Could a European Super Energy Efficient Standard Be Suitable for the U.S.?

John Broniek, IBACOS Inc., Pittsburgh, PA

Abstract

The European Passive House residential energy efficiency standard has produced thousands of homes in Germany that have a peak heating load of less than 10W/m^2 and a maximum annual heating consumption of 15kWh/m^2. As part of Building America research for developing and implementing zero energy homes on a widespread basis, research has been conducted on how this construction standard could translate to U.S. climate zones, especially with respect to constructability, interior temperatures and comfort.

This paper reports on this research with results from applying Passive House standards to a two-story house model and the subsequent thermal enclosure packages required in Cold, Mixed-Humid and Hot-Humid U.S. climate zones. A TRNSYS model was developed for each compliant design, and room-by-room distribution of hourly, daily, seasonal, and annual loads for heating and cooling was determined.

Very energy-efficient house designs resulted, achieving an average 65.7 percent Building America whole house source energy savings and an average HERS Index value of 41. Mixed-Humid and Hot-Humid design locations required mechanical cooling. The thermal enclosure design packages in Mixed-Humid locations required the least stringent energy efficiency measures. Hot-Humid design locations required a significant reduction in window area (from the original floor plan), and the Miami design needed an extremely airtight building enclosure—resulting in constructability and consumer appeal challenges.

The Passive House source energy consumption target could not be met in five of the six house models. Building to the Passive House standard would be more feasible and less challenging for builders in the Mixed-Humid climate zone and in IECC Climate Zone 5. Builders in the Hot-Humid climate zone and in IECC Climate Zone 6 would likely find the standard less suitable since it requires construction measures that they may consider as too unfamiliar and too challenging to build. TRNSYS models for each house design indicate that the low capacity heating (10.5 kW) and cooling (7 KW) systems used displayed sufficient capacity to maintain set point temperatures at all times.

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/m^2 (Passivhaus Institute 2007). Recently the standard has added a cooling consumption

---

John Broniek is Senior Research Project Manager, IBACOS Inc., Pittsburgh, PA.

target of 15 kWh/m^2 in order to make it more applicable to southern European climate zones.

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 costs, constructability and comfort. Research was focused on the following objectives and outcomes:

- For several different climate zones, identify building enclosure design packages that have a maximum annual heating consumption of 15 kWh/m^2 and a maximum annual (sensible) cooling consumption of 15 kWh/m^2
- Optimize costs, constructability and homeowner comfort by identifying systems-based strategies appropriate for the energy saving enclosure designs developed.

To reach these objectives and outcomes the following work plan was initiated:

- Using Passive House software, develop six house design models that achieve the residential energy efficiency standard in three U.S. climate zones (Cold, Mixed Humid and Hot Humid) and outline the thermal enclosure packages for each design.
- Determine whole house source energy savings for Building America program reference.
- Develop TRNSYS model for each Passive House design model utilizing room-by-room schedules for internal gains, lighting, and occupancy.
- Determine room-by-room distribution of hourly, daily, seasonal, and annual loads for heating and cooling for each TRNSYS model.

Development of Thermal Enclosure Packages

In 2007, a new version of the Passive House Performance Package (PHPP) software was released (Passivhaus Institute 2007). This version is able to calculate sensible cooling energy, thereby providing capability to model Mixed-Humid and Hot-Humid locations. The house model locations chosen for each of the climate zones are shown in Table 1. Each PHPP model built was based on the research house constructed in Fort Wayne, Indiana, for which IBACOS has developed a detailed TRNSYS model (IBACOS 2006). The TRNSYS model for the Fort Wayne house was validated against temperature measurements taken on-site (IBACOS 2007). The house model has two floors and a garage underneath second-floor living space, and its front faces east.

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

For each model, thermal enclosure design packages were developed to meet the following performance targets established by the Passivhaus Institute, the organization overseeing Passive House work (Passivhaus Institute 2007):

- An annual heating consumption maximum value of 15 kWh per m^2 of floor area (specific energy requirement for space heating).
- An annual sensible cooling consumption maximum value of 15 kWh per m^2 of floor area (specific energy requirement for space cooling).
- A source energy consumption maximum value of 120 kWh per m^2 of floor area for the sum of all energy consumptions within the house (primary energy requirement).
- The frequency of temperatures that exceed 25°C needs to be 10 percent or less for the year (frequency of overheating) or mechanical measures to reduce the cooling load must be used.

Enclosure designs drew from experience with IBACOS prototype house and Austrian Passivhaus (Drössler 2001) work and were chosen according to the least expensive first cost and ease of construction. The designs adhered closely to the following recommendations from the Passivhaus Institute:

- Building enclosure components have a maximum U-value under 0.15 W/m^2·K.
- Building enclosure components do not contain thermal bridges in order to limit energy losses and increase occupant comfort and building durability.
- The building enclosure is airtight enough to achieve a value of 0.6 ACH at 50 Pa depressurization when tested with a blower door.
- To minimize heating consumption windows have center of glass U-value less than 0.8 W/m^2·K and a solar heat gain coefficient (SHGC or g) of 0.50 or greater.
- To minimize heat loss windows have a total U-value less than 0.8 W/m^2·K.
- Heat recovery ventilators are high-efficiency (sensible efficiency greater than 75 percent) and minimal electrical consumption.
- Domestic hot water generation and distribution system has minimal heat loss in order to deliver hot water efficiently.
- High-efficiency use of household electricity is essential.

Passive House Modeling Results

An interior (heating) design temperature of 20°C was used in the PHPP models according to Passive House modeling guidelines (Passivhaus Institute 2007). Designs that, after the inclusion of natural air ventilation, exhibited a frequency of overheating during the year greater than 10 percent were given a mechanical cooling system. Values for internal heat gains, occupancy and floor area to be considered (treated floor area) followed Passive House modeling guidelines. Also in accordance with guidelines, the site to source multipliers used were 2.7 for electricity and 1.1 for natural gas.

The thermal enclosure packages for each model were developed assuming that the following conditions existed for the house systems:

- Foundations are slab-on-grade except for the Minneapolis location, where basement foundations are prevalent. A frost-protected shallow foundation was used in Fort Wayne to protect its slab-on-grade from frost-heaving situations.
- The exterior cladding is vinyl siding installed over insulated sheathing.
- Natural air ventilation through open (casement) windows provided nighttime cooling during summer conditions. The natural air change rate was determined by the PHPP software based on the area of open windows and climatic conditions.
- Interior shading of windows occurred during daylight hours when cooling was likely. The shading model follows Passive House modeling recommendations and reflects the use of an indoor blind that reduces the solar heat gain through windows by 63 percent (Passivhaus Institute 2007).
- The mechanical ventilation system consisted of a heat recovery ventilator operating continuously with 83 percent sensible efficiency and 49 Watts average power usage. In accordance with ASHRAE standard 62.2, the continuous ventilation rate for the house design is 28 l/s (ASHRAE 2007).
- The domestic hot water system consisted of a natural gas-fired instantaneous condensing water heater with an energy factor of 0.92. Domestic hot water pipes are entirely insulated and contained within the house. Hot water consumption was determined as per the Building America Research Benchmark Definition (Hendron 2007).
- Ninety percent of interior, garage and exterior lighting have fluorescent (linear or compact) lamps.
- Major appliances, including refrigerator, clothes washer and dryer, dishwasher, and oven/range are energy efficient. The refrigerator was assumed to be highly energy efficient with 450 kwh/yr energy consumption. To minimize source energy use, gas cooking ranges and gas clothes dryers were selected, except where noted. Major appliance and miscellaneous electrical energy load usage was determined as per the Building America Research Benchmark Definition.

Several heating and cooling systems were examined for use in each house model location. For house models only requiring heating the following systems were considered: electric baseboard, electric air-source heat pump, natural gas condensing boiler with an air handler, and natural gas condensing boiler with baseboard radiators. For house models requiring heating and cooling the use of a mini-split heat pump system and an electric air-source heat pump were considered. Final heating and cooling system choices reflected the option that was energy efficient, minimized source energy consumption and was the most production-ready. 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 an air handler. The fan energy used by the air handler was accounted for in the PHPP software. These houses did not contain a mechanical cooling system, thereby relying on natural air ventilation to minimize overheating during the summer. For whole house energy savings determination, as per Building America Research Benchmark Definition, houses without a mechanical cooling system are assumed to have a 10 SEER window air conditioning unit which represents a possible future installation.

- 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 7 kW (nominal) capacity outdoor unit and a 10.6 kW (nominal) capacity air handling unit. The system has two stages for heating and cooling thereby making it applicable for a wide range of heating and cooling loads. A 5kW auxiliary heater was part of the system. Energy use for dehumidification was accounted for in the PHPP software.
- Each house model 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. EnergyGauge USA software is the most prevalent software used for this purpose in the Building America Program. To best model the enclosure design packages systems developed in PHPP using EnergyGauge USA, the total effective U-values determined were used as inputs, instead of system characteristics. In this work, the software's inability to model the full extent of insulation placed under a basement floor slab or a slab on grade foundation is a limitation that results in inaccuracies in space conditioning energy usage. In addition, EnergyGauge USA was used to determine the HERS Index for each design package. The determination of whole house source energy savings followed the procedures outlined in the Building America Research Benchmark Definition.

Table 2 presents the enclosure design packages, performance target results, and energy usage information for the Cold climate models. Total effective U-values were determined by PHPP 2007 software.

Table 2. Highly efficient thermal enclosure design package for Fort Wayne, Indiana and Minneapolis, Minnesota models

System	Minneapolis, Minnesota Specification	Fort Wayne, Indiana Specification
Floor Slab	Concrete slab for basement with 356 mm XPS insulation underneath; Total Effective U-value: 0.079 W/m^2·K	Concrete slab-on-grade central portion with 204 mm XPS* insulation underneath; Total Effective U value: 0.135 W/m^2·K Concrete slab-on-grade perimeter (frost-protected edge) with 102 mm XPS insulation underneath; Total Effective U-value: 0.266 W/m^2·K
Foundation	Precast concrete wall with 64	Not applicable

Walls	mm XPS insulation on exterior face and fiberglass batt insulation within cavity, and 38 x 140 mm wood stud wall inboard with fiberglass batt insulation within cavity; Total Effective U-value: 0.128 W/m^2·K	
Exterior Walls	Double 38 x 89 mm wood stud wall with 254 mm interior cavity (432 mm total depth) with damp spray cellulose insulation throughout and 51 mm layer of polyisocyanurate foam sheathing on exterior face; Total Effective U-value: 0.078 W/m^2·K	Double 38 x 89 mm wood stud wall with 153 mm interior cavity (341 mm total depth) with damp spray cellulose insulation throughout and 51 mm layer of polyisocyanurate foam sheathing on exterior face; Total Effective U-value: 0.097 W/m^2·K
Attic/Roof	Blown-in cellulose insulation, total depth 560 mm; Total Effective U-value: 0.065 W/m^2·K	Blown-in cellulose insulation, total depth 432mm; Total Effective U-value: 0.087 W/m^2·K
Windows	Triple-glazed with argon gas fills and low-emissivity coatings. Fixed units, center of glass U-value: 0.880 W/m^2·K; Total window average U-value: 0.970 W/m^2·K; Solar heat gain coefficient (SHGC or g): 0.59 Two East facing windows 1.76 m^2 and two West facing windows 1.98 m^2 converted to exterior wall	Triple-glazed with argon gas fills and low-emissivity coatings. Fixed units, center of glass U-value: 0.880 W/m^2·K; Total window average U-value: 0.970 W/m^2·K; Solar heat gain coefficient (SHGC or g): 0.59
Building Enclosure Airtightness	0.4 ACH at 50 Pa depressurization as tested with a blower door**	0.6 ACH at 50 Pa depressurization as tested with a blower door**
Annual Heating Consumption	15 kWh/m^2	15 kWh/m^2
Source Energy Consumption	119 kWh/(m²·a)	144 kWh/(m²·a)
Whole House Site Energy Usage	Electrical: 6786 kWh (5678 kWh)* Gas: 12218 kWh	Electrical: 6729 kWh (5667 kWh)*, Gas: 12072 kWh

*Usage if no air conditioning in model (contrary to Building America Research Benchmark Definition)

** In accordance with CGSB Standard 149.10 (CGSB 1986)

Table 3 presents the enclosure design packages, performance target results, and energy usage information for the Mixed-Humid climate models. Total effective U-values were determined by PHPP 2007 software.

Table 3. Highly efficient thermal enclosure design package for St. Louis, Missouri and Atlanta, Georgia models

System	**St. Louis, Missouri Specification**	**Atlanta, Georgia Specification**
Floor Slab	Concrete slab with 102 mm XPS underneath; Total Effective U-value: 0.256 W/m^2·K	Concrete slab with 102 mm XPS underneath; Total Effective U-value: 0.256 W/m^2·K
Exterior Walls	38 x 190 mm wood stud wall with damp spray cellulose insulation within cavity and 13 mm layer of XPS foam sheathing on exterior face; Total Effective U-value: 0.206 W/m^2·K	38 x 190 mm wood stud wall with damp spray cellulose insulation within cavity and 25 mm layer of XPS foam sheathing on exterior face; Total Effective U-value: 0.190 W/m^2·K
Attic/Roof	Blown-in cellulose insulation, total depth 305 mm; Total Effective U-value: 0.130 W/m^2·K	Blown-in cellulose insulation, total depth 305 mm; Total Effective U-value: 0.130 W/m^2·K
Windows	Triple-glazed with argon gas fills and low-emissivity coatings. Fixed units, center of glass U-value: 0.880 W/m^2·K; Total window average U-value: 0.970 W/m^2·K; Solar heat gain coefficient (SHGC or g): 0.59 Casement units (4), center of glass U-value: 0.890 W/m^2·K; Total window average U-value: 1.110 W/m^2·K; Solar heat gain coefficient (SHGC or g): 0.61	Double-glazed with argon gas fill and low solar gain emissivity coating. Fixed units, center of glass U-value: 1.560 W/m^2·K; Total window average U-value: 1.714 W/m^2·K; Solar heat gain coefficient (SHGC or g): 0.44 Casement units (4), center of glass U-value: 1.660 W/m^2·K; Total window average U-value: 1.870 W/m^2·K; Solar heat gain coefficient (SHGC or g): 0.46
Building Enclosure Airtightness	0.6 ACH at 50 Pa depressurization as tested with a blower door*	0.6 ACH at 50 Pa depressurization as tested with a blower door*
Annual Heating Consumption	15 kWh/m^2	15 kWh/m^2
Annual Cooling	10 kWh/m^2	7 kWh/m^2

Consumption		
Source Energy Consumption	145 kWh/(m²·a)	143 kWh/(m²·a)
Whole House Site Energy Usage	Electrical: 10492 kWh Gas: 7003 kWh	Electrical: 8421 kWh, Gas: 6593 kWh

* In accordance with CGSB Standard 149.10

Table 4 presents the enclosure design packages, performance target results, and energy usage information for the Hot-Humid climate models. Total effective U-values were determined by PHPP 2007 software.

Table 4. Highly efficient thermal enclosure design packages for Dallas, Texas and Miami, Florida

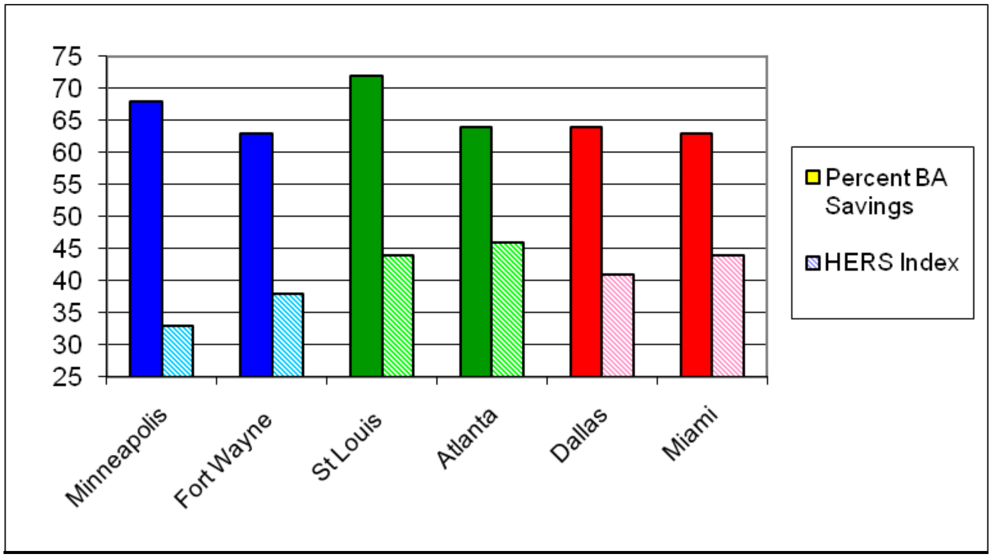
System	**Dallas, Texas Specification**	**Miami, Florida Specification**
Floor Slab	Concrete slab with 102 mm XPS underneath; Total Effective U-value: 0.256 W/m^2·K	Concrete slab-on-grade central portion with 204 mm XPS insulation underneath; Total Effective U-value: 0.135 W/m^2·K
Exterior Walls	38 x 190 mm wood stud wall with damp spray cellulose insulation within cavity with 51 mm layer of polyisocyanurate foam sheathing on exterior face; Total Effective U-value: 0.149 W/m^2·K	190 mm concrete block masonry wall with double 38 x 89 mm wood studs containing 153 mm interior cavity (341 mm total depth) with damp spray cellulose insulation throughout and 51 mm layer of polyisocyanurate foam sheathing on exterior face; Total Effective U-value: 0.096 W/m^2·K
Attic/Roof	Blown-in cellulose insulation, total depth 458 mm; Total Effective U-value: 0.087 W/m^2·	Blown-in cellulose insulation, total depth 508 mm; Total Effective U-value: 0.078 W/m^2·K
Windows	Triple-glazed with argon gas fills and low-emissivity coatings. All fixed units with center of glass U-value: 1.260 W/m^2·K; Total window average U-value: 1.290 W/m^2·K; Solar heat gain coefficient (SHGC or g): 0.36 4.61 m^2 east-facing windows and 3.07 m^2 west-facing windows converted to exterior wall	Triple-glazed with argon gas fills and low-emissivity coatings. All fixed units with center of glass U-value: 1.260 W/m^2·K; Total window average U-value: 1.290 W/m^2·K; Solar heat gain coefficient (SHGC or g): 0.36 8.67 m^2 east-facing windows and 12.22 m^2 west-facing windows converted to exterior wall including sliding glass door (replaced by insulated door)

Building Enclosure Airtightness	0.6 ACH at 50 Pa depressurization as tested with a blower door*	0.4 ACH at 50 Pa depressurization as tested with a blower door*
Annual Heating Consumption	3 kWh/m^2	0 kWh/m^2
Annual Cooling Consumption	15 kWh/m^2	15 kWh/m^2
Source Energy Consumption	144 kWh/(m²·a)	148 kWh/(m²·a)
Whole House Site Energy Usage	Electrical: 7742 kWh Gas: 6270 kWh	Electrical: 7269 kWh Gas: 5450 kWh

* In accordance with CGSB Standard 149.10

The percentage of Building America whole house source energy savings (solid bars) and the HERS Index values (hatched bars) for each house design model location are displayed in Figure 1.

Figure 1. Building America whole house source energy savings and HERS Index values for each house design model



Observations on Passive House Modeling

In Cold and Mixed-Humid climate house designs, achieving the heating consumption energy target governed the formulation of each thermal enclosure design package. In Hot-Humid climate house designs, meeting the sensible cooling consumption energy target guided the energy efficiency measures necessary.

Referring to Figure 1, Building America whole house source energy savings for the house designs varied from 63 to 72 percent, with the average being 65.7 percent. The thermal enclosure design packages in Mixed-Humid locations required the least stringent energy efficiency measures, with the Atlanta house design registering the highest HERS Index value (46). The Minneapolis house model recorded the lowest HERS Index value (33), with the average 41.0. It is interesting to note that to be considered net zero electrical energy the Fort Wayne design package, which has the lowest electrical consumption of all the house designs with a predicted site electrical energy usage of 5667 kWh (no air conditioning case), would require a photovoltaic system with more than 5.0 kW dc production (NREL) capability. Only the Cold climate house designs did not require mechanical cooling as their frequency of overheating, as defined earlier, was maintained at 10 percent or less.

To achieve Passive House energy performance targets, each highly efficient thermal enclosure design package has building systems with extremely high levels of insulation. Thermal enclosure design packages include exterior walls with total effective U-value varying from 0.206 W/m^2·K (St. Louis) to 0.078 W/m^2·K (Minneapolis), with double 38 x 89 mm wood stud wall construction used in three out of six designs. Of note, the St. Louis house design utilized a more energy-efficient window than its Mixed-Humid climate counterpart, thereby avoiding double 38 x 89 mm wood stud wall construction to meet the annual heating consumption target. Furthermore, the Miami house design required a double 38 x 89 mm wood stud wall system adjacent to the structural masonry wall (concrete block) to achieve the annual cooling consumption target. A minimum of 102 mm XPS insulation was needed under all concrete floor slabs, with Fort Wayne and Miami house designs requiring 204 mm and Minneapolis requiring 356 mm. Attics needed a minimum of 305 mm of insulation (total effective U value of 0.130 W/m^2·K) in Mixed-Humid climate house designs and a maximum level of 560 mm of insulation was required in Minneapolis.

The house designs used windows that were either triple-glazed with an argon gas fill and low-emissivity coatings or double-glazed with an argon gas fill and low solar gain emissivity coating. Two different types of triple-glazed windows were used, each exhibiting excellent thermal performance due to a total U-value of 1.290 W/m^2·K or less. It is their solar heat gain coefficient (SHGC) value that determined their application (Thermotech 2007). One triple-glazed window has a SHGC of 0.59 (fixed units), allowing heat gains during the heating season. The other selected triple-glazed window has a low SHGC of 0.36 (fixed units) that limits heat gain during the cooling season. In the Minneapolis, Dallas, and Miami house models, the most practical approach to meeting the annual heating or cooling consumption target was to reduce the number of windows in exterior walls. In the Hot-Humid location designs, the number of east- and west-facing windows converted to exterior wall was very architecturally significant as the area of glazing in each was reduced by 29 percent in Dallas and a whopping 79 percent in Miami.

The Minneapolis and Miami house designs required more stringent building airtightness measures than the other designs. These designs required an enclosure that would need to achieve an airtightness of 0.4 ACH at 50 Pa depressurization as tested with a blower door. Constructing a house to meet this target would be very challenging.

Hot water consumption values used, which followed Building America Research Benchmark Definition guidelines, were twice the level recommended in the software reflecting the difference between European and American hot water usage. The use of a condensing (EF = 0.92) natural gas-fired instantaneous water heater for domestic hot water production, although rare in the marketplace, was used to limit source energy consumption. An indirect water heater system was considered for some house models but was not used because it was less energy efficient.

The value input for miscellaneous electrical load usage was much greater than typical value noted by the Passivhaus Institute for that application and as a result the source energy consumption rose. Although electrical energy used by appliances was minimized with the use of a super energy-efficient refrigerator (450 kWh/yr), a gas dryer, a gas cooking range and a very energy-efficient water heater, the source energy consumption target could not be met in five of the six house models. The complying house model benefited from having a greater floor area for the target calculation due to its basement configuration. For house designs that use an electric heat pump for heating and cooling, the source energy consumption target was exceeded by at least 23 kWh/(m^2·a) or 19 percent. Gas-engine driven heat pumps may be a possible alternative cooling system but their large system capacities limit their applicability for low load houses. The use of a solar thermal hot water system to supplement hot water production was found to reduce source energy consumption by an average of 19.8 kWh/(m^2·a) and resulted in house designs a lot closer to the source energy consumption target level.

In summary, building to the Passive House standard would be more feasible/less challenging for builders in the Mixed-Humid climate zone and in IECC Climate Zone 5 (part of Building America’s Cold climate zone). Builders in the other studied house design locations would likely find the standard less suitable since it requires several construction measures, such as a super-tight building enclosure, double stud wall construction and a reduction in glazing, which they may consider as too exotic and too challenging to build and market to potential customers.

TRNSYS Modeling

The thermal enclosure packages developed were translated into individual TRNSYS house models for each location. All TRNSYS simulations are based on six-minute time steps to best reflect operating conditions. A bulk airflow model, CONTAM version 2.4, was developed for the same prototypical house plan used in Passive House modeling. Although the CONTAM model offers more accurate representation of the air movement each zone experiences, it was found to not be a reliable TRNSYS component for time periods greater than a month. Therefore, to determine the seasonal and annual modeling results, a simpler approach to inter-zonal air movement was used. The approach did not include the air movement effects due to an air distribution system.

For TRNSYS modeling, certain assumptions were followed. Natural air ventilation through open windows took place in second-floor rooms when indoor temperatures were above the cooling setpoint and outdoor temperature and humidity conditions were favorable for cooling. Windows became “closed” once the indoor temperature dropped below 23ºC (73ºF) so that over-cooling did not occur. The shading of windows follows Passive House recommendations and reflects the use of an indoor blind that reduces the solar heat gain through windows by 63 percent. Room-by-room schedules for miscellaneous loads, major appliances, lighting, and occupancy were based on Building America research (NREL 2007). Appliances were distributed into zones based on their typical use (eg. dishwasher in kitchen zone). Internal gains were derived for each energy use according to Building America research.

For the Cold climate house models, which only required space heating, a 92 percent AFUE natural gas condensing boiler, with 10.5 kW capacity was used with an air handler. For the house models that required a mechanical cooling system, a two-stage heat pump system with 18.4 SEER and 7.65 HSPF energy performance was chosen. Based on a summer design temperature of 35°C, 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, a maximum sensible cooling capacity of 6.0 kW and a maximum heating capacity of 6.6 kW (Lennox 2005). 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) was used to calculate zonal heating and cooling loads based on each house model design. These procedures were followed, because it is the industry standard for load calculations and sizing of space conditioning systems. 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, and the cooling set point was 24.4°C.

TRNSYS Modeling Results and Observations

From the six-minute data, hourly loads, temperatures, and relative humidity values within each zone were determined to understand the room-by-room distribution of hourly, daily, seasonal, and annual loads for heating and sensible cooling. Figure 2 displays the total daily load values for four house zones in the St. Louis TRNSYS house model. Sensible cooling loads are displayed as negative values. As a Mixed-Humid location, this house model is representative of the room-by-room distribution of loads observed during the heating and cooling season in the other house models. It’s not surprising that the kitchen/living room zone, which had the largest volume, also had the greatest loads.

Figure 2. Heating and Sensible Cooling Total Daily Loads in St. Louis (Mixed-Humid Climate Zone) for One Year

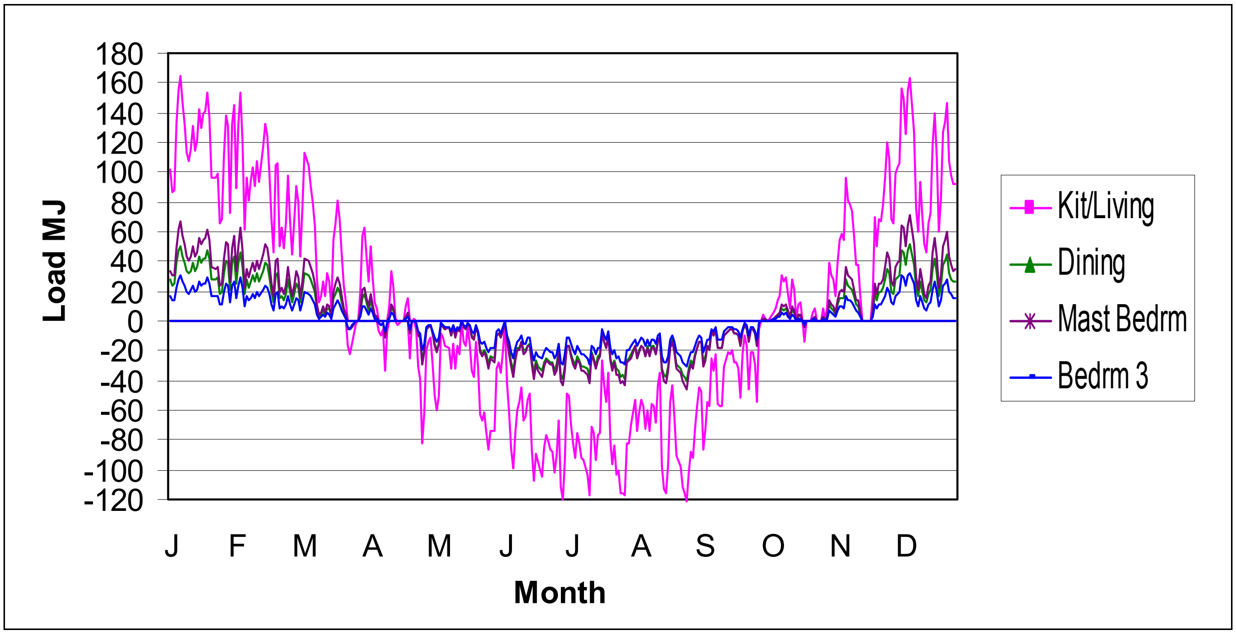
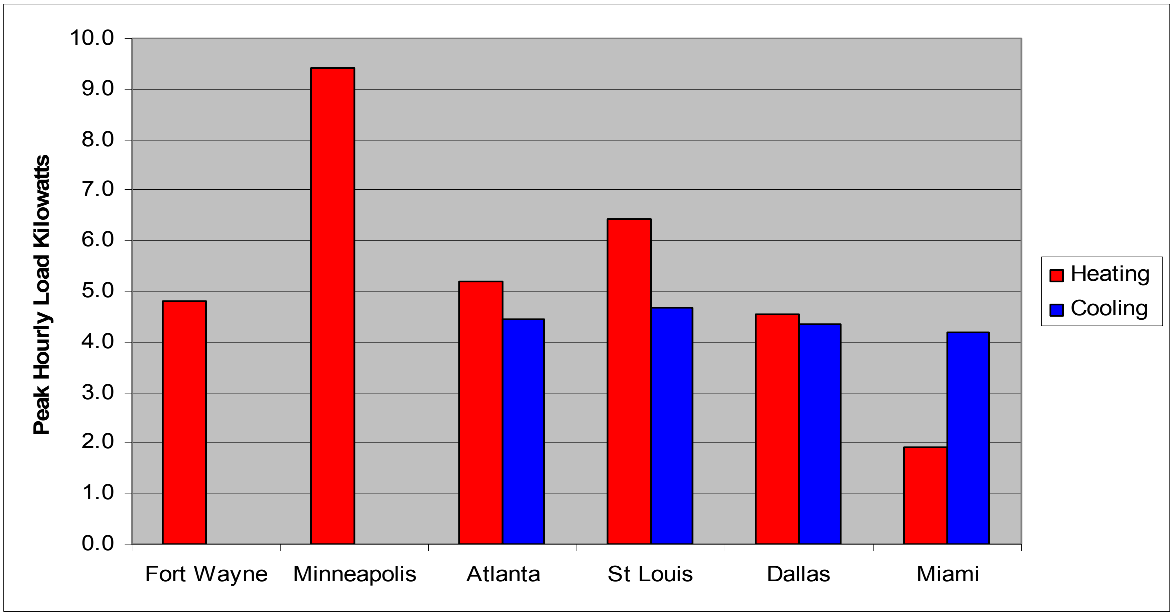


Figure 3 displays peak hourly loads calculated in the TRNSYS models for each location. Peak hourly heating and sensible cooling loads were within the respective space conditioning equipment capacities for all house design locations. Of note, the heat pump system chosen would have just enough heating capacity to meet the peak hourly heating demand of the St. Louis house design. Peak hour sensible cooling capacity requirements for the four house designs that required mechanical air conditioning were very similar. Each of the house design’s sensible cooling requirements should be satisfied with a cooling system with 5.3 kW sensible cooling capacity. Latent cooling loads could not be determined in the TRNSYS model.

Figure 3. Peak Hourly Heating and Sensible Cooling Load Values for the House Design Locations



Temperature and relative humidity information for each house model was compiled to evaluate space conditioning system performance. Figure 4 displays daily temperatures in Dallas in two zones for the cooling season. Temperatures in the dining room/entry zone (the zone with the thermostat) vary no more than 0.5°C from the cooling setpoint during the entire cooling season, except for a few days in May when over-cooling occurred. Based on this information, the cooling system appears to have adequate sensible cooling capacity. From the beginning of June through to October, the kitchen/living room zone is over-cooled. The disparity in temperatures, when the zones are being conditioned, is largely a reflection of the air delivery into each. The distribution of air into each zone is based on its ratio of the load as determined by ACCA Manual J calculations, the industry standard for such calculations.

Figure 4. Daily Temperature Values in Dallas during the Cooling Season

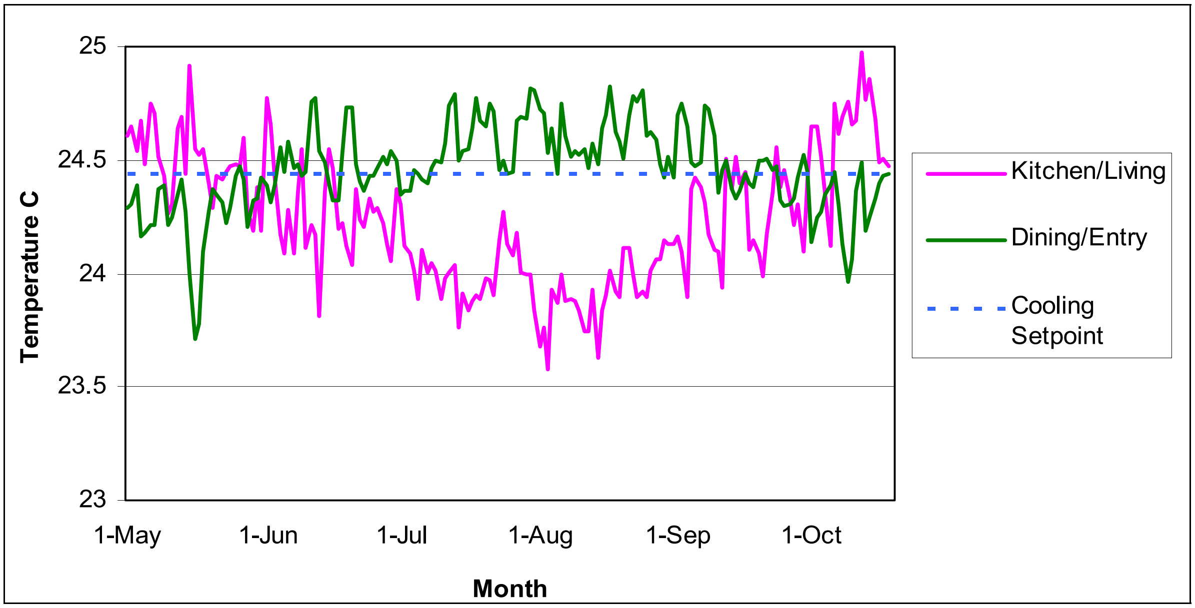
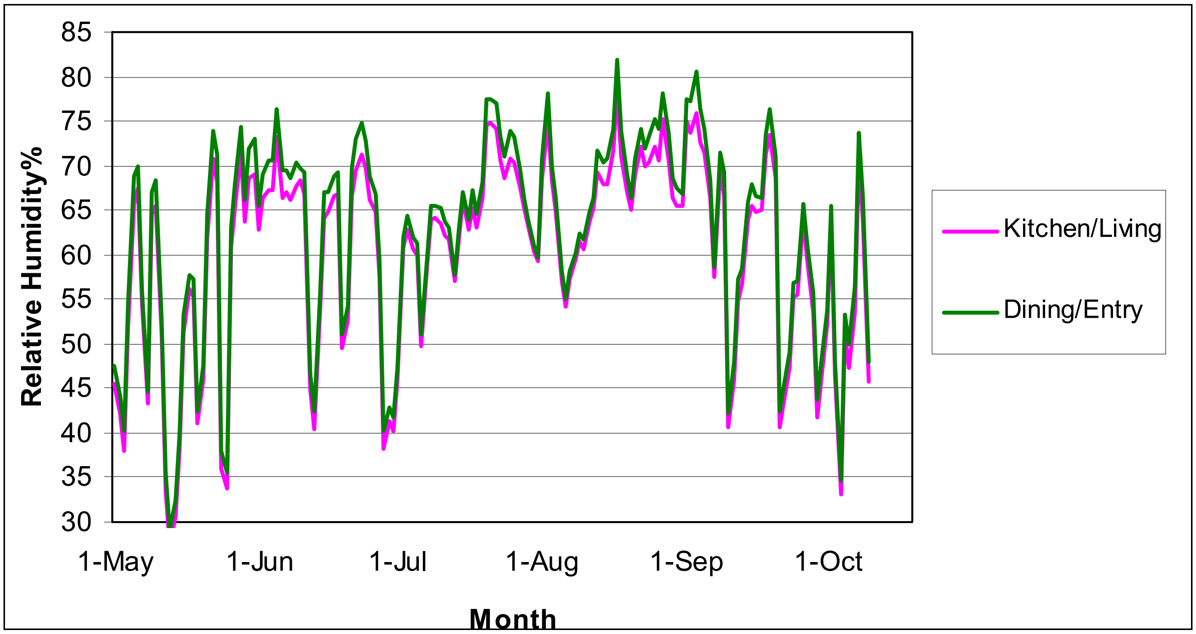


Figure 5 shows the daily relative humidity values in Dallas for the cooling season in the same two zones displayed in Figure 4. Daily relative humidity values reached over 75 percent several times during the cooling season. If models include a thermostat with dehumidification control lower relative humidity rates should result. Although latent cooling loads were not determined in TRNSYS, ACCA Manual J load calculations indicated that the 7 kW heat pump system chosen for the Dallas house design and the other house designs has adequate total cooling capacity, but with a small margin of safety.

Figure 5. Daily Relative Humidity Values in Dallas during the Cooling Season



Conclusions

The Passive House Performance Package software was used to develop house design packages in three U.S. climate zones that met Passive House energy consumption targets, namely a heating target of 15 kWh per m^2 of floor area per year and a sensible cooling target of 15 kWh per m^2 of floor area per year. Very energy-efficient house designs resulted, achieving an average 65.7 percent Building America whole house source energy savings and an average HERS Index value of 41. Mixed-Humid and Hot-Humid design locations required mechanical cooling.

House designs featured exterior walls with U-values ranging from 0.206 $W/m^2 \cdot K$ (St. Louis) to 0.078 $W/m^2 \cdot K$ (Minneapolis), with double wood stud wall construction used in three out of six designs. A minimum of 102 mm of extruded polystyrene insulation was needed under all concrete floor slabs. Triple-glazed windows, of varying SHGC value, were necessary in all design locations except for Atlanta. Hot-Humid designs required a significant reduction in window area (from the original floor plan), thereby greatly affecting architectural appearance of the designs and likely making them less attractive to potential customers. In addition, the Miami house design required exceptional building enclosure airtightness (0.4 ACH at 50 Pa depressurization), thereby making it more challenging to construct. The house designs in Mixed-Humid locations required the least stringent energy efficiency measures. Despite efforts to keep source energy levels at a minimum, the Passive House source energy consumption target could not be met in five of the six house models studied.

Building to the Passive House standard would be more feasible and less challenging for builders in the Mixed-Humid climate zone and in IECC Climate Zone 5. Builders in the Hot-Humid climate zone and in IECC Climate Zone 6 would likely find the standard less suitable since it requires construction measures that they may consider as too unfamiliar and too challenging to build.

TRNSYS house models for each house design indicate that the low capacity heating (10.5 kW) and cooling (7 KW) systems used displayed sufficient capacity to maintain set point temperatures at all times. For each of the house designs that required cooling, their peak load sensible cooling requirements should be satisfied with a cooling system with 5.3 kW sensible cooling capacity. Although latent cooling loads were not determined in the TRNSYS models, ACCA Manual J load calculations indicate that the 7 kW heat pump system chosen has adequate total cooling capacity to serve all applicable house designs, but with a small margin of safety.

Acknowledgments

The author acknowledges the support of the U.S. Department of Energy’s Building America Program.

References

ACCA. Manual J: Residential Load Calculation 8th Edition. Arlington, VA. Air Conditioning Contractors of America. 2001.

ASHRAE. Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential, ASHRAE Standard 62.2-2007, Atlanta, GA. American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 2007.

CGSB. Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method. CGSB Standard 149.10-M86. Ottawa, Canada. Canadian General Standards Board. 1986

Drössler E. Krapmeier H, CEPHEUS – Living Comfort without Heating (English translation), Vienna, Austria. CEPHEUS Austria Partners, 2001.

Hendron, R., et. al., Building America Research Benchmark Definition. Golden, Colorado. National Renewable Energy Laboratory, 2007.

IBACOS. KAAX-3-33410-11.A.2 Evaluation of Advanced System Research Plan. Pittsburgh, PA. IBACOS. 2006.

IBACOS. KAAX-3-33410-14.B.1 Evaluation of Advanced System Concepts. Pittsburgh,. PA. IBACOS. 2007.

IECC. 2006 International Energy Conservation Code. Country Club Hills, IL. International Code Council. 2006.

Lennox® Engineering Data, 2005.

NCDC. National Climatic Data Center, National Oceanic and Atmospheric Administration Internet site http://lwf.ncdc.noaa.gov/oa/documentlibrary/hcs/hcs.html

NREL. National Renewable Energy Laboratory, 2007. Building America Performance Analysis Resources Internet site http://www.eere.energy.gov/buildings/building_america/pa_resources.html

Passivhaus Institute, Passive House Planning Package 2007 (English translation). Darmstadt, Germany. Passivhaus Institute. 2007.

Thermotech, Thermotech Fiberglass Fixed Windows -Thermal Performance, Internet site www.thermotechfiberglass.com. 2007.