Modeling the Impacts of Performance Components in Super Energy Efficient House Designs in Different Climate Zones

John Broniek, IBACOS Inc.

ABSTRACT

As part of Building America work, research has been conducted on how the European Passive House residential energy efficiency standard could translate to six locations in three U.S. climate zones. For each super energy efficient house design a TRNSYS model was developed providing detailed system performance information. During this work, the impact of several key performance components became better understood: natural air ventilation and mechanical ventilation; soil thermal conductivity; interior and exterior shading of windows; and central and zonal controlled conditioning systems. Understanding the impacts of these components will help increase modeling accuracy and design expertise.

Modeling in a Cold climate house design showed that more comfortable conditions occur when natural air ventilation used for cooling enters at a higher air flow and the HRV is not operating. Determining the precise soil thermal characteristics in house designs with superbly insulated basements is not as important as it is for less well insulated basements. Temporary window shading devices have considerable influence on cooling loads, and, therefore, their shading characteristics should be determined as accurately as possible. Having shading characteristics information on domestic window shading devices would aid the accuracy of modeling work in this area. Central air distribution systems did a better job of maintaining zones at the required setpoint temperatures if based on median load calculation methodology instead of the industry standard methodology. An individually zone-controlled system provided greater temperature control in a Cold climate design than a central forced air system.

Introduction

Throughout central Europe the Passive House residential energy efficiency standard has produced thousands of super energy-efficient homes with a peak heating load of less than $10W/m^2$ and a maximum annual heating consumption of 15 kWh per m^2 of floor area (Passivhaus Institute 2007). The houses are known for using solar gains to provide passive heating, not using a dedicated heating system, and having a mechanical ventilation system. Recently the standard has added a (sensible) cooling consumption target of 15 kWh per m^2 of floor area in order to make it more applicable to southern European climate zones. Also, the standard limits primary (source) energy consumption to 120 kWh per m^2 of floor area. In addition, if the frequency of indoor temperatures that exceed 25°C (77°F) during the year is greater than 10 percent (designated as the frequency of overheating), then mechanical cooling must be used.

As part of Building America research for developing and implementing zero energy homes on a widespread basis, research was initiated on how this standard could translate to U.S. climate zones, especially with respect to constructability and comfort. House designs that conform to the standard were developed in accordance with Passivhaus Institute procedures with practical Building America experience used to create constructible designs. The next step was to determine whole house source energy savings for each house design for Building America program reference. Lastly, for each compliant house design, a detailed simulation model, TRNSYS, was used to assess performance characteristics in detail.

Passive House Modeling

The 2007 version of the Passive House Performance Package (PHPP) software (Passivhaus Institute 2007) was used to create house designs that meet the Passive House standard. House designs were located in three U.S. climate zones: Cold, Mixed Humid and Hot Humid. The house model locations chosen for each of the climate zones are shown in Table 1.

Table 1. Information on House Model Locations

Location	Building America Climate Zone	2006 IECC Climate Zone Number (IECC)	Heating Degree Days (HDD) 18°C Base (NCDC)	Cooling Degree Days (CDD) 18°C Base (NCDC)
Minneapolis, Minnesota	Cold	Zone 6	4376	388
Fort Wayne, Indiana	Cold	Zone 5	3447	461
St. Louis, Missouri	Mixed Humid	Zone 4	2643	867
Atlanta, Georgia	Mixed Humid	Zone 3	1571	574
Dallas, Texas	Hot Humid	Zone 3	1317	1427
Miami, Florida	Hot Humid	Zone 1	83	4361

Each PHPP model built was based on the research house constructed in Fort Wayne, Indiana, for which IBACOS has developed a detailed TRNSYS model and validated against on-site measurements (IBACOS 2007). The building is considered a typical production house with 203m² (2182 ft²) of floor area covering two floors, and it rests on a slab-on-grade or basement foundation. Its front faces east with 53% of the glazing area facing west, 42% facing east, and 5% facing north.

Each house design was developed assuming that the following conditions existed for its key systems:

- Foundations are slab-on-grade except for the Minneapolis location, where basement foundations are prevalent.
- Natural air ventilation through open (casement) windows provided nighttime cooling during favorable conditions.
- Temporary interior shading of windows occurred during daylight hours when a cooling system would likely be running. Shading modeling follows Passive House modeling recommendations and reflects the use of an indoor blind that reduces the solar heat gain through windows by 63 percent.
- The mechanical ventilation system consisted of a heat or energy recovery ventilator with 83 percent sensible efficiency and 49 Watts average power usage running continuously.

The following design conditions describe the heating and cooling systems used:

- House models that only required space heating used a 92 percent AFUE natural gas condensing boiler with 10.5 kW (36,000 Btu/h) capacity and an air handler. These houses relied on natural air ventilation to minimize summer overheating.
- House models that required space heating and space cooling used an electric air-source heat pump. The heat pump system has 18.4 SEER and 7.65 HSPF energy performance, a 2-Ton (nominal) outdoor unit and a 3-Ton (nominal) air handling unit. The system has two stages for heating and cooling and includes a 5kW auxiliary heater. Based on a summer design temperature of 35°C (95°F), the highest design value of the four locations that require a cooling system, the heat pump system has a maximum total cooling capacity of 7.0 kW (24,000 Btu/h), a maximum sensible cooling capacity of 6.0 kW (20,600 Btu/h) and a maximum heating capacity of 6.6 kW (22,600 Btu/h).
- Each house model that requires cooling had an air distribution system that is compact, insulated, entirely within conditioned space and is assumed to exhibit no air leakage.

Based on the PHPP models developed, EnergyGauge USA software version 2.7.02 was used to calculate site energy usage for each design package and to compare this with the Building America Research Benchmark Definition (Hendron 2007). In addition, EnergyGauge USA was used to determine the HERS Index for each design package.

Passive House Modeling Results and Observations

Building America whole house source energy savings for the Passive House designs varied from 63 to 72 percent, with the average being 65.7 percent. The HERS Index values ranged from 46 in Atlanta to 33 in the Minneapolis house model, with the average 41.0. Houses designed to the Passive House standard can be considered super energy efficient.

To achieve Passive House energy performance targets, each house design has building systems with extremely high levels of insulation. Exterior walls required nominal R-value varying from R-30 (St. Louis) to R-74 (Minneapolis), with double 2x4 wood stud wall construction used in three out of six designs. A minimum of R-20 insulation was needed under all concrete floor slabs, with Fort Wayne and Miami house designs requiring R-40 and Minneapolis requiring R-70. Attics needed a minimum of R-43 insulation in Mixed-Humid climate house designs, and a maximum level of R-86 insulation was required in Minneapolis. The Minneapolis and Miami house designs required an enclosure that would achieve an airtightness of 0.4 ACH at 50 Pa depressurization as tested with a blower door. The other house designs would need an enclosure airtightness of 0.6 ACH at 50 Pa depressurization. Five of the house designs used windows that were triple glazed with an argon gas fill and low-emissivity coatings, with only the Atlanta house design getting by with a double-glazed window with similar characteristics.

TRNSYS Modeling

The Passive House compliant house designs developed were translated into individual TRNSYS house models for each location. Each house model contained nine zones, three on the first floor and six on the second floor along with garage, attic and (if applicable) a basement zone. All TRNSYS simulations are based on six-minute time steps to best reflect operating conditions and provide detailed performance information. Building America developed room-by-room schedules for internal gains, lighting, and occupancy (NREL 2008) were used.

For TRNSYS modeling, certain assumptions were followed. Natural air ventilation through open windows took place in second floor bedrooms during nighttime when the master bedroom's temperature was greater than 23ºC (73ºF) and outdoor temperatures and humidity conditions were favorable for cooling. Windows became "closed" once the master bedroom's temperature dropped below 23ºC (73ºF) or the outdoor air was more humid than the indoor air. The initial temporary window shading model reflects the use of an indoor blind that reduces the solar heat gain through windows by 63 percent. Airflow between connected zones was facilitated by assuming connecting doors were open. Room-by-room schedules for miscellaneous loads, major appliances, lighting, and occupancy were based on Building America research.

Space conditioning systems used in TRNSYS modeling were the same as used in the PHPP models. For both sets of equipment, detailed engineered data from their manufacturer was used, with the heat pump system component model requiring specific data sets as inputs. A software program following ACCA Manual J procedures (ACCA 2003) was used to calculate zonal heating and cooling loads based on each house design's thermal enclosure package. Air flow allocations to each house model zone were proportional to the calculated heating and cooling loads. The thermostat was located in the dining room and entry zone. The heating set point was 21.7°C (71°F) and the cooling set point was 24.4°C (76°F).

From the six-minute data, loads, temperatures, and relative humidity values within each zone were determined to understand the room-by-room distribution of loads for heating and sensible cooling, and to understand interior comfort conditions. Due to a limitation in the design of each model, latent cooling loads were not calculated.

The Impact of Key Performance Components

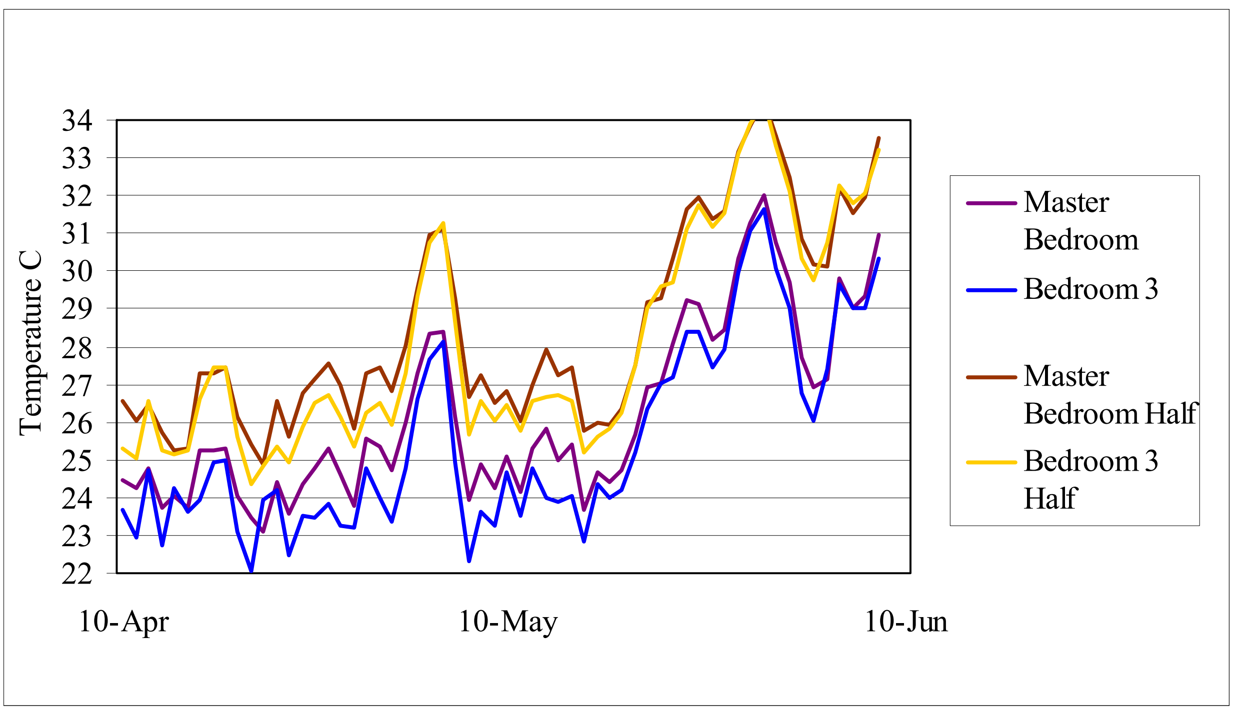
As the TRNSYS models were run, the impact of certain key performance components on modeling results stood out. To better understand the performance of super energy-efficient house designs and to increase modeling accuracy and design expertise, particularly with respect to comfort conditions, the impact of the key performance components were studied in greater detail. The components are: summer natural air ventilation and mechanical ventilation; soil thermal conductivity; interior and exterior window shading using blinds; and central or zone controlled conditioning systems. The impacts that the key components made to the design models with respect to interior temperature conditions or room-by-room loads for heating and cooling follow.

Impact of Natural Air Ventilation and Mechanical Ventilation Components

House designs in Fort Wayne and Minneapolis rely solely on natural air ventilation during nighttime to provide cooling when required, while the other house designs have mechanical cooling systems. A heat recovery ventilator was assumed to provide mechanical ventilation. To understand more fully the relationship between nighttime natural air ventilation rates and HRV operation and the resulting impact on interior temperatures, the Fort Wayne TRNSYS house model was studied more closely.

Each second-floor bedroom zone is assumed to have the same area of window open for natural air ventilation. Of note, modeling of the contribution of natural air ventilation for cooling can have unrealistic tendencies, since it assumes windows close and open automatically based on the need for cooling in the master bedroom zone when favorable outdoor temperatures and humidity conditions are occurring. This can lead to situations where windows are open and closed several times a night, an unlikely occurrence. Nevertheless, the effect of two different natural air ventilation flow rates during a two-month spring period, when cooling requirements were initiated and the HRV component was disabled, was examined. Initially a natural air ventilation rate of 94 m^3/h (55 cfm) per window was assumed, a value derived from PHPP modeling. A ventilation rate of 94 m^3/h (55 cfm) per window is equivalent to air flow of 1.05 to 2.37 air changes per hour for the four bedroom zones, or an average air flow of 1.87 air changes per hour. To provide contrast, a natural air infiltration rate half as great, 47 m^3/h (27 cfm), was also modeled. The daily temperatures that resulted in each situation in two zones are shown in Figure 1. Temperatures in both bedrooms were higher in the half natural air ventilation rate circumstance (brown and gold lines)—an average of 2.3ºC (4.1°F) in the master bedroom and 2.6ºC (4.7°F) in bedroom 3. Temperatures reached an uncomfortable 31ºC (87.8°F) in early May with the lower ventilation rate. Room temperatures in both situations were at least greater than 26ºC (78.8°F) starting in late May. This heat buildup was evident throughout the summer and strongly suggests that mechanical cooling is necessary for the Fort Wayne house design. When temperature data from first floor rooms was examined, less sensitivity to the different natural air ventilation rates was observed with temperature differences in each zone less than 1.0ºC (1.8°F).

Figure 1. Daily Temperatures in Two Fort Wayne Bedrooms Subject to 94 m^3/h and 47 m^3/h Natural Air Ventilation Rates

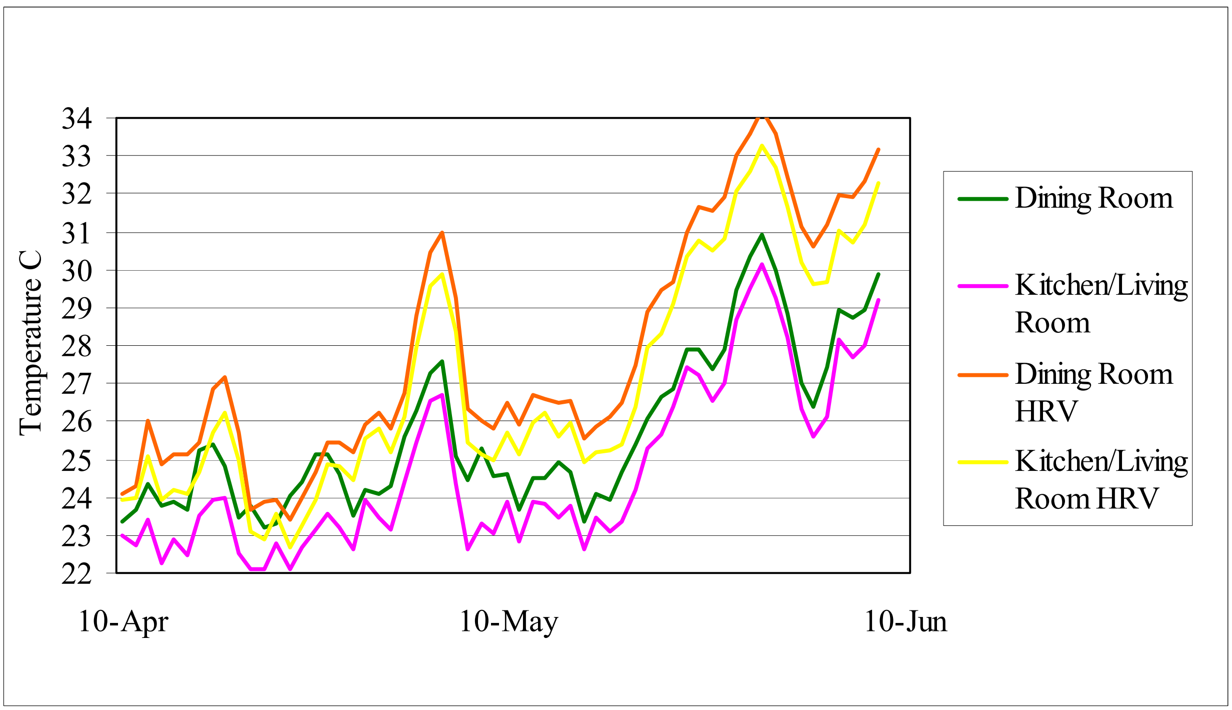


When the HRV component model was activated, the unit was assumed to run continuously and deliver air to all house zones at a flow rate proportional to each zone's volume.

On the following page, Figure 2 displays the effect that natural air infiltration at 94 m³/h (55 cfm) per window, with and without the HRV operating, has on first-floor zone temperatures. Temperatures are largely more comfortable when natural air ventilation is occurring and the HRV is not running (green and pink lines). The effect was noticed to be less predominate in second-floor zones. For the HRV to be turned off during warm outdoor weather is a course of action often taken by occupants of Cold-climate houses that do not have air conditioning. It appears that this approach to indoor temperature management has some merit.

Overall, more comfortable temperatures occur in house designs when natural air ventilation is occurring at a higher rate, 94 m³/h (55 cfm) per window and the HRV is not running. Since the HRV is assumed to run continuously, warm air brought in by it is likely responsible for raising indoor temperatures. It appears that occupant influence is beneficial for obtaining comfortable temperatures during summertime conditions in Cold-climate super energy efficient houses that do not have air conditioning.

Figure 2. Daily Temperatures in Two Fort Wayne First Floor Zones with Natural Air Ventilation Occurring With and Without HRV Operation



Impact of Soil Thermal Conductivity Component

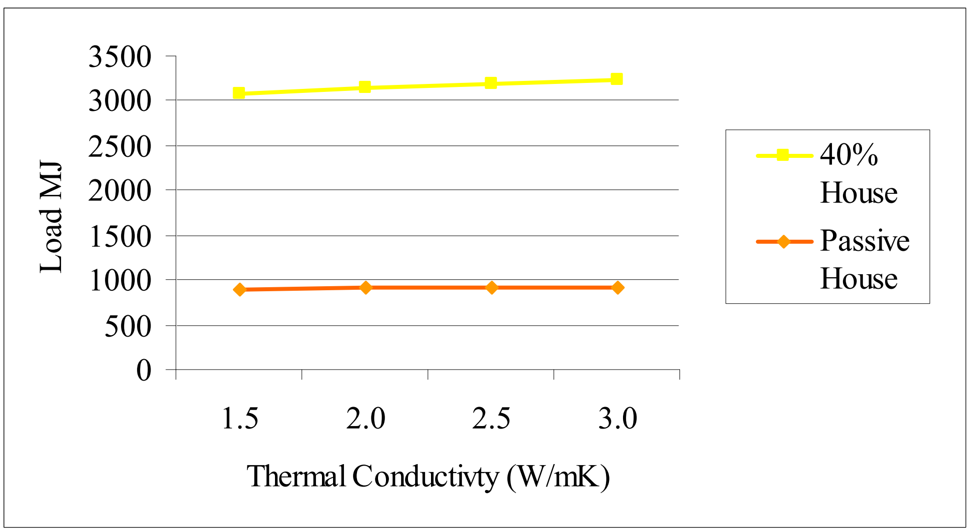
In TRNSYS house models, a value for soil thermal conductivity is required. Since specific soil thermal performance characteristics are rarely known in housing projects, information on the predominate soil type in the regional location can be sought, but often cannot be found. As a result, the value used for thermal conductivity is usually an estimate, thereby creating uncertainty as to the accuracy of the model. Since TRNYS has the ability to vary soil thermal conductivity values, the influence of this design component on heating loads in basements was studied for a Cold climate house design. A soil thermal conductivity of 1.5

W/mK is representative of silt/clay and dry sand soils, 2.0 W/mK reflects wet sand and moist clay soils, and 3.0 W/mK indicates saturated clay soils (Passivhaus Institute 2007).

On the following page, Figure 3 displays how basement loads vary with different soil thermal conductivity values during February in the Minneapolis house design. One house model is based on the Passive House compliant design, and the other is based on a 40% whole house energy savings design (as determined by Building America procedures). The Passive House design has a precast concrete wall system with R-12.5 extruded polystyrene (XPS) insulation on the exterior face and R-19 insulation within its cavity, along with a 2x6 wood stud wall inboard with R-19 insulation within the cavity and it features R-70 under slab insulation. The less energy-efficient 40% house design has a pre-cast concrete wall system with R-12.5 XPS insulation on the exterior face and no under slab insulation. Modeling results indicate that the basement load in one month in the 40% house design can vary as much as 7%, if saturated clay is assumed to be the soil type instead of silt/clay. For the Passive House design this difference is less than one percent, indicating less sensitivity to thermal conductivity values.

In summary, determining the precise soil thermal characteristics in house designs with superbly insulated basements is not as important as it is for less well insulated basements. In super energy-efficient house designs, varying soil thermal conductivity values have a minimal impact on basement loads, and, therefore, using approximate soil thermal conductivity values should be sufficient for modeling.

Figure 3. Heating Load in Basement in Minneapolis for Different Soil Thermal Conductivities for Two Different Insulated House Designs



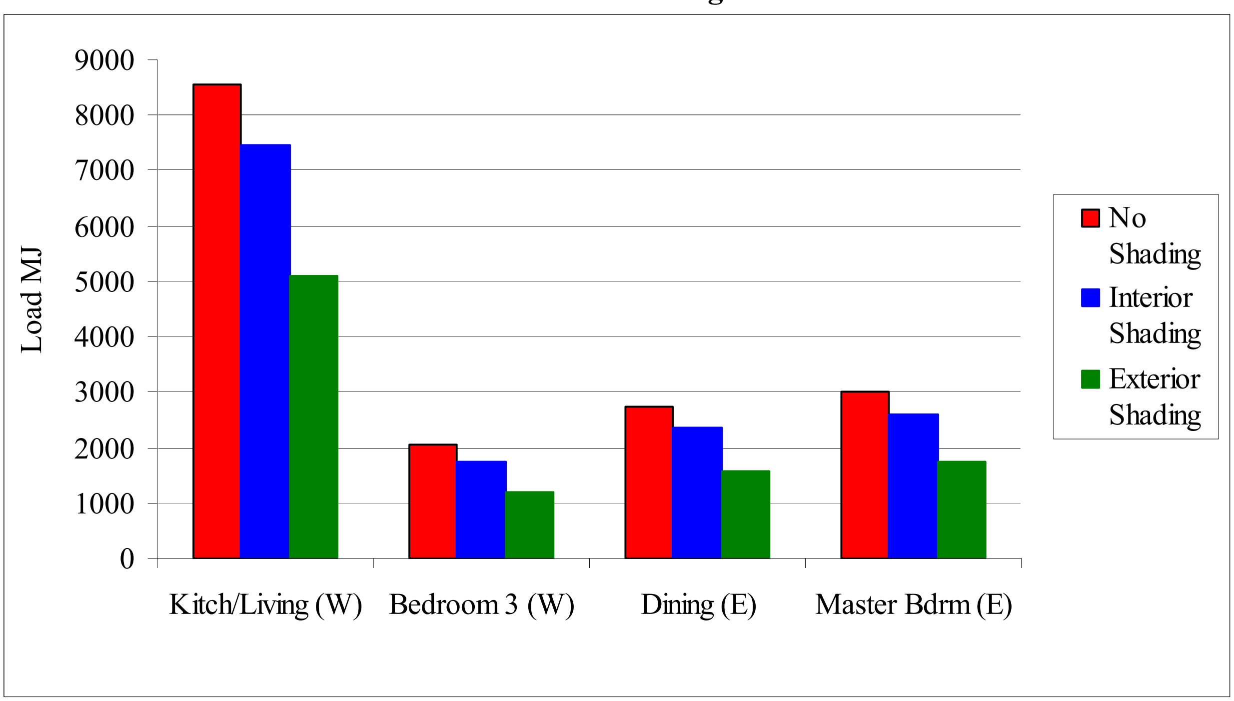
Impact of Temporary Interior and Exterior Shading of Windows Component

In Building America energy savings calculations procedures, temporary window shading is assumed to occur and the solar heat gain coefficient (SHGC) for windows must be lowered accordingly (Hendron 2007). In TRNSYS, the reduction of solar gains due to temporary window shading devices, which is assumed to consist of blinds, can be accounted for by a shading fraction value applied to the interior and/or exterior surfaces of a window. Since the shading fraction value is an unfamiliar quantity, a better understanding of its impact on cooling loads for super energy-efficient house design was sought.

The Atlanta house design, with windows with a SHGC of 0.44, was chosen to study the effect of different temporary window shading measures on its cooling load, and three cases were examined. Window shading cases studied included no shading, shading of windows with an interior blind, and shading of windows by an exterior blind. A window shading fraction of 63 percent was used for the interior blind, a value based on a triple-glazed window with a low-emissivity coating covered during 70% of daylight hours, as noted in Passive House documentation (Passivhaus Institute 2007). A window shading fraction value of zero is equal to no shading. Equivalent domestic information that outlines shading fraction values for different blinds was not found. To keep comparisons uncomplicated, the same window shading factor was assumed for the exterior blind. The effects of the different temporary window shading measures have on cooling loads from May 1 to October 1 are shown in Figure 4. Two east-facing zones and two west-facing zones were chosen to represent each floor. The cooling load dropped by an average 41 percent in west-facing zones and 42 percent in east-facing zones, from the unshaded condition, when exterior shading was applied. The effect of placing interior shading was less beneficial, with the average drop in cooling loads determined to be 13 percent in west-facing zones and 14 percent in east-facing zones.

In conclusion, the window shading fraction displayed considerable influence on the cooling load of a super energy-efficient house design and therefore its value should be determined as accurately as possible. The window shading fraction values used are based on German information, and similar domestic information would aid the accuracy of design and modeling work in this area. The change in cooling load between an unshaded condition and an exterior shaded condition is very significant. Equal window shading fractions for interior and exterior blinds yield more favorable energy savings for the latter. Cooling load reductions were found to be proportional in east- and west-oriented windows for different shading cases.

Figure 4. Total Cooling Load in Four Zones in Atlanta for Three Different Window Shading Conditions

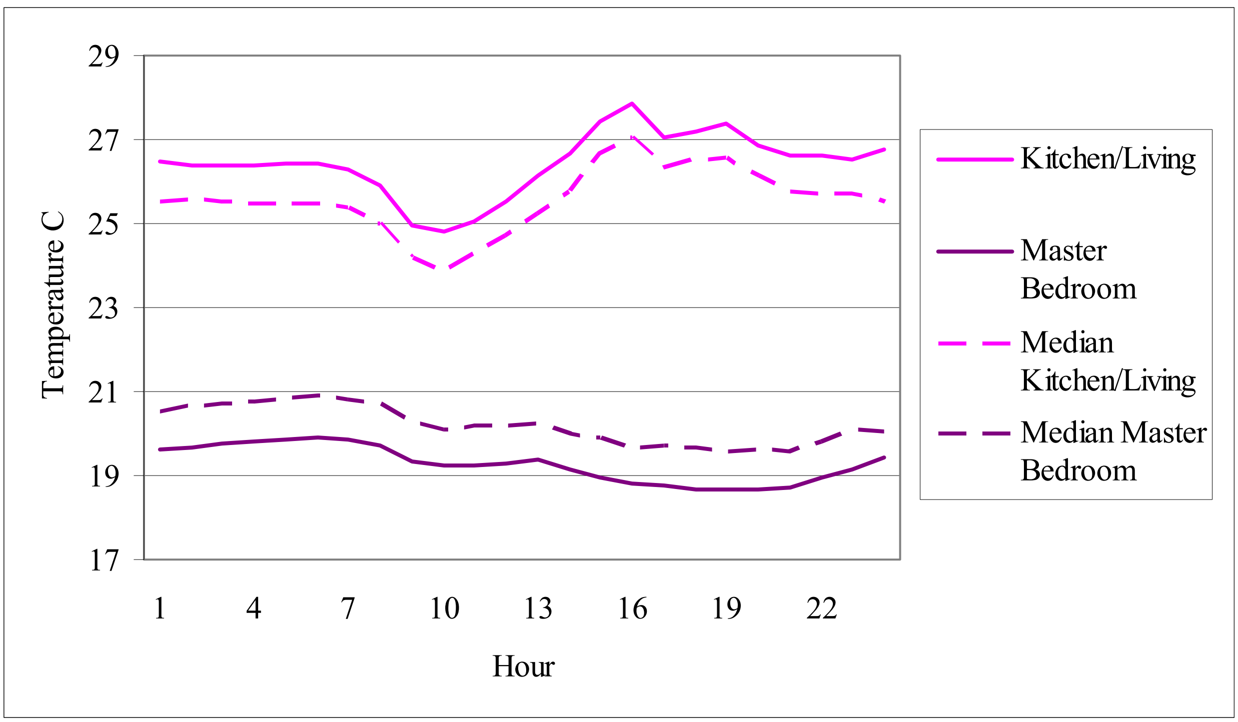


Impact of Central and Zonal Controlled Conditioning System Components

In Cold climate house designs, uneven temperature conditions between zones were apparent when a central forced air heating system was used. Similar uneven temperature conditions were observed in Mixed-Humid and Hot-Humid house design locations with their central air distribution system. This potential comfort issue was studied further to determine what remedies could make the situation more acceptable.

Figure 5 shows the hourly temperature distribution within two first-floor zones on the peak heating day (December 31) in the Minneapolis house design. This temperature distribution is typical for the entire heating season in the Minneapolis and Fort Wayne house models and represents uncomfortable conditions. The kitchen and living room zone (pink line) was over-heated while the master bedroom was under-heated (violet line). Further examination of the TRNSYS model indicated that the disparity in temperatures in the zones from the heating set point of 21.7°C (71°F) is largely a reflection of the air delivery into each. Airflow distribution is based on ACCA Manual J load calculation methodology.

Figure 5. Hourly Temperature Distribution on the Peak Heating Day in Two First Floor Zones in Minneapolis for Two Different Load Calculation Methods



IBACOS has explored using an alternative load calculation methodology based on median load days to distribute airflow to zones (IBACOS 2006). The median load day method considers the median heating and cooling load, in lieu of the peak load, on a daily basis for each zone. Using this method with Minneapolis heating load values, new air distribution values were allocated for each zone. The adjustment to air flow proportions resulted in the temperature values for the peak heating day distributing closer to the heating set point as shown (with dotted lines for each zone) in Figure 5. This indicates that the median load calculation method may be more suitable for central air distribution calculations in the house designs; although the over-heating and under-heating conditions occurring in their respective zones remain, indicating that it is not an ideal method.

The effect of individually zone controlled electric baseboard heating systems in a Cold climate house design was also examined as an alternative to a central system. Manual J loads were used to determine the capacity of each electric baseboard heater in each zone based on 50W increments. As shown on the following page in Figure 6, temperature values from modeling on the peak heating day, show closer conformity to the setpoint temperature in three of four zones. After these results, the capacity of the bedroom 3 electric baseboard heating system was decreased by trial and error, from 250 Watts to 100 Watts, until setpoint temperatures were more closely maintained.

Figure 6. Hourly Temperature Distribution on the Peak Heating Day in Key Zones in Minneapolis for an Electric Baseboard Heating System

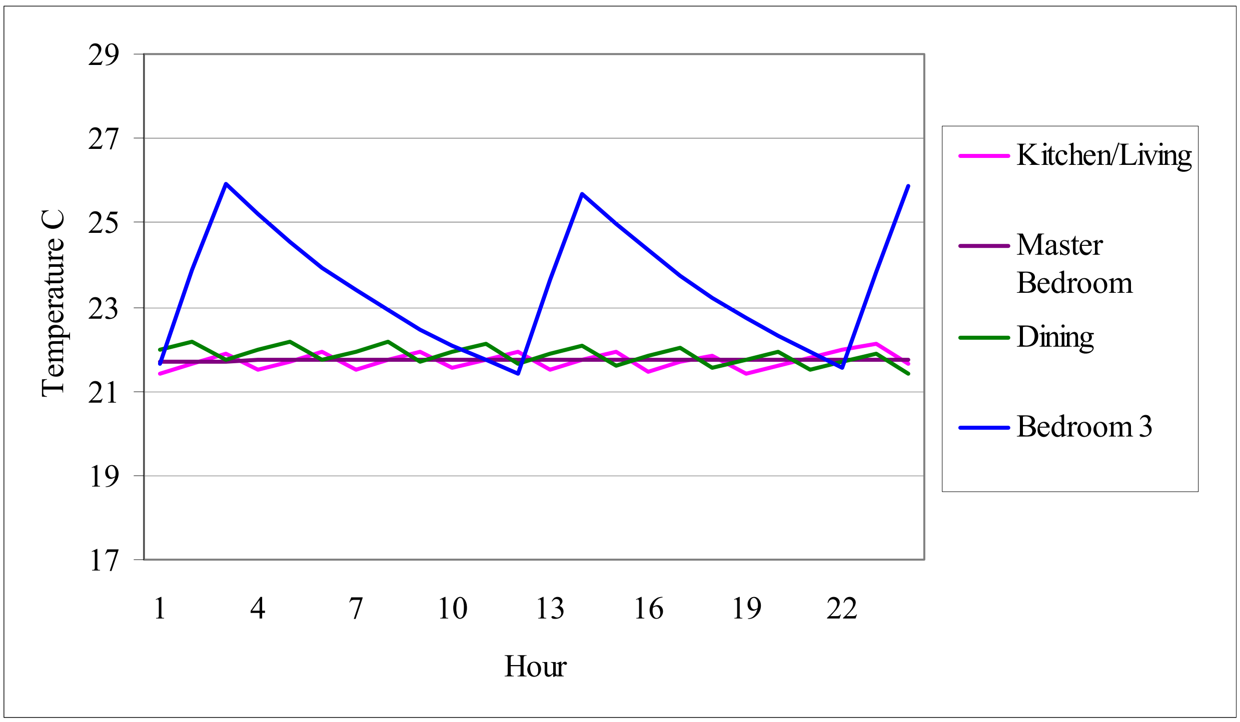
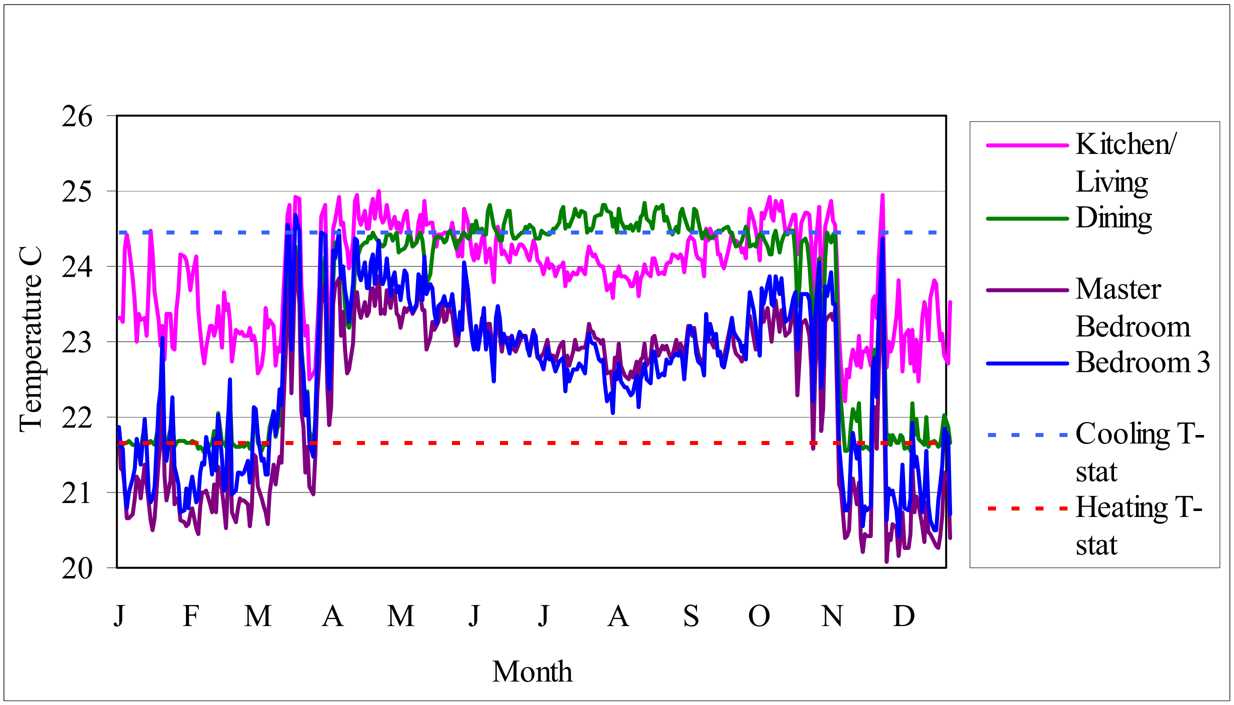


Figure 7 displays daily temperatures in Dallas on an annual basis. The temperature in the dining room and entry zone (green line) represents the thermostat temperature. During the beginning of the year, when heating occurred, the kitchen and living room zone (pink line) were over-heated and the master bedroom (violet line) was often under-heated. From the beginning of June through to October, all three zones (other than the dining room zone) are over-cooled. The disparity in temperatures is similar to the Cold climate forced air heating case and is a reflection of the air delivery into each zone, which is based on loads determined by ACCA Manual J. The other house models with central heating and cooling systems, which includes all Mixed-Humid and Hot-Humid house design locations, displayed the same temperature pattern in their key zones. The median load day method was used in the Dallas house design and resulted in more balanced temperature distribution in zones. Insufficient engineering information from manufacturers deterred the modeling of mini-heat pump systems that would allow for individually zone controlled systems with heating and cooling capability.

Figure 7. Daily Temperature Values in Key Zones in Dallas for One Year



In summary, TRNSYS modeling results showed that central air distribution systems did a poor job of maintaining zones at the required setpoint temperatures when based on Manual J load distribution method. Results based on a median load based load calculation method displayed improved comfort conditions. In a Cold climate house design, an individually zone controlled electric baseboard heating system offers temperatures more consistently near the setpoint level and therefore more comfortable conditions than a central air distribution system, regardless of the method of zonal airflow determination.

Conclusions

TRNSYS models with a six-minute time step were developed for six super energy-efficient house designs in three climate zones, all compliant with European Passive House standards. The impacts of several key performance components on these house designs were studied to improve our house design expertise and modeling accuracy.

In a Cold climate location, more comfortable temperatures took place when natural air ventilation is occurring at a rate of 94 m^3/h (55 cfm) per window and the HRV is not operating. If the natural air ventilation rate is decreased by half, indoor temperatures rise.

An examination of heating loads in a basement in a Cold climate house design determined that obtaining precise soil thermal characteristics in house designs with superbly insulated basements is not as important as it is for less insulated basements. Since varying soil thermal conductivity values have a minimal impact on basement loads, using approximate soil thermal conductivity values in super energy-efficient house designs should be sufficient.

In a Mixed-Humid house design, a window shading fraction, which represents the impact of temporary window shading, has considerable influence on the cooling load, and, therefore, its value should be determined as accurately as possible. The window shading fraction values used are based on German information, and similar domestic information would aid the accuracy of design and modeling work in this area. Using the same window shading fraction for interior and exterior blinds yielded more favorable energy saving results for the latter shading situation.

Central air distribution systems did a poor job of maintaining zones at the required setpoint temperatures when based on Manual J load distribution method, displaying worse comfort conditions than a median load based load calculation method. In a Cold climate house design, an individually zone controlled electric baseboard heating system offers temperatures more consistently near the setpoint level and therefore more comfortable conditions than a central air distribution system, regardless of the method of zonal airflow determination.

Acknowledgments

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