Detailed Modeling Study on How Different Assemblies Affect Comfort Conditions in Zero-Energy House Designs

John Broniek, PEng

ABSTRACT

As part of Building America (BA) research for developing and implementing zero-energy homes on a widespread basis, IBACOS has conducted very detailed modeling to determine the comfort implications of different high-performance exterior wall and window assemblies at this level of construction. IBACOS used TRNSYS software to build a representative two-story house design located in cold, mixed-humid, and hot-dry climate zones. Using the house design, information was obtained on temperature and humidity conditions, which was used to produce comfort indices for each room and determine space-conditioning energy usage. Altogether, 15 wall assemblies were modeled, including double-wall, 2 in. × 8 in. wood-framed, and structural insulated panels (SIPs). The modeled windows feature many of the highest-performance varieties available in the domestic marketplace.

Research results indicate that the comfort benefits for upgrading from standard to higher-performance wall construction are greater in a cold climate zone. In each of the climate zones studied, three wall types equally exhibited the best comfort situations. These walls have a minimum of 2 in. (51 mm) of exterior insulating sheathing, a minimum of 2 in. × 6 in. (38 mm × 140 mm) wood framing, and a nominal thermal performance of at least 41 h·ft^2·°F/Btu (7.2 m^2·K/W).

Windows with triple glazing, a U-factor of 0.19 Btu/h·°F·ft^2 (1.1 W/m^2·K) or less, and a solar heat gain coefficient of 0.22 or less provided the best comfort situations in all three climate zones. However, even with these windows, discomfort from overheating occurred in south-facing bedrooms in the hot-dry climate zone, reinforcing the value of exterior and permanent shading devices. Using high solar heat gain windows in the cold climate zone resulted in overheating and discomfort during the shoulder seasons.

INTRODUCTION

As part of Building America (BA) research for developing and implementing zero-energy houses on a widespread basis, Integrated Building and Construction Solutions (IBACOS) is building a very energy-efficient house in the Pittsburgh, PA, region. The house is being designed to a level of energy efficiency that will result in 70% whole-house energy savings according to the BA Research Benchmark Definition (Hendron 2008), and with the addition of a photovoltaic system it may achieve net zero energy usage. As part of this work, the systems and approaches needed to build a super-energy-efficient house in a mass production environment were researched. In particular, research focused on above-grade wall and window systems, examining available systems and taking a comprehensive look at a variety of related performance issues. Part of this work included conducting very detailed modeling to determine the comfort implications of different high-performance exterior wall and window assemblies at this level of construction.

MODELING APPROACH

To facilitate very detailed modeling of the super energy efficient house design, TRNSYS (version 16.01), a transient systems simulation program, was chosen (Klein et al. 2007). TRNSYS modeling yields more detailed information than other residential software tools on the thermal performance,

***John Broniek** is a senior building performance specialist with IBACOS Inc., Pittsburgh, PA.*

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energy performance, and indoor environmental characteristics of a house design. The detailed modeling allows for precise temperature and relative humidity (RH) values to be determined for house designs with different wall and window assemblies, helping to quantify the effect of varying loads.

Compared to other programs, TRNSYS modeling more accurately reflects the framing configurations of different wall systems, allowing for a more precise determination of loads, temperature, and humidity conditions. This is because each wall is divided into common material sections (framing and insulation), resulting in situations where wood studs that do not travel the entire width of the wall, such as in a staggered stud approach, to be modeled accurately. Therefore, the modeling precisely accounts for the potential effects of thermal bridging. Each wall system section is made up of layers that consist of material components, with information on their density, thermal capacitance, and conductivity input to construct a very detailed profile.

For modeling windows, TRNSYS requires performance maps derived from the WINDOW 5.2 computer program from Lawrence Berkley Laboratory (LBL 2003). These performance maps provide very detailed information on the center glazing performance characteristics of a window, allowing the user to more precisely calculate indoor comfort and determine temperature and humidity conditions experienced by a window modeled in TRNSYS. Each window model in TRNSYS also contains detailed thermal performance information on its glazing spacer and framing with the percentage of framing determined for each window size.

House Design Used in Study

All of the TRNSYS modeling work was based on the same two-story house design that will be used for the super energy efficient house. The house design has 1975 ft^2 (183 m^2) of floor area with two floors, four bedrooms, and a fully conditioned basement. The front of the house faces south and has 198.5 ft^2 (18.441 m^2) of window areas facing north, 75.83 ft^2 (7.045 m^2) facing south, and 31.67 ft^2 (2.942 m^2) facing west.

The super-energy-efficient house design features a thermal enclosure that promotes the energy efficiency level IBACOS is striving to achieve, including a subslab insulation system with a nominal R-value of 10 h·ft^2·°F/Btu (1.8 m^2·K/W), a foundation wall system with a nominal R-value of 32 h·ft^2·°F/ Btu (5.6 m^2·K/W), an attic with a nominal R-value of 60 h·ft^2·°F/Btu (10.6 m^2·K/W), and a building enclosure airtightness level of 0.6 air changes at 50 Pa (depressurization with a blower door). The roof overhang was modeled as 12 in. (305 mm). In modeling the wall systems, the windows were assumed to have a U-factor of 0.25 Btu/h·°F·ft^2 (1.4 W/m^2·K) and a solar heat gain coefficient (SHGC) of 0.27. In modeling the windows, IBACOS used a staggered stud 2 in. × 8 in. (38 mm × 89 mm) wall with 2 in. (51 mm) of extruded polystyrene insulating sheathing that has a nominal thermal performance of 41 h·ft^2·°F/Btu (7.2 m^2·K/W).

In the design, a ground-source heat pump with a desuperheater provides space conditioning and handles a portion of the hot-water load, while a heat recovery ventilator provides mechanical ventilation on a continuous basis. The air distribution system is entirely within the conditioned space, completely airtight, and able to maintain cooling-season temperatures at 76°F (24.4°C) and heating-season temperatures at 71°F (21.7°C). All lighting and appliances are energy-efficient, meeting ENERGY STAR® criteria or better.

Each TRNSYS house model contains nine zones (representative of key rooms), four on the first floor and five on the second floor, along with garage, attic, and basement zone. All TRNSYS simulations are based on 6 minute time steps to best reflect operating conditions and to understand the room-by-room distribution of loads, temperatures, and relative humidity conditions.

For TRNSYS modeling, certain assumptions were followed. The airflow between connected zones was facilitated by assuming that connecting doors were open. Room-by-room schedules for miscellaneous loads, major appliances, lighting, and occupancy were based on BA research (NREL 2009). Lights and appliances were distributed in zones based on their typical use (e.g., dishwasher in the kitchen zone). One air-balancing strategy was used for each modeling location, and each was based on *ACCA Manual J* peak load calculations (ACCA 2001). Windows were shaded by interior blinds according to a schedule in the BA research benchmark definition. Thermostats were located in the zones representing the first-floor family room and the second-floor master bedroom, both of which had north-facing windows.

Scope of Research

IBACOS chose to research geographic locations representative of the cold, mixed-humid, and hot-dry climate zones. These locations were Pittsburgh, PA, Atlanta, GA, and Phoenix, AZ.

IBACOS chose 15 wall systems to study, including unfamiliar or seldom-used wood framed wall systems like the staggered stud 2 × 8, the double wall (with two rows of 2 × 4 studs), any wall with more than 1 in. (25 mm) of exterior insulating sheathing, structural insulated panels (SIPs) system construction, and a base wall system (representing the walls used in one of our local BA program prototype houses). Table 1 summarizes the characteristics of the wall systems we evaluated.

A total of six window systems were studied, a number limited by the availability of suitable performance maps for use in TRNSYS. Double- and triple-glazed high-performance units and a base window (representing the windows used in one of our local BA program prototype houses) were selected. Table 2 summarizes the characteristics of the window systems we evaluated. The total unit U and SHGC values are based on National Fenestration Rating Council (NFRC) labeling values.

Table 1. Summary of Wall Systems in Study

Wall System	Name of Wall System	Nominal Thermal Performance	Description
	Base wall	20 h·ft^2·°F/Btu (3.5 m^2·K/W)	2 in. × 6 in. (38 mm × 140 mm) single stud wood framed wall, 19% FF,[1] 5 1/2 in. (140 mm) thick fiberglass batts within cavities, OSB sheathing
1	Staggered-stud 2 × 8 wall with R-5 (RSI 0.9) insulating sheathing	36 h·ft^2·°F/Btu (6.3 m^2·K/W)	Staggered-stud 2 in. × 8 in. (38 mm × 190 mm) wall (using staggered 2 × 4s)[2], 7 1/4 in. (190 mm) thick blown-in fiberglass within cavities, 1 in. (25 mm) thick unfaced XPS insulating sheathing
2	Staggered-stud 2 × 8 wall with R-10 (RSI 1.8) insulating sheathing	41 h·ft^2·°F/Btu (7.2 m^2·K/W)	Staggered-stud 2 in. × 8 in. (38 mm × 190 mm) wall (using staggered 2 × 4s), 7 1/4 in. (190 mm) blown in fiberglass within cavities, 2 in. (51 mm) unfaced XPS insulating sheathing, vertical strapping[3]
3	Staggered-stud 2 × 8 wall with layer of closed-cell spray polyurethane foam and R-5 (RSI 0.9) insulating sheathing	39 h·ft^2·°F/Btu (6.9 m^2·K/W)	Staggered-stud 2 in. × 8 in. (38 mm × 190 mm) wall (using staggered 2 × 4s), 6¼” (165 mm) blown-in fiberglass and 1 in. (25 mm) closed-cell spray polyurethane within cavities, 1 in. (25 mm) unfaced XPS insulating sheathing, vertical strapping
4	Double wall with R-5 (RSI 0.9) insulating sheathing	34 h·ft^2·°F/Btu (6.0 m^2·K/W)	Double wall using two rows of staggered 2 × 4s[2] (38 mm × 140 mm) studs, 7 in. (178 mm) thick blown-in fiberglass within cavities, 1 in. (25 mm) unfaced XPS insulating sheathing, separately framed walls with 2 in. × 4 in. (38 mm × 140 mm) top and bottom plates
5	Double wall with 1 in. spacing and R-5 (RSI 0.9) insulating sheathing	38 h·ft^2·°F/Btu (6.7 m^2·K/W)	Double wall using two rows of staggered 2 × 4s (38 mm × 140 mm) studs with 1 in. (25 mm) space between rows, 8 in. (203 mm) thick blown-in fiberglass within cavities, 1 in. (25 mm) unfaced XPS insulating sheathing, separately framed walls with 2 in. × 4 in. (38 mm × 140 mm) top and bottom plates
6	2 × 6 wall with closed-cell spray polyurethane foam and R-5 (RSI 0.9) insulating sheathing	38 h·ft^2·°F/Btu (6.7 m^2·K/W)	2 in. × 6 in. (38 mm × 140 mm) single stud wood framed wall,[2] 16% FF, 5 in. (127mm) thick[4] closed-cell spray polyurethane within cavities, 1 in. (25 mm) unfaced XPS insulating sheathing
7	2 × 6 wall with closed-cell spray polyurethane foam and R-10 (RSI 1.8) insulating sheathing	43 h·ft^2·°F/Btu (7.6 m^2·K/W)	2 in. × 6 in. (38 mm × 140 mm) single-stud wood-framed wall, 16% FF, 5 in. (127 mm) thick closed-cell spray polyurethane within cavities, 2 in. (51 mm) unfaced XPS insulating sheathing, vertical strapping
8	2 × 6 wall with layer of closed-cell spray polyurethane foam and R-10 (RSI 1.8) insulating sheathing	36 h·ft^2·°F/Btu (6.3 m^2·K/W)	2 in. × 6 in. (38 mm × 140 mm) single-stud wood-framed wall, 16% FF, 4 1/2 in. (114 mm) thick blown-in fiberglass and 1 in. (25 mm) closed-cell spray polyurethane within cavities, 2 in. (51 mm) unfaced XPS insulating sheathing, vertical strapping
10	2 × 6 wall with R-5 (RSI 0.9) insulating sheathing	28 h·ft^2·°F/Btu (4.9 m^2·K/W)	2 in. ×6 in. (38 mm × 140 mm) single-stud wood-framed wall, 16% FF, 5 1/2 in. (140 mm) thick blown-in fiberglass within cavities, 1 in. (25 mm) unfaced XPS insulating sheathing
11	2 × 6 wall with R-10 (RSI 1.8) insulating sheathing	33 h·ft^2·°F/Btu (5.8 m^2·K/W)	2 in. × 6 in. (38 mm × 140 mm) single-stud wood-framed wall, 16% FF, 5 1/2 in. (140 mm) thick blown-in fiberglass within cavities, 2 in. (51 mm) unfaced XPS insulating sheathing, vertical strapping
12	2 × 6 wall with R-15 (RSI 2.6) insulating sheathing	38 h·ft^2·°F/Btu (6.7 m^2·K/W)	2 in. × 6 in. (38 mm × 140 mm) single-stud wood-framed wall, 16% FF, 5 1/2 in. (140 mm) thick blown-in fiberglass within cavities, RSI 2.6 (R-15) unfaced XPS insulating sheathing, vertical strapping
13	2 × 6 wall with R-20 (RSI 3.5) insulating sheathing	43 h·ft^2·°F/Btu (7.6 m^2·K/W)	2 in. × 6 in. (38 mm × 140 mm) single-stud wood-framed wall, 16% FF, 5 1/2 in. (140 mm) thick blown-in fiberglass within cavities, RSI 3.5 (R-20) unfaced XPS insulating sheathing, vertical strapping
14	SIPS 8 1/4 in. (210 mm) thick	32 h·ft^2·°F/Btu (5.6 m^2·K/W)	SIPS 8 1/4 in. (210 mm) thick, two 7/16 in. (11 mm) OSB skins with 7 3/8 in. (187 mm) EPS core
15	SIPS 10 1/4 in. (260 mm) thick	43 h·ft^2·°F/Btu (7.6 m^2·K/W)	SIPS 10 1/4 in. (260 mm) thick, two 7/16 in. (11 mm) OSB skins with 9 5/8 in. (244 mm) EPS core

[1] FF = Framing fraction of wall system
[2] All framing at 24 in. (600 mm) on center (o.c.)
[3] All exterior vertical strapping at 24 in. (600 mm) o.c.
[4] Per typical industry practice, spray polyurethane foam insulation does not fill entire wall cavity

Table 2. Summary of Window Systems in Study

Window System	Description	Total Unit U-Factor	Total Unit SHGC
Base window	Double-glazed, argon gas and air fill, one low-emissivity coating, vinyl frame	0.30 Btu/h·°F·ft^2 (1.7 W/m^2·K)	0.34
Window A	Double-glazed with suspended film, argon and krypton gas fill, low-emissivity coatings, vinyl frame	0.22 Btu/h·°F·ft^2 (1.2 W/m^2·K)	0.33
Window B	Triple-glazed with suspended film, krypton and air gas fill, low-emissivity coatings, fiberglass frame	0.19 Btu/h·°F·ft^2 (1.1 W/m^2·K)	0.22
Window C	Triple-glazed, krypton gas fill, two low-emissivity coatings, fiberglass-reinforced vinyl frame	0.17 Btu/h·°F·ft^2 (1.0 W/m^2·K)	0.16
Window D	Triple-glazed, krypton-enhanced argon gas fill, vinyl frame	0.21 Btu/h·°F·ft^2 (1.2 W/m^2·K)	0.47
Window E	Double-glazed, krypton gas fill, two low-emissivity coatings, vinyl frame	0.25 Btu/h·°F·ft^2 (1.4 W/m^2·K)	0.27

MODELING RESULTS

Quantifying Comfort in TRNSYS Modeling

To facilitate comparisons of indoor comfort conditions between house designs, the thermal comfort performance index (TCPI) parameter developed by IBACOS was used (Rittelmann 2008). The TCPI compares the predicted mean vote (PMV) against predetermined neutral comfort criteria according to *ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy*, at each simulation time step. The TCPI value is calculated by dividing the number of values that meet the criteria by the total number of values calculated, with a value of 100 representing perfectly acceptable comfort. The neutral comfort condition (PMV equals zero) for each season is "tuned" to zero by adjusting the clothing level and work level of the virtual occupant and then holding those values constant for the season while the temperature and humidity levels vary in response to the simulation. The relative humidity value at the neutral condition is assumed to be 50% RH in the summer and 35% RH during the heating season. Temperature assumptions for the neutral value are equal to the system temperature set points. Unless noted otherwise, all modeling outputs are monthly average values, a level of detail considered appropriate for this study because significant findings became visible at that point.

Modeling of Wall Systems

Figure 1 displays the whole-house TCPI results derived from the TRNSYS modeling for each studied wall system in each house design location. A TCPI value between 98 and 100 is considered to be the best situation. In each model, the air-balancing strategy for the location was held constant so this factor would not influence the TCPI value.

All of the high-performance wall systems in the Pittsburgh and Atlanta house design locations scored the best with annual average TCPI values of 98.7 and 98.8, respectively. TCPI values were lower in Phoenix, with an average value of 96.5 calculated for all wall systems that were modeled. The wall systems that exhibited the best TCPI performance varied between locations. In none of the house design locations did the best-performing wall system exceed its closest competing system by more than 0.1 TCPI points. In Pittsburgh, the highest-performing wall system was wall #13, the 2 × 6 wall with R-20 (RSI 3.5) insulating sheathing, with an annual average TCPI value of 99.1. Seven different wall systems, with an annual average TCPI value of 98.9, performed the best in Atlanta. In Phoenix, eight different wall systems with an annual average TCPI value of 96.6 performed the best. Wall #13 was a comfort performance leader in each location.

The comfort benefit associated with using a high-performance wall system design over the base wall system, which has R-20 (RSI 3.5) nominal thermal performance, varied between the three house design locations. The annual average TCPI value for each base wall was less than the highest scoring wall system's TCPI value by

- 4.2 points in Pittsburgh
- 0.7 points in Atlanta
- 2.5 points in Phoenix

In Pittsburgh, the highest-performing wall, wall #13 (the 2 × 6 wall with R-20 [RSI 3.5] insulating sheathing), experienced its lowest average TCPI values during January and February in the master bedroom, which has three north-facing windows and three exterior walls. Monthly average mean radiant temperature (MRT) values were highest in July in the west- and north-facing kitchen at 76.8°F (24.9°C), and they were lowest in the master bedroom at 69.8°F (21.0°C) in January. In comparison, the base wall's MRT peak values during the heating season were colder on average by 1.4°F (0.8°C). For the

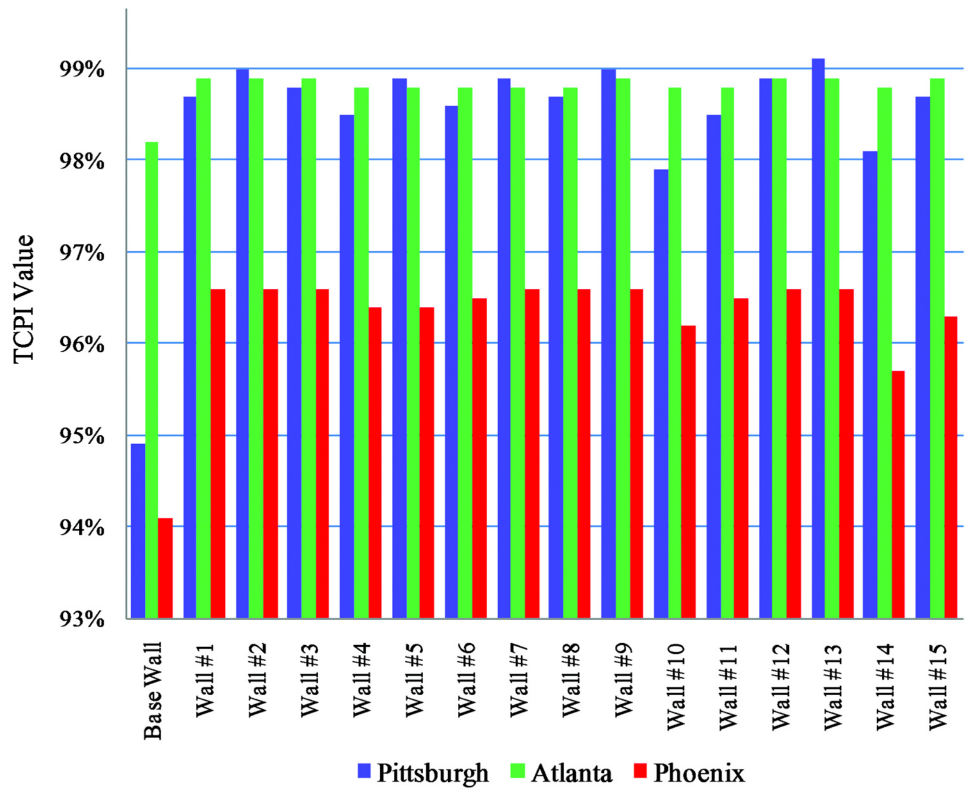

Figure 1 *Whole-house annual average TCPI values for the high-performance wall system house designs conducted in all study locations.*

highest-performing wall, the relative humidity levels were highest in the dining room (south-facing) in April, peaking at 50.5%, and lowest in February, with a value of 23.7. Overall for this location, the walls that exhibited the highest TCPI values also exhibited the least amount of annual heating and cooling energy use, with wall #13 leading both categories.

In Atlanta, annual average TCPI values for all high-performance wall systems varied little between each other. The high-performance walls with the lowest energy use in Atlanta were the same walls with the lowest energy use in Pittsburgh. Wall #15 had the highest TCPI value, along with six other wall systems, even though it exhibited high energy usage relative to other wall systems, as shown in Figure 2. The wall with the lowest heating and cooling energy usage, wall #13 (the 2 × 6 wall with R-20 [RSI 3.5] insulating sheathing), displayed 124 kWh/yr less annual energy usage, or 7% less than the 10 1/4 in. (260 mm) thick SIPS wall. In wall #13, 78% of space conditioning energy use was due to cooling. With respect to the base wall, wall #15 displayed slightly lower peak MRT for all zones.

In Phoenix, TCPI values for all walls were lower than their counterparts in the other locations, averaging 2.3 TCPI points less. Each of the eight highest-performing walls experienced very low minimum TCPI values in the 70.4 range during November in the bedroom with three south-facing windows. The magnitude of this low TCPI score for the leading walls indicates a significant discomfort situation, particularly compared to its Pittsburgh counterpart, which has a TCPI value of 88.1 as its lowest score. In comparison, the base wall's lowest TCPI value was 44.3, indicating that the leading walls have vastly improved comfort conditions in spite of their shortcomings. Each of the highest-performing walls also exhibited the least amount of annual heating and cooling energy use, and in each, 99% of space conditioning energy use was due to cooling.

Across all of the house design locations, three walls exhibited the best comfort conditions, with an average annual TCPI value of 98.2:

- Wall #2, the staggered stud 2 × 8 wall with R-10 (RSI 1.8) insulating sheathing
- Wall #9, the 2 × 6 wall with layer of closed-cell spray polyurethane foam and R-15 (RSI 2.6) insulating sheathing
- Wall #13, the 2 × 6 wall with R-20 (RSI 3.5) insulating sheathing

Modeling of Windows

Figure 3 displays the whole-house annual average TCPI results derived from the TRNSYS modeling for each studied window system in each modeling location.

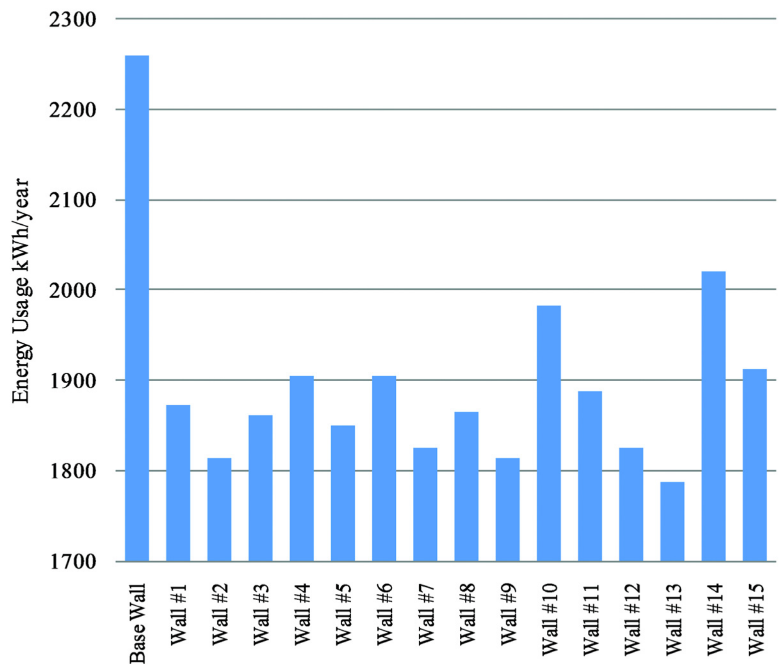

Figure 2 *Annual heating and cooling energy use estimates for each studied wall system in Atlanta.*

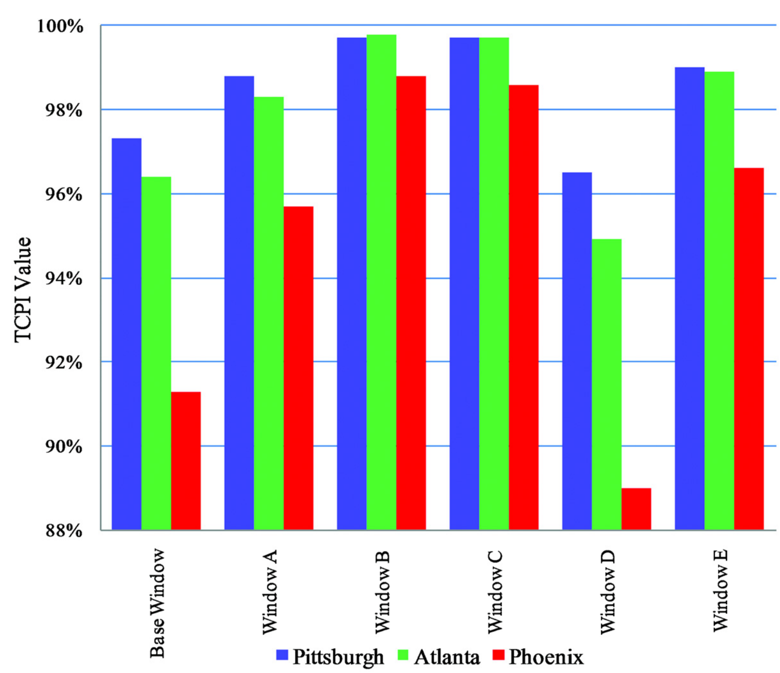

Figure 3 *Whole-house annual average TCPI values for the high-performance window system house designs conducted in all study locations.*

Table 3. Key Annual Average Temperature Values for Window B House Design in Each Location

Temperature	Pittsburgh	Atlanta	Phoenix
Zone	73.4°F (23.0°C)	74.5°F (23.6°C)	75.4°F (24.1°C)
Window frame interior	70.3°F (21.3°C)	73.2°F (22.9°C)	76.3°F (24.6°C)
Window glazing interior	72.5°F (22.5°C)	74.5°F (23.6°C)	76.5°F (24.7°C)

The window B house design achieved the highest annual average TCPI value for all locations, edging out the window C house design with a TCPI value 0.1 point higher. Window B is a unit with triple glazing, krypton and air gas fill, a low-conductivity fiberglass frame, a U-factor of 0.19 Btu/h·°F·ft^2 (3.5 kJ/h·m^2·K), and a SHGC of 0.22. As noted in Table 2, window C's NFRC ratings for thermal performance and solar heat gain control are also very good, with values lower than window B. Both of these windows had almost perfect comfort (TCPI value of 100) for the Pittsburgh and Atlanta house design locations and a high level of comfort for Phoenix. In the warmer climate locations, both windows did well to keep the bedroom with south-facing windows comfortable and at set-point temperature over the summer months. Window C's lower TCPI score than window B was reflected by higher average zone temperatures exhibited in second floor bedrooms from October to December, when space conditioning was used less frequently. The window C house design also exhibited more annual cooling energy usage and higher annual average interior glazing temperatures in the warmer climate locations. This result is in spite of the fact that window C has a greater framing fraction than window B, 27% versus 22% for a window 15.8 ft^2 (1.47 m^2) in size, and therefore less glazing per window opening. Of note, pricing information per window area indicates that window C can be purchased for \$20/ft^2 (\$215/m^2) less than window B, suggesting that it is the more cost-effective solution of the two, since their TCPI values are almost equal.

The next highest-rated window for comfort was window E, which has double glazing, krypton gas fill, vinyl framing, a U-factor of 0.25 Btu/h·°F·ft^2 (5.1 kJ/h·m^2·K), and a SHGC of 0.27. The window E house design appears most suitable for the Pittsburgh and Atlanta locations, where it had an average TCPI value of almost 99. With a SHGC of 0.27, this window does not offer as much solar heat gain control as the two leading windows (B and C), characterized by its lower TCPI value in Phoenix.

Window D is marketed as a cold-climate window, since it has a low U-factor in comparison to many competitors, but its high SHGC (0.47) characteristics adversely affect its TCPI value in all locations. Overheating in Pittsburgh and Atlanta during October led to discomfort situations and a lower TCPI score. The window D house design was outperformed by the base window house design by an annual average of 1.5 TCPI points in all locations.

The high-performance windows had the toughest time maintaining comfort during the heating season in Pittsburgh (except for window D, which had its lowest TCPI value in October), during October and November in Atlanta, and during December in Phoenix. Even high-performance windows with excellent solar heat gain characteristics were not able to prevent discomfort from occurring in Phoenix house designs in the south-facing bedroom, suggesting that measures like permanent shading devices (which do not require homeowner intervention) should be included in designs for this location.

Table 3 displays the effect that house design location has on key temperature parameters for window B. It shows the annual average temperature for all house zones, the interior of the window frame, and the interior of the window glazing. Annual average temperatures increase for each parameter as the design location moves south. The incremental change in each parameter was about the same in each instance, with zone temperatures rising about 1.0°F (0.6°C), framing temperatures rising about 3.0°F (1.7°C), and glazing temperatures rising about 2.0°F (1.1°C).

Figure 4 provides insight into the different temperatures experienced by the window house design with the greatest comfort (window B) and the base window house design for the same three key temperature parameters at each house design location. The average seasonal temperatures represent temperatures from January to March in Pittsburgh, October to December in Atlanta, and July to September in Phoenix. In Pittsburgh, the only significant temperature difference between the windows occurs at the interior of the window glazing, where the base window is colder by 2.9°F (1.6°C), reaching 66.4°F (19.1°C), which signifies that there is less thermal comfort at the glazing surface of that window during the heating season. In Atlanta, temperatures are higher than in Pittsburgh for all parameters for both windows during the autumn; only the glazing temperature in window B is significantly higher than the base window value. Window B should offer more thermal comfort for occupants standing beside this window during the autumn. In Phoenix, all temperature parameters are higher than those exhibited in other house design locations, with the base window experiencing higher temperature values than window B during the summer, with glazing temperatures peaking at 80.6°F (27.0°C). Window B does a better job at minimizing solar gains and would keep occupants more comfortable.

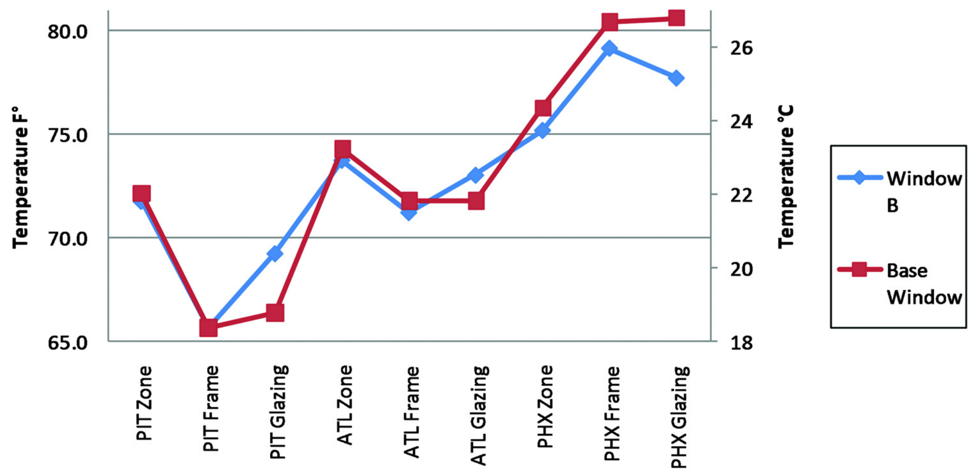

Figure 4 *Key seasonal average temperature values for window B and base window house designs for all zones at the window frame interior and window glazing interior.*

OBSERVATIONS

Wall Systems

There was a greater comfort benefit to building higher-performance walls over standard construction in Pittsburgh versus the other modeling locations. The comfort benefit over the base R-20 (RSI 3.5) wall system was most evident in Pittsburgh because the leading high-performance wall system had a significantly greater TCPI score (4.2 points), and on average, it was able to keep the coldest room in the design closer to the set-point temperature during the heating season. With the Pittsburgh house design, comfort conditions were higher for those walls with higher nominal thermal performance characteristics; the three best-performing walls had a minimal nominal thermal performance of 41 h·ft^2·°F/Btu (7.2 m^2·K/W). For the Pittsburgh modeling, there was strong correlation between high TCPI values and low annual heating and cooling energy usage.

In Atlanta, TCPI values for all high-performance wall system designs varied no more than 0.1 point from each other. This degree of uniformity in comfort characteristics, while considering reasonable modeling tolerances, indicates that each of the 15 wall systems studied could perform well in the mixed-humid climate zone from a comfort perspective. A comparison between TCPI value and annual heating and cooling energy usage for each wall system showed that the wall systems with the highest nominal thermal performance used less space-conditioning energy than others. This result indicates that there are several high-performance wall choices that offer suitable comfort in Atlanta; after space-conditioning energy use is considered, these choices can be reduced to a smaller group of leading wall systems. In addition, there were only small comfort benefits for building higher-performance walls over the base R-20 (RSI 3.5) wall system. In this case, energy savings provide the motivation for using high-performance wall systems, since their use can result in up to 21% savings in annual heating and cooling energy usage.

In Phoenix, TCPI values for all wall systems were lower than their counterparts in the other locations, indicating poorer overall comfort. This is due to low TCPI values occurring during November in south-facing second-floor rooms as a result of elevated temperatures. TCPI values are higher for walls with higher nominal thermal performance characteristics, and a good correlation exists between high TCPI values and low space-conditioning energy usage for the leading wall systems. The high-performance walls offer very significant comfort improvements over the base wall, particularly for the worst-case comfort situation.

Across all of the climatic locations, three walls exhibited the best comfort conditions. Each had a minimum of 2 in. of exterior insulating sheathing and a nominal thermal performance of at least 41 h·ft^2·°F/Btu (7.2 m^2·K/W).

Window Systems

The house design with window B achieved the highest annual average TCPI value for all locations, edging out the window C design, in spite of the fact that its NFRC ratings for thermal performance and solar heat gain control were higher. The difference in TCPI values stems from the window C house design retaining more heat in Atlanta and Phoenix from October to December, thereby experiencing slightly more discomfort than the window B design. But overall, there is very little difference between the comfort conditions associated with these two windows, and either one would be a suitable choice for the climate zones studied.

All of the window house designs had lower comfort values in Phoenix. When a window with a lower SHGC than the default window was used, the TCPI value rose 2.0 points, indicating the importance of window selection in this location. However, even the window designs with excellent SHGC characteristics were not able to prevent discomfort from occurring in south-facing bedrooms in Phoenix, suggesting the value of shading devices, preferably exterior and permanent, to control solar gains.

The window with the lowest U-factor did not necessarily offer the best comfort conditions in Pittsburgh. This outcome is evident with the window D house design, which has a low U-factor and high-solar-heat-gain fenestration characteristics, often deemed favorable in cold climates. This window exhibited overheating situations and a decrease in comfort during the shoulder seasons. Because the base window house design had a higher TCPI value than the window D house design in Pittsburgh, the solar heat gain control should not be overlooked in cold climate locations.

CONCLUSIONS

Using TRNSYS, IBACOS determined the TCPI, a parameter that quantifies interior comfort, for a super-energy-efficient house design with different high-performance wall and window systems in three different climate zones.

TRNSYS modeling showed that more comfort benefits come from upgrading to higher-performance wall construction from standard construction in a cold-climate zone than in mixed-humid and hot-dry locations. Across all of the climate zones, three wall types equally exhibited the best comfort conditions in their house designs. Each wall system had a minimum of 2 in. (51 mm) of exterior insulating sheathing, a minimum of 2 in. × 6 in. (38 mm × 140 mm) wood framing, and a nominal thermal performance of at least 41 $h \cdot ft^2 \cdot °F/Btu$ (7.2 $m^2 \cdot K/W$).

In the Pittsburgh models, good correlation between comfort index values and annual heating and cooling energy use was observed for the three leading wall systems. In Atlanta, all the wall systems studied could be considered suitable for super-energy-efficient house designs from a comfort perspective. However, the heating and cooling energy usage varied as much as 7% between wall systems, although the walls with the highest nominal thermal performance used the least amount of space-conditioning energy. In Phoenix, more than half of the wall systems studied exhibited the same top level of comfort, but TCPI values here were lower than their counterparts in the other locations, indicating poorer overall comfort. This is due to low comfort index values occurring during November that resulted from elevated temperatures in south-facing second-floor rooms.

Overall, the window that provided the best comfort across all study locations was the unit with triple glazing, krypton and air gas fill, a low-conductivity fiberglass frame, a U-factor of 0.19 $Btu/h \cdot °F \cdot ft^2$ (3.5 $kJ/h \cdot m^2 \cdot K$), and a SHGC of 0.22. A window with a slightly lower total window U-factor and SHGC can be considered to offer equivalent good comfort in all of the study locations. All of the window house designs had lower comfort values in Phoenix. Even the window designs with excellent SHGC values were not able to prevent discomfort from occurring in south-facing bedrooms in Phoenix, suggesting the value of using shading devices, preferably exterior and permanent, to control solar heat gain.

A window with a low U-factor is important in a cold climate, but if it has a high SHGC (e.g., 0.47), TRNSYS modeling shows that overheating and decreased comfort occurred during the shoulder seasons, thereby lowering overall comfort for the house design. Therefore, solar heat gain control in windows should not be disregarded in a cold climate location.

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REFERENCES

ACCA. 2001. *Manual J: Residential load calculation*, 8th ed. Arlington, VA: Air Conditioning Contractors of America.

ASHRAE. 2005. *ASHRAE Standard 55-2005, Thermal Environmental Conditions for Human Occupancy.* Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

Hendron, R. 2008. *Building America Research Benchmark Definition, updated December 19, 2008*. Golden, CO: National Renewable Energy Laboratory.

IECC. 2009. *2009 international energy conservation code*. Country Club Hills, IL: International Code Council.

Klein, S.A., W.A. Beckman, and J.W. Mitchell. 2007. *TRNSYS: A transient system simulation program user manual—Version 16.1*. Madison, WI: The Solar Energy Laboratory, University of Wisconsin.

LBL. 2003. *WINDOW 5.2: A PC program for analyzing window thermal performance for fenestration products.* Berkeley, CA: Windows and Daylighting Group, Lawrence Berkeley Laboratory.

NREL. 2009. *Building America*. US Department of Energy, Energy Efficiency and Renewable Energy Building Technologies Program. http://www1.eere.energy.gov/buildings/building_america/perf_analysis.html.

Rittelmann, W. 2008. Thermal comfort performance: Field investigation of a residential forced-air heating and cooling system with high sidewall supply air outlets. *BEST1 Conference: Building for Energy Efficiency and Durability at the Crossroads*, Minneapolis, Mn.