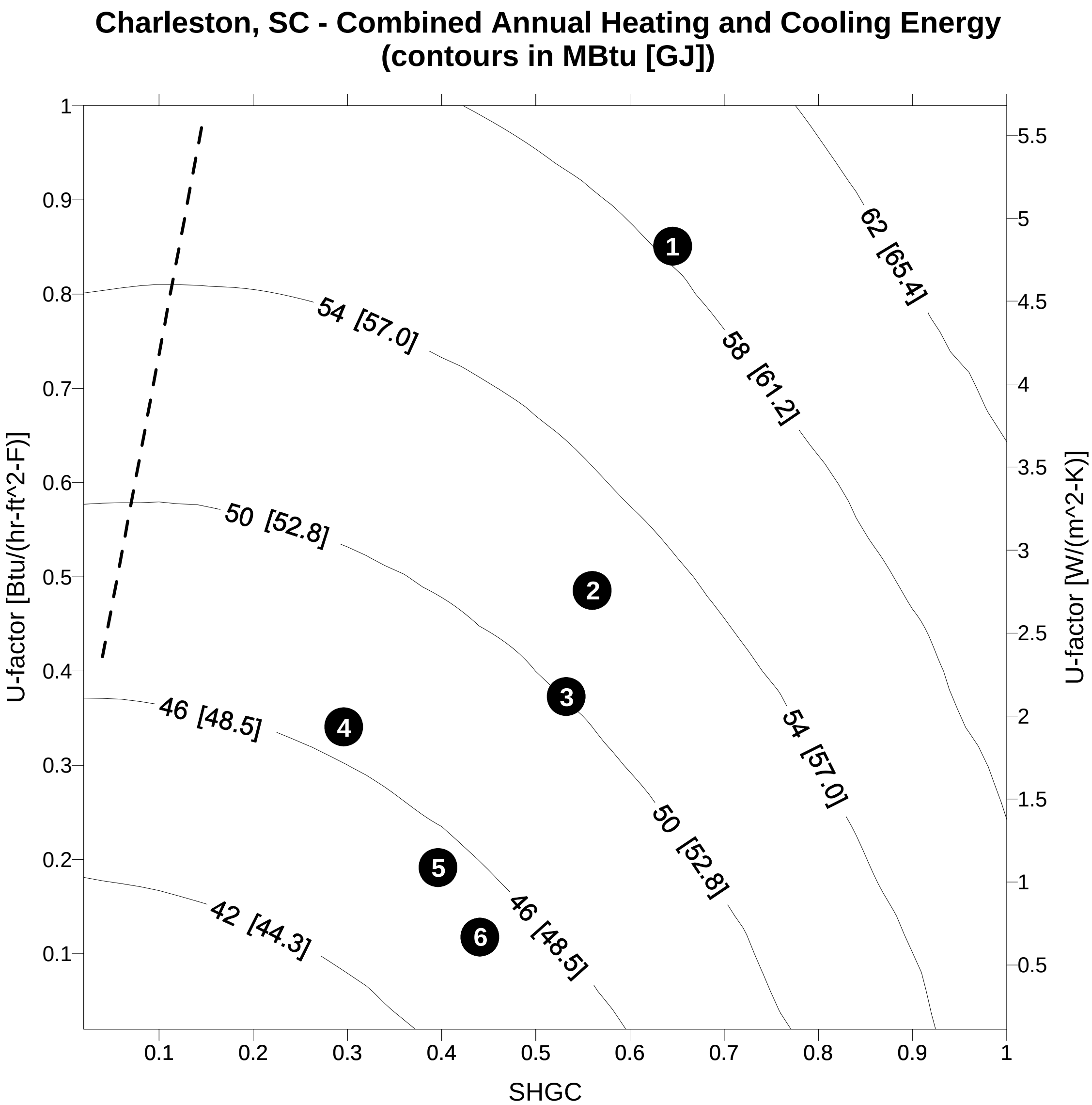
4 U=0.34 Btu/(hr-ft^2-F) [1.93 W/(m^2-K)], SHGC=0.30 - 29.8 MBtu [31.4 GJ] - double, low gain low-e, Ar, wood/vinyl

5 U=0.18 Btu/(hr-ft^2-F) [1.02 W/(m^2-K)], SHGC=0.40 - 27.3 MBtu [28.8 GJ] - triple, moderate gain low-e, Kr, insulated

6 U=0.12 Btu/(hr-ft^2-F) [0.68 W/(m^2-K)], SHGC=0.44 - 26.6 MBtu [28.1 GJ] - improved triple, moderate gain low-e, Kr

– – minimum energy SHGC for a given U-factor

Figure 4 – Riverside, CA: Lines of equal annual source energy (combined heating and cooling, in MBtu and [GJ]) as a function of window U-factor and SHGC for a typical new house.



1 U=0.84 Btu/(hr-ft^2-F) [4.77 W/(m^2-K)], SHGC=0.64 - 58.1 MBtu [61.3 GJ] - single, clear, wood/vinyl

2 U=0.49 Btu/(hr-ft^2-F) [2.78 W/(m^2-K)], SHGC=0.56 - 52.2 MBtu [55.1 GJ] - double, clear, air, wood/vinyl

3 U=0.37 Btu/(hr-ft^2-F) [2.10 W/(m^2-K)], SHGC=0.53 - 50.0 MBtu [52.7 GJ] - double, high gain low-e, Ar, wood/vinyl

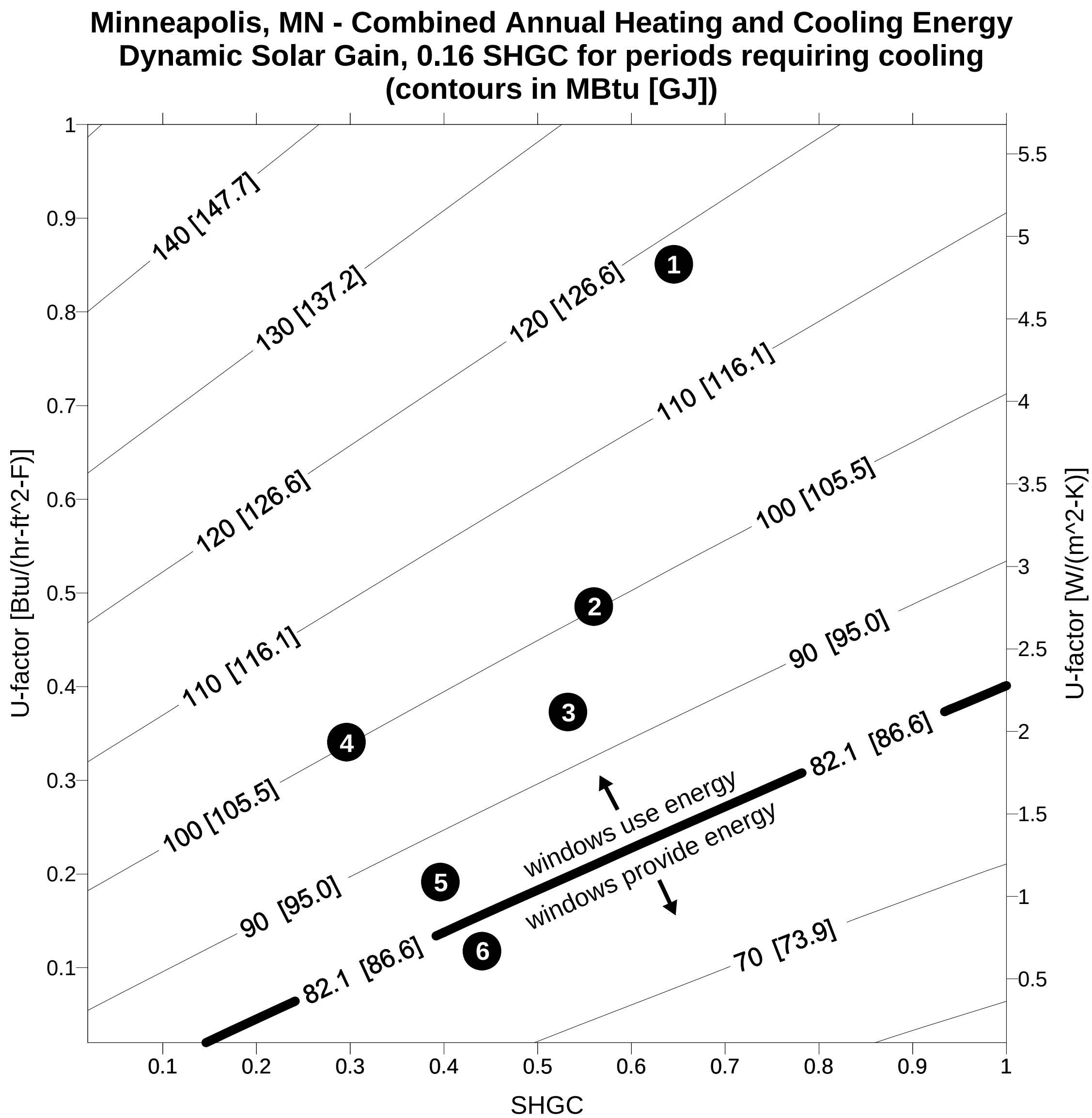
4 U=0.34 Btu/(hr-ft^2-F) [1.93 W/(m^2-K)], SHGC=0.30 - 46.7 MBtu [49.3 GJ] - double, low gain low-e, Ar, wood/vinyl

5 U=0.18 Btu/(hr-ft^2-F) [1.02 W/(m^2-K)], SHGC=0.40 - 45.1 MBtu [47.6 GJ] - triple, moderate gain low-e, Kr, insulated

6 U=0.12 Btu/(hr-ft^2-F) [0.68 W/(m^2-K)], SHGC=0.44 - 44.8 MBtu [47.2 GJ] - improved triple, moderate gain low-e, Kr

– – minimum energy SHGC for a given U-factor

Figure 5 – Charleston, SC: Lines of equal annual source energy (combined heating and cooling, in MBtu and [GJ]) as a function of window U-factor and SHGC for a typical new house.



1 U=0.84 Btu/(hr-ft^2-F) [4.77 W/(m^2-K)], SHGC=0.64 - 117.8 MBtu [124.3 GJ] - single, clear, wood/vinyl

2 U=0.49 Btu/(hr-ft^2-F) [2.78 W/(m^2-K)], SHGC=0.56 - 100.5 MBtu [106.0 GJ] - double, clear, air, wood/vinyl

3 U=0.37 Btu/(hr-ft^2-F) [2.10 W/(m^2-K)], SHGC=0.53 - 93.9 MBtu [99.1 GJ] - double, high gain low-e, Ar, wood/vinyl

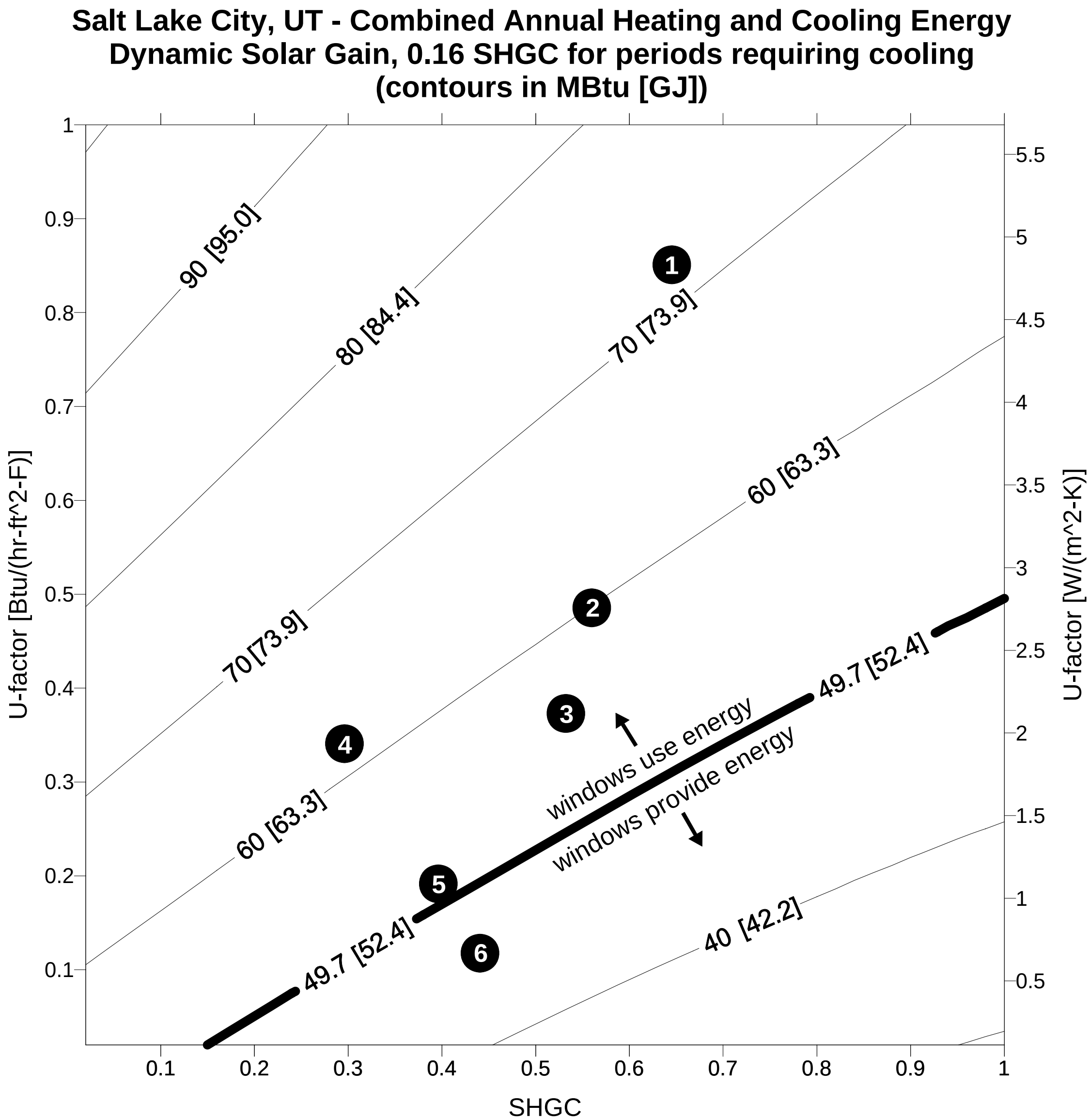
4 U=0.34 Btu/(hr-ft^2-F) [1.93 W/(m^2-K)], SHGC=0.30 - 100.0 MBtu [105.5 GJ] - double, low gain low-e, Ar, wood/vinyl

5 U=0.18 Btu/(hr-ft^2-F) [1.02 W/(m^2-K)], SHGC=0.40 - 85.2 MBtu [89.9 GJ] - triple, moderate gain low-e, Kr, insulated

6 U=0.12 Btu/(hr-ft^2-F) [0.68 W/(m^2-K)], SHGC=0.44 - 79.4 MBtu [83.8 GJ] - improved triple, moderate gain low-e, Kr

neutral energy impact of windows (energy consumption of building with no windows)

Figure 6 – Minneapolis, MN: Lines of equal annual source energy (combined heating and cooling, in MBtu and [GJ]) as a function of window U-factor and heating-season SHGC for a typical new house. Cooling season SHGCs are set at 0.16 to represent a seasonally dynamic window.



1 U=0.84 Btu/(hr-ft^2-F) [4.77 W/(m^2-K)], SHGC=0.64 - 71.5 MBtu [75.5 GJ] - single, clear, wood/vinyl

2 U=0.49 Btu/(hr-ft^2-F) [2.78 W/(m^2-K)], SHGC=0.56 - 60.1 MBtu [63.4 GJ] - double, clear, air, wood/vinyl

3 U=0.37 Btu/(hr-ft^2-F) [2.10 W/(m^2-K)], SHGC=0.53 - 55.7 MBtu [58.7 GJ] - double, high gain low-e, Ar, wood/vinyl

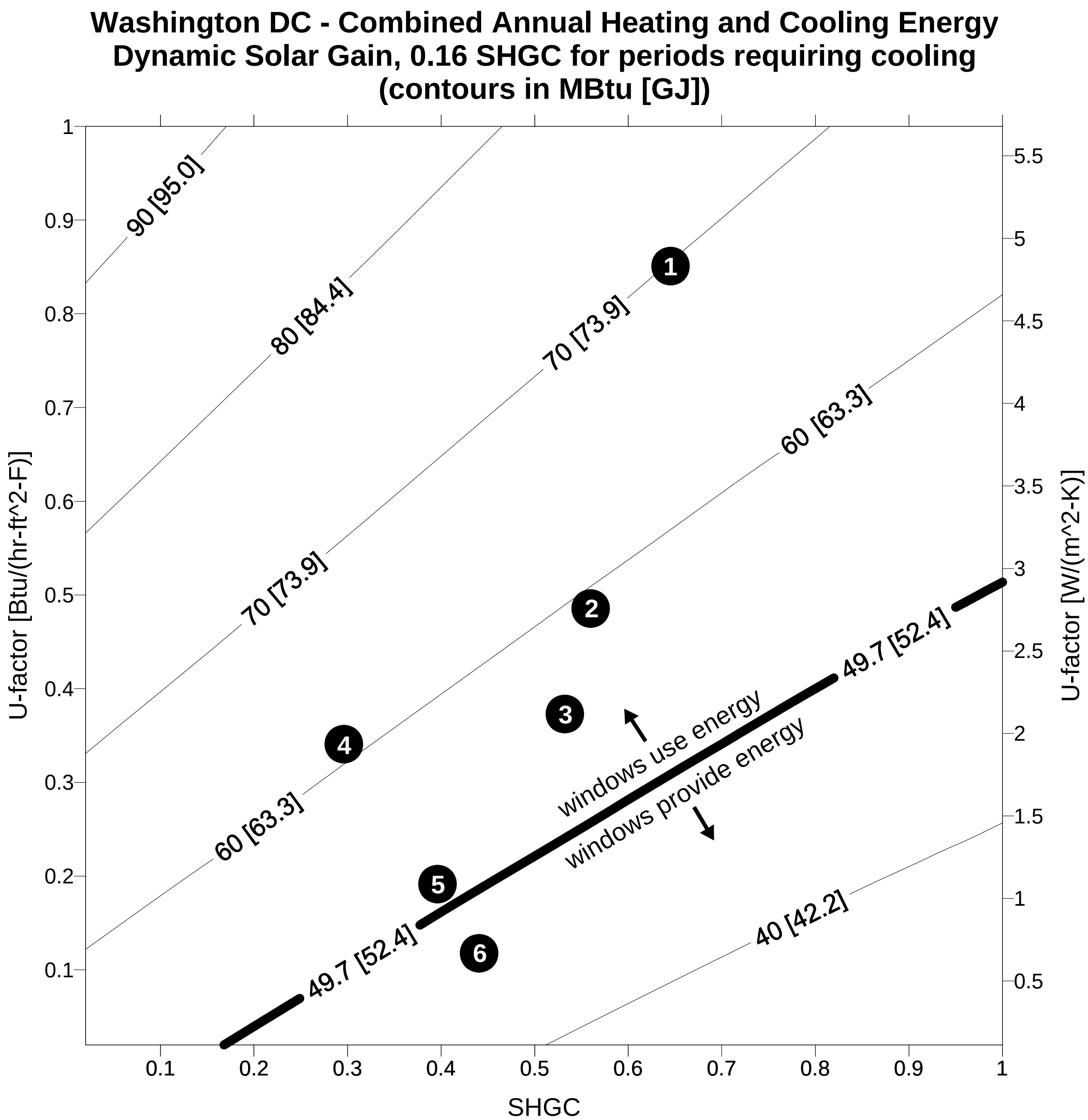
4 U=0.34 Btu/(hr-ft^2-F) [1.93 W/(m^2-K)], SHGC=0.30 - 61.6 MBtu [65.0 GJ] - double, low gain low-e, Ar, wood/vinyl

5 U=0.18 Btu/(hr-ft^2-F) [1.02 W/(m^2-K)], SHGC=0.40 - 50.2 MBtu [53.0 GJ] - triple, moderate gain low-e, Kr, insulated

6 U=0.12 Btu/(hr-ft^2-F) [0.68 W/(m^2-K)], SHGC=0.44 - 45.9 MBtu [48.4 GJ] - improved triple, moderate gain low-e, Kr

neutral energy impact of windows (energy consumption of building with no windows)

Figure 7 – Salt Lake City, UT: Lines of equal annual source energy (combined heating and cooling, in MBtu and [GJ]) as a function of window U-factor and heating-season SHGC for a typical new house. Cooling season SHGCs are set at 0.16 to represent a seasonally dynamic window.



1. U=0.84 Btu/(hr-ft^2-F) [4.77 W/(m^2-K)], SHGC=0.64 - 69.6 MBtu [73.4 GJ] - single, clear, wood/vinyl
2. U=0.49 Btu/(hr-ft^2-F) [2.78 W/(m^2-K)], SHGC=0.56 - 59.3 MBtu [62.5 GJ] - double, clear, air, wood/vinyl
3. U=0.37 Btu/(hr-ft^2-F) [2.10 W/(m^2-K)], SHGC=0.53 - 55.2 MBtu [58.3 GJ] - double, high gain low-e, Ar, wood/vinyl
4. U=0.34 Btu/(hr-ft^2-F) [1.93 W/(m^2-K)], SHGC=0.30 - 60.8 MBtu [64.1 GJ] - double, low gain low-e, Ar, wood/vinyl
5. U=0.18 Btu/(hr-ft^2-F) [1.02 W/(m^2-K)], SHGC=0.40 - 50.6 MBtu [53.3 GJ] - triple, moderate gain low-e, Kr, insulated
6. U=0.12 Btu/(hr-ft^2-F) [0.68 W/(m^2-K)], SHGC=0.44 - 46.6 MBtu [49.2 GJ] - improved triple, moderate gain low-e, Kr

— neutral energy impact of windows (energy consumption of building with no windows)

Figure 8 – Washington DC: Lines of equal annual source energy (combined heating and cooling, in MBtu and [GJ]) as a function of window U-factor and heating-season SHGC for a typical new house. Cooling season SHGCs are set at 0.16 to represent a seasonally dynamic window.

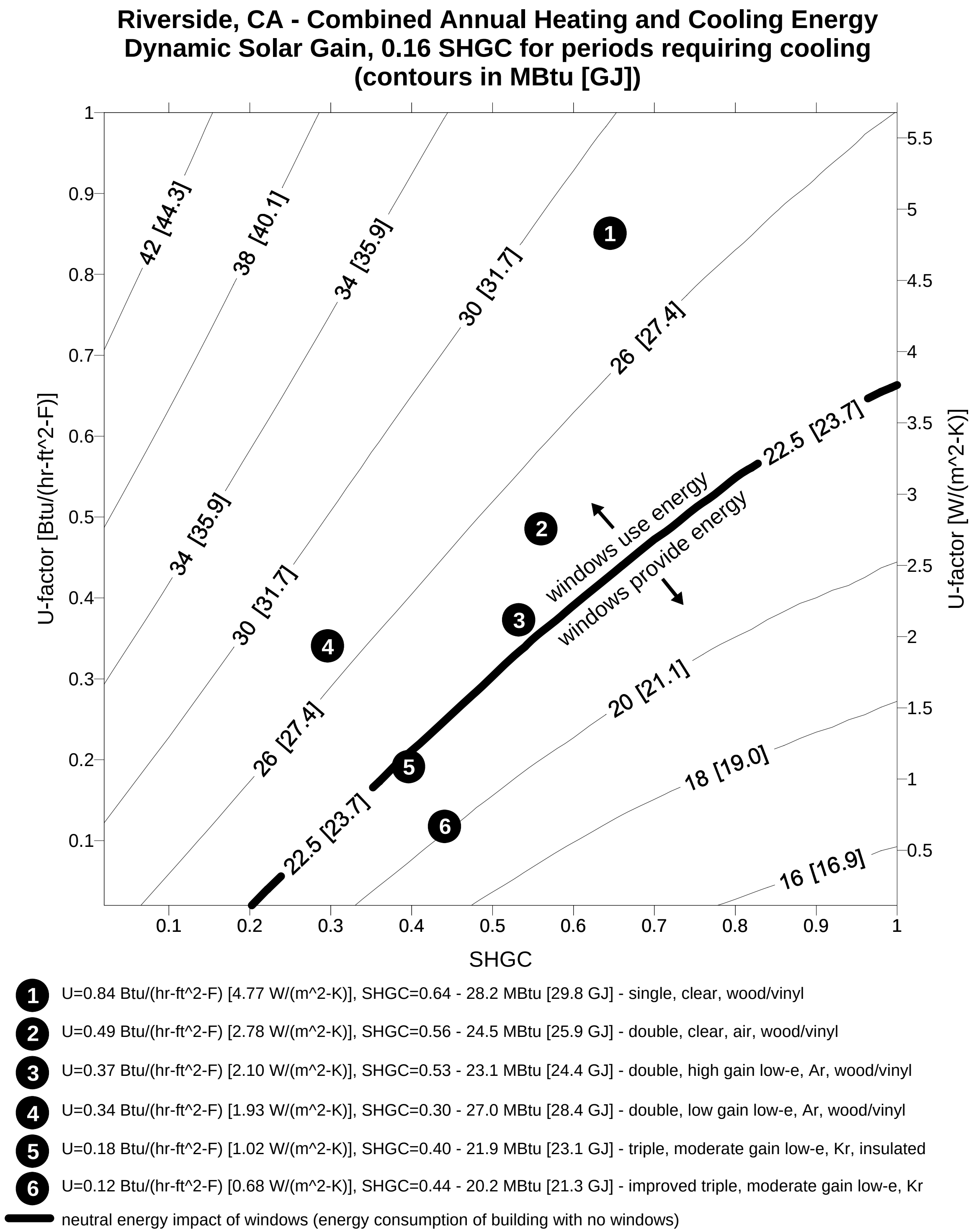
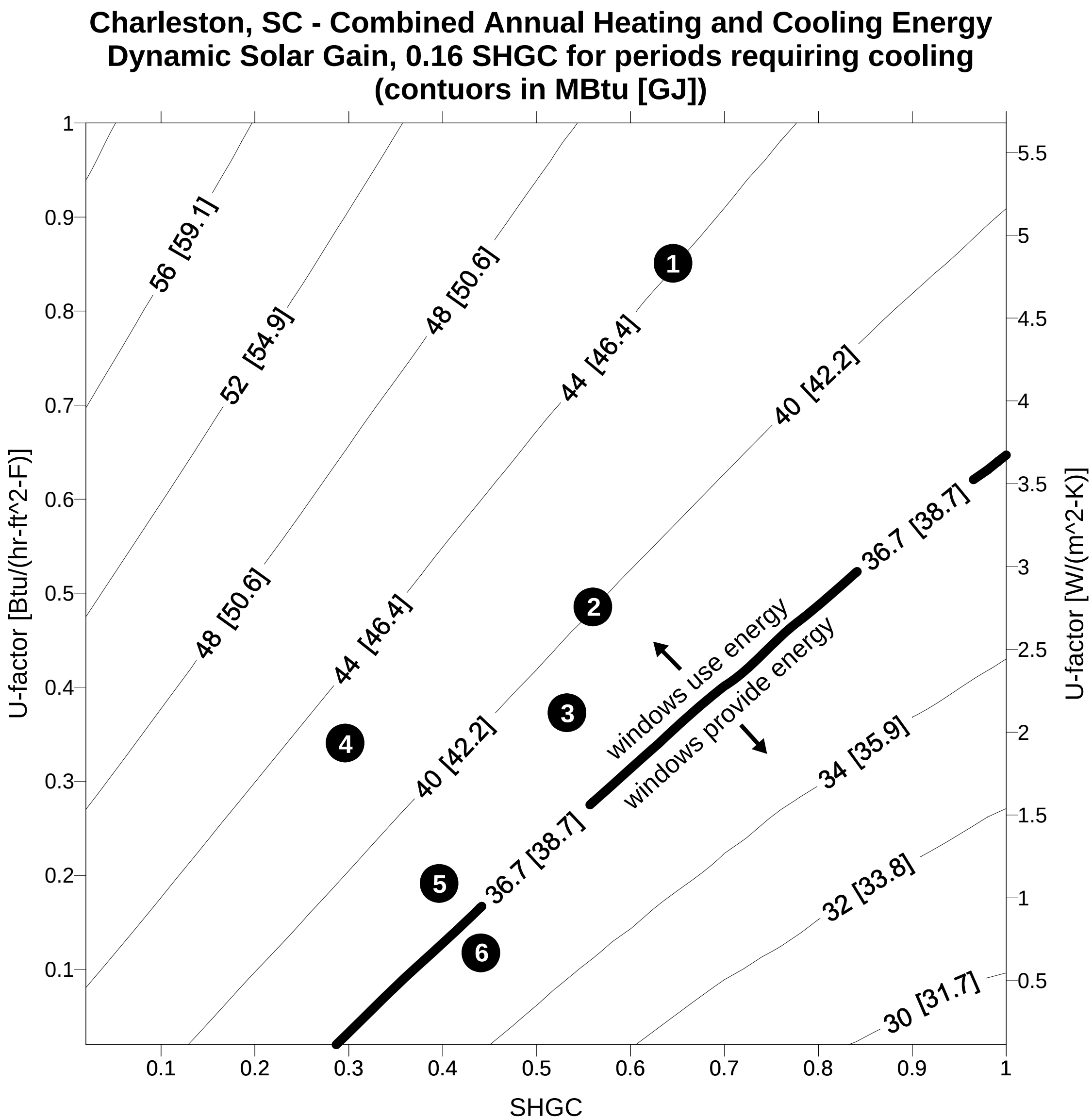


Figure 9 – Riverside, CA: Lines of equal annual source energy (combined heating and cooling, in MBtu and [GJ]) as a function of window U-factor and heating-season SHGC for a typical new house. Cooling season SHGCs are set at 0.16 to represent a seasonally dynamic window.



1. U=0.84 Btu/(hr-ft^2-F) [4.77 W/(m^2-K)], SHGC=0.64 - 44.0 MBtu [46.4 GJ] - single, clear, wood/vinyl
2. U=0.49 Btu/(hr-ft^2-F) [2.78 W/(m^2-K)], SHGC=0.56 - 40.1 MBtu [42.3 GJ] - double, clear, air, wood/vinyl
3. U=0.37 Btu/(hr-ft^2-F) [2.10 W/(m^2-K)], SHGC=0.53 - 38.7 MBtu [40.8 GJ] - double, high gain low-e, Ar, wood/vinyl
4. U=0.34 Btu/(hr-ft^2-F) [1.93 W/(m^2-K)], SHGC=0.30 - 42.5 MBtu [44.9 GJ] - double, low gain low-e, Ar, wood/vinyl
5. U=0.18 Btu/(hr-ft^2-F) [1.02 W/(m^2-K)], SHGC=0.40 - 37.6 MBtu [39.7 GJ] - triple, moderate gain low-e, Kr, insulated
6. U=0.12 Btu/(hr-ft^2-F) [0.68 W/(m^2-K)], SHGC=0.44 - 35.9 MBtu [37.9 GJ] - improved triple, moderate gain low-e, Kr

neutral energy impact of windows (energy consumption of building with no windows)

Figure 10 – Charleston, SC: Lines of equal annual source energy (combined heating and cooling, in MBtu and [GJ]) as a function of window U-factor and heating-season SHGC for a typical new house. Cooling season SHGCs are set at 0.16 to represent a seasonally dynamic window.

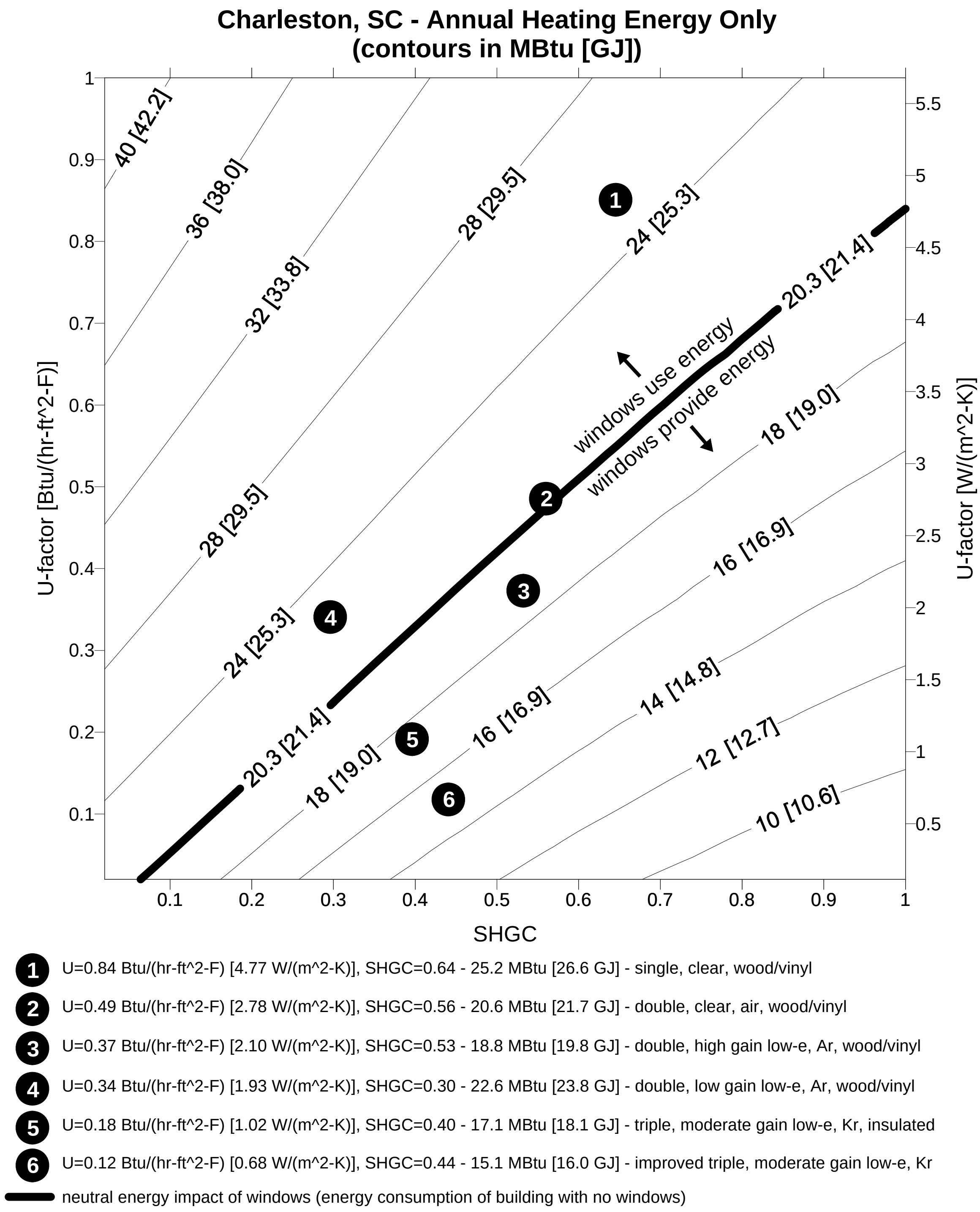
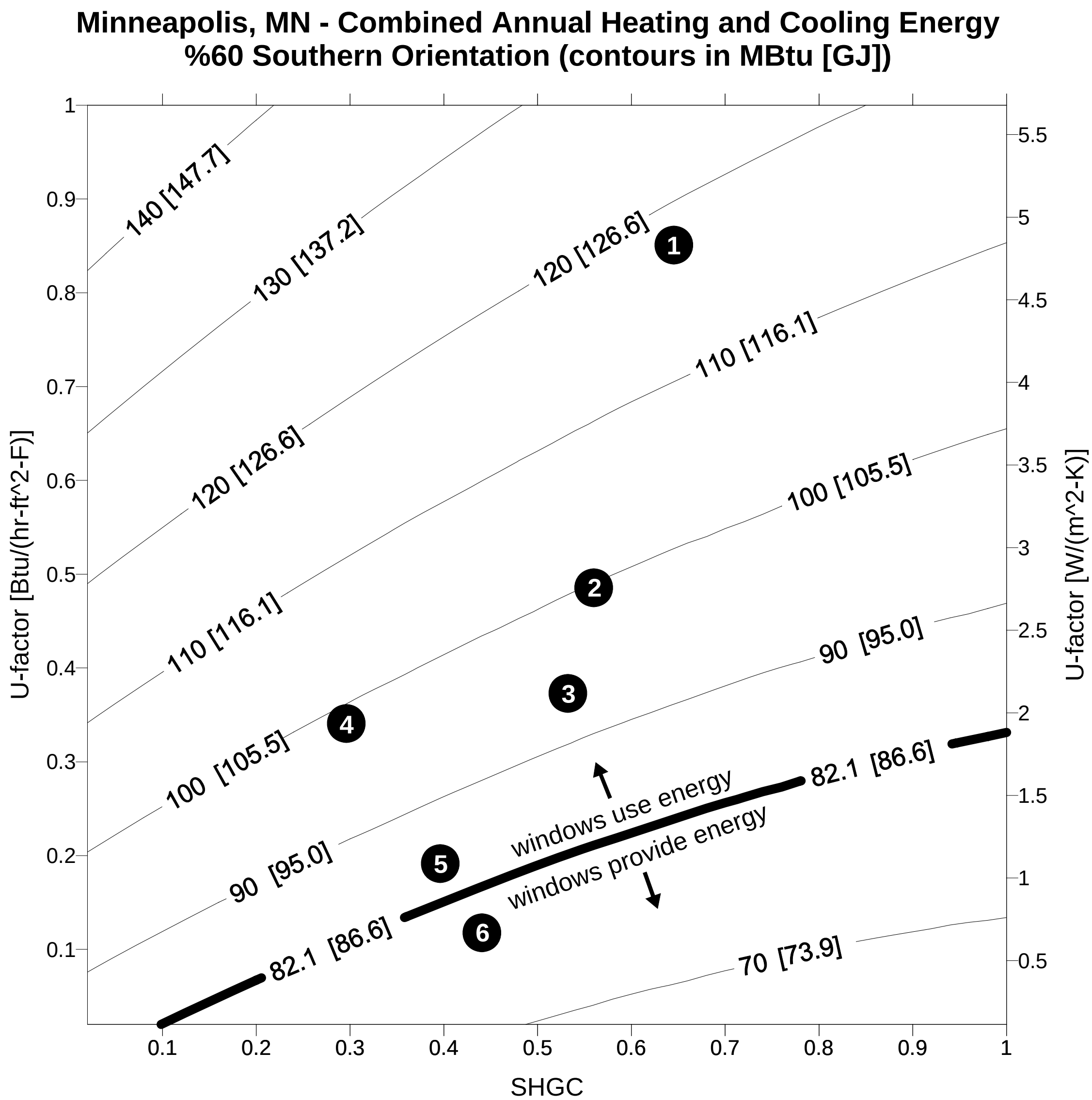


Figure 11 – Charleston, SC. Lines of equal annual heating energy (in MBtu and [GJ]) as a function of window U-factor and SHGC for a typical new house.



1. U=0.84 Btu/(hr-ft^2-F) [4.77 W/(m^2-K)], SHGC=0.64 - 116.8 MBtu [123.2 GJ] - single, clear, wood/vinyl
2. U=0.49 Btu/(hr-ft^2-F) [2.78 W/(m^2-K)], SHGC=0.56 - 99.6 MBtu [105.1 GJ] - double, clear, air, wood/vinyl
3. U=0.37 Btu/(hr-ft^2-F) [2.10 W/(m^2-K)], SHGC=0.53 - 93.0 MBtu [98.1 GJ] - double, high gain low-e, Ar, wood/vinyl
4. U=0.34 Btu/(hr-ft^2-F) [1.93 W/(m^2-K)], SHGC=0.30 - 98.2 MBtu [103.6 GJ] - double, low gain low-e, Ar, wood/vinyl
5. U=0.18 Btu/(hr-ft^2-F) [1.02 W/(m^2-K)], SHGC=0.40 - 83.9 MBtu [88.5 GJ] - triple, moderate gain low-e, Kr, insulated
6. U=0.12 Btu/(hr-ft^2-F) [0.68 W/(m^2-K)], SHGC=0.44 - 78.5 MBtu [82.8 GJ] - improved triple, moderate gain low-e, Kr

━ neutral energy impact of windows (energy consumption of building with no windows)

Figure 12 - Minneapolis, MN: Lines of equal annual source energy (combined heating and cooling, in MBtu and [GJ]) as a function of window U-factor and SHGC for a typical new house. Window orientation is selected for energy efficiency with 60% south facing; 20% north facing, and 10% each east and west facing.

Appendix 1: Modeling Assumptions

Fixed Parameters for a Typical House

Table 1: Summary

PARAMETER	Typical House
Floor Area	Fixed: 2000 ft^2 (184 m^2).
House Construction:	New Construction (Frame, 1-Story). Details dependant on location (see Table 2)
Foundation:	Foundation is based on location and is one of the following (see Table 2): ▪ Basement ▪ Slab-on-Grade ▪ Crawlspace
Fenestration Type	User Defined.
Fenestration Area & Distribution	Fixed: 15% of total floor area (300 ft^2, 28 m^2), equally distributed on all four cardinal orientations.
Solar Gain Reduction	Typical[(a)]**:** to represent a statistically average solar gain reduction for a typical house, this option includes all of the following: ▪ Interior shades (Seasonal SHGC multiplier, summer value = 0.80, winter value = 0.90); ▪ 1 ft (0.3 m) overhang; ▪ a 67% transmitting same-height obstruction 20 ft (6.1 m) away intended to represent adjacent buildings. ▪ To account for other sources of solar heat gain reduction (insect screens, trees, dirt, building & fenestration self-shading), the SHGC multiplier was further reduced by 0.1. This results in a final winter SHGC multiplier of 0.8 and a final summer SHGC multiplier of 0.7.
Insulation	Envelope insulation levels are based on location: (see Table 2)
Infiltration	ELA=0.77 ft^2 (0.07 m^2) (0.58 ACH)
Structural Mass	3.5 lb/ft^2 (17.1 kg/m^2) of floor area, in accordance with the Model Energy Code and NFRC Annual Energy Performance Subcommittee recommendation (September 1998). Includes gypsum wallboard.
Internal Mass Furniture	8.0 lb/ft^2 (39.1 kg/m^2) of floor area, in accordance with the Model Energy Code and NFRC Annual Energy Performance Subcommittee recommendation (September 1998).
HVAC System	Gas furnace & electric air conditioner
HVAC System Sizing	For each climate, system sizes are fixed for all fenestration options. Fixed sizes are based on the use of DOE-2 auto-sizing for the same house as defined in the analysis, with the most representative fenestration for that specific climate. An auto-sizing multiplier of 1.3 used to account for a typical safety factor. [(b)]
HVAC Efficiency	AFUE = 0.78, A/C SEER=10.0
Duct Losses	Heating: 10% Cooling: 10%
Part-Load Performance	Part-load curves for DOE2 (Henderson 1998)
Thermostat Settings	Heating: 70^{o}F (21.1^{o}C), Cooling: 78^{o}F (25.6^{o}C) Basement (partially conditioned): Heating 62^{o}F (16.7^{o}C), Cooling 85^{o}F (29.4^{o}C)

Night Heating Setback	65^{o}F (18.3^{o}C) (11 PM – 6 AM[(c)])
Internal Loads	Sensible: 43 kBtu/day (45.4 MJ/day) + floor area * 8.42 Btu/ft^{2}-day (8.9 kJ/day) for lighting Latent: 12.2 kBtu/day (12.9 MJ/day)
Natural Ventilation	Enthalpic – Sherman-Grimsrud: 78^{o}F (25.6 ^{o}C) or 72^{o}F (22.2^{o}C) based on 4 days' history[(d)]

Footnotes:

(a) These assumptions are intended to represent the average solar heat gain reduction for a large sample of houses. A one-foot (0.3 m) overhang is assumed on all four orientations in order to represent the average of a two-foot (0.6 m) overhang and no overhang. A 67% transmitting obstruction 20 ft (6.1 m) away on all four orientations represents the average of obstructions (such as neighboring buildings and trees) 20 ft (6.1 m) away on one-third of the total fenestration and no obstructions in front of the remaining two-thirds of fenestration products. An interior shade is assumed to have a Solar Heat Gain Coefficient multiplier of 0.9 during the winter and 0.8 during the summer. To account for solar heat gain reducing effects from other sources such as screens, trees, dirt, and self-shading of the building, the SHGC multiplier was further reduced by 0.1 throughout the year. This amounts to a 12.5% decrease in the summer and an 11.1% decrease in the winter. The final SHGC multipliers (0.8 in the winter and 0.7 in the summer) thus reflect the combined effects of shading devices and other sources.

(b) For each climate, DOE-2's auto-sizing feature was used with the fenestration product most likely to be installed in new construction (assumed to be the MEC default). Table 2 shows the required prescriptive U-factors for fenestration for the 5 climates. For climates where the U-factor requirement is between 0.65 Btu/h-ft^{2}-F (3.7 W/m^{2}-K) and 1.0 Btu/h-ft^{2}-F (5.7 W/m^{2}-K), an aluminum frame window with double glazing (U-factor = 0.87 Btu/h-ft^{2}-F (4.9 W/m^{2}-K); SHGC = 0.66) is used. For climates where the U-factor requirements are below 0.65 Btu/h-ft^{2}-F (3.7 W/m^{2}-K), a vinyl frame window with double glazing (U-factor = 0.49 Btu/h-ft^{2}-F (2.78 W/m^{2}-K); SHGC = 0.57) is used for the sizing calculation.

(c) RESFEN 3.1 models a moderate setback of 65^{o}F (18.3^{o}C) in recognition that some but not all houses may use night setbacks. Recent studies of residential indoor conditions have shown that, during the heating season, nighttime temperatures are significantly lower than daytime temperatures (Ref: "Occupancy Patterns and Energy Consumption in New California Houses," Berkeley Solar Group for the California Energy Commission, 1990).

(d) RESFEN 3.1 uses a feature in DOE-2 that allows the ventilation temperature to switch between a higher heating (or winter) and a lower cooling (or summer) temperature based on the cooling load over the previous four days.

Table 2. New Construction Insulation Values (Default foundation. in bold.) (CABO, 1993)

		Fresno CA (near Riverside CA)	Washington DC	Minneapolis MN	Charleston SC	Salt Lake City UT
MEC Zone		6	10	15	5	12
MEC Pkg #		4	3	3	3	3
Glz %		15	15	15	15	15
Fenestration U-factor	Btu/h-ft2-F	0.7	0.55	0.4	0.7	0.4
	W/m2-K	4.0	3.1	2.3	4.0	2.3
Ceiling R-value	(h-ft2-F)/Btu	38	38	38	30	38
	(m2-K)/W	6.7	6.7	6.7	5.3	6.7
Wall R-value	(h-ft2-F)/Btu	14	19	19	14	19
	(m2-K)/W	2.5	3.3	3.3	2.5	3.3
Floor R-value	(h-ft2-F)/Btu	19	19	30	11	19
	(m2-K)/W	3.3	3.3	5.3	1.9	3.3
Basement R-value	(h-ft2-F)/Btu	6	9	15	--	9
	(m2-K)/W	1.1	1.6	2.6	--	1.6
Slab R-value	(h-ft2-F)/Btu	6	--	--	0	--
	(m2-K)/W	1.1	--	--	0	--
Crawl space R-value	(h-ft2-F)/Btu	7	--	--	6	--
	(m2-K)/W	1.2	--	--	1.1	--