Thermal Enclosure Design Challenges for a Cold Climate Net Zero Energy House

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ABSTRACT

As part of IBACOS' Building America research toward zero energy homes, we conducted detailed research into high performance thermal enclosure systems. This paper examines our thermal enclosure research, including its challenges and solutions, for a cold climate net zero energy house to be built by a production builder.

We focused our research on several key areas—basement slabs, basement foundation walls, and exterior wall, window, and door systems. We evaluated the thermal enclosure designs using five important criteria—energy efficiency, comfort, constructability, cost, and durability. This evaluation included using advanced modeling software to examine different system designs for energy efficiency and comfort. When looking at constructability, cost, and durability, we built full-scale mock-ups and consulted industry-leading manufacturers and homebuilders, allowing us to fully understand the implications behind using certain system designs over others. In particular, we investigated the integration of sub-slab insulation, the detailing necessary for well-insulated basement foundations at grade level and with above-grade wall systems, the installation of thicker levels of insulating sheathing on above-grade walls, and the water management and installation details for windows and doors in thick exterior wall assemblies.

This paper summarizes our research, touching upon the design challenges, the detailed modeling information, the constructability solutions, and the favored thermal enclosure systems that emerged in each research area. The systems selected show that net zero energy production houses can be built durably with existing products and new strategies and that the constructability characteristics of a system rate as highly as its energy efficiency.

Introduction

As part of Building America (BA) research for developing and implementing zero energy houses on a widespread basis, IBACOS is designing a super energy efficient house in the Pittsburgh, Pennsylvania region to be built by a local production homebuilder. 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). The house will use electricity only, with its remaining energy needs offset by electrical generation through a photovoltaic system, making it possible to achieve net zero energy usage on an annual basis. The house design has two floors covering 2,160 ft^2 (201 m^2) of floor area, three bedrooms, and a fully conditioned, partially finished basement.

As a part of this work, IBACOS researched the systems and approaches needed for building a super energy efficient house in a mass production environment. In particular, we conducted research on thermal enclosure systems, extensively studying the key areas—basement slabs, basement foundation walls, exterior walls, windows, and doors. The main design challenges for each thermal enclosure area were to determine what additional thermal performance and durability measures were necessary for systems to achieve energy efficiency goals while promoting quality construction. In tackling this challenge, a detailed evaluation process was used to narrow the number of possible solutions. Feedback from builders, product manufacturers, and other industry stakeholders contributed greatly to this evaluation. Of particular importance for production builders for any solution is a system's cost and constructability, two areas where our homebuilding partner contributed extensive information. We have summarized the design challenges and solutions encountered in four thermal enclosure areas to help those in the residential industry learn from our experience.

Basement Slab

The main design challenges for basement slab construction were to determine the thermal performance benefit of sub-slab insulation (if any), the optimum amount of insulation that should be used if wanted, and the cost and construction implications of such actions.

To understand the thermal performance effect of using insulation under the basement slab of the house design, we ran several TRNSYS (version 16.01) models with different thicknesses of extruded polystyrene (XPS) insulation (Klein et. al. 2007); this modeling helped to determine the annual heating and cooling energy use associated with each system. Each TRNSYS house model contained nine zones representative of key rooms, along with the garage, attic, and a basement zone. All TRNSYS simulations were based on six-minute time steps supplemented with detailed operational schedules to best reflect operating conditions and to understand the room-by-room distribution of loads, interior conditions, and whole-house energy use.

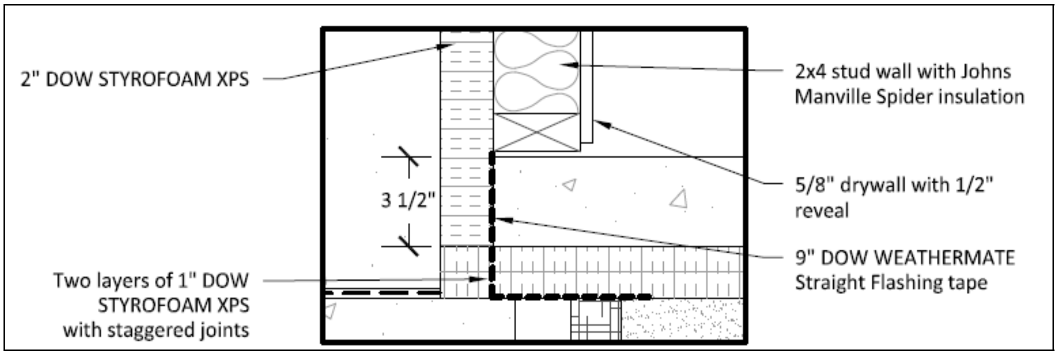
The TRNSYS modeling indicated that using R-10 (RSI 1.8) sub-slab insulation offers 212 kWh/yr heating and cooling energy savings, or a 9.6% reduction, compared to an un-insulated slab. In comparison, R-20 (RSI 3.5) sub-slab insulation offered only 25 kWh/yr more heating and cooling energy savings. For constructability assistance, IBACOS contacted one of its builder partners for its thoughts on insulating under a basement slab, a practice the builder had done before. The builder found the R-10 (RSI 1.8) insulation system easy to integrate with its foundation wall system, and because the system is 2” (51 mm) thinner than an R-20 (RSI 3.5) system, drastic technical changes to the construction of the basement slab were unnecessary. Based on local supplier pricing, the material cost to add an additional 1” (25 mm) of XPS insulation beyond R-10 (RSI 1.8) would be $607; if 2” (51 mm) of XPS insulation were added, the additional cost would be $972. Based on the relatively high cost of each extra inch of insulation versus the amount of energy saved, as well as on constructability considerations, the favored approach for insulating under the slab was to use 2” (51 mm) of XPS insulation to achieve R-10 (RSI 1.8) thermal performance and substantial energy savings.

With R-10 (RSI 1.8) sub-slab insulation recommended for the house design, the vapor resistance of the slab assembly needed to be examined as well. If two 1” (25 mm) sheets of XPS insulation were installed with the joints staggered so no gaps existed through the insulation system, moisture penetration concerns would be less than with an approach consisting of a layer of 2” (51 mm) thick sheets of XPS insulation with gaps present in the joints. In the latter case, it is possible to tape the joints, but doing so would significantly increase the installation cost. The foam board forms a vapor retarder due to the low permeability of the XPS and the continuous insulation coverage offered by the staggered joint approach. This eliminates the need for a separate sheet of polyethylene under the slab, a result confirmed by local code officials.

Another construction consideration included insulating under the column pads that support the structural steel columns used to support structural wood beams. With this situation, a hole in the XPS insulation layers would be needed to facilitate placing and attaching the steel column to the concrete column pad below. Although the gap in thermal performance is regrettable, it is minimized. To make this area airtight, flexible flashing could be placed around the steel column with another piece of flashing attached to it and the XPS layer to seal the gap where the column meets the XPS layer, an air sealing technique for all slab penetrations.

Another area that required detailing was the integration of sub-slab insulation with the insulated foundation walls. To provide continuous thermal performance at the slab edge, the layers of sub-slab insulation need to be placed against the interior layer of the foundation wall XPS insulation (see section below for foundation wall details). But before the sub-slab insulation is installed, flashing would need to be installed at the slab perimeter to form a termite break, as shown in Figure 1.

Figure 1. Construction Detail at the Foundation Wall and Basement Slab Intersection Highlights a Termite Treatment using Flashing Tape at the Slab Edge



Basement Foundation Walls

The design of the basement foundation walls creates challenges that include deciding the optimum amount of insulation to meet energy use savings targets, what specific insulation and wall system components should be employed, and what the design considerations are for integrating the basement walls with the above-grade walls.

In order to assess the heating and cooling energy savings associated with different basement foundation wall systems, TRNSYS was used because of its ability to accurately detail each layer of a foundation wall. A total of ten foundation wall insulation systems were modeled with TRNSYS, including poured concrete, precast concrete, and insulated concrete form systems.

The benefit of insulating the foundation walls beyond code-compliant systems was exemplified by the modeling results, which indicated that a nominal R-26 (RSI 4.6) wall system would save 156 kWh/yr in heating and cooling energy over an R-10 (RSI 1.8) exterior insulated foundation wall system. The modeling showed that the energy performance of a wall system increases as insulation is designed into it, with little difference in energy use between systems once they are within reach of a nominal R-value of R-28 (RSI 4.9).

At that point in the research, the selection process focused more on what system the builder would prefer from constructability and cost standpoints and what would work best for the project's particular design considerations. The builder preferred a poured concrete system for several reasons. The system was more familiar to the builder, it was available at a low construction cost from its trade partner, it was applicable for a site with varying grade levels, and it could be easily integrated with brick and vinyl siding.

Before promoting to the builder the need for below-grade exterior insulation on poured concrete foundation walls, IBACOS conducted TRNSYS and THERM modeling to gain a greater understanding of the thermal performance implications involved with it. Research into using XPS foam board insulation below-grade indicated that fire retardants in the material could potentially pollute the ground, so we had to be sure of the benefits of this product before advocating it. Modeling was based on a foundation wall with and without below-grade exterior R-10 (RSI 1.8) XPS insulation. Without insulation, THERM modeling showed there would be an insignificant temperature drop (0.1°C) on the interior face of the foundation wall at its most vulnerable location (the slab interface). With insulation, TRNSYS modeling indicated that a total of 33 kWh in heating and cooling energy would be saved annually. Since external below-grade foundation insulation can drain water away from a foundation wall, increasing the wall's durability, this benefit along with the amount of energy savings were considered substantial enough to warrant the use of a drainage board with insulating properties.

After researching products and holding discussions with the builder and its structural engineer, a drainage board made of recycled waste products (with no fire retardants) and assumed to have R-3 (RSI 0.5) thermal performance was chosen. The above-grade exterior portions of the foundation wall will have R-5 (RSI 0.9) XPS insulation, a level of insulation that will provide adequate thermal performance while keeping the overall thickness of the foundation wall reasonable. The thickness of the foundation wall will increase from 8" (203 mm) to 14" (356 mm) as it transitions to the below-grade portion to accommodate a ledge for the brick (and the XPS insulation behind it) placed to grade (for both brick and vinyl siding cladding systems). Although XPS board insulation could be placed horizontally on the brick ledge to eliminate a thermal break in the wall, the brick would be sitting directly on the foam board and the risk of brick movement and mortar cracks occurring would be too great, even though the foam board is strong enough for this application. At the footings, a plastic modular product will act as a concrete form and interior and exterior perimeter drainage system.

To provide the required level of thermal performance and to prevent condensation from occurring at the interior surface of the poured concrete foundation wall, one layer of 2" (51 mm) thick XPS insulation board, with no facing and R-10 (RSI 1.8) thermal performance, will be used. Next to the insulation board, an insulated wood framed wall with a pressure-treated plate, a drywall reveal, and R-13 (RSI 2.4) fiberglass insulation within the wall cavities will be used to finish the basement walls and bring their nominal thermal performance up to a minimum of R-26 (RSI 4.8). A portion of the basement will be unfinished. IBACOS chose 3" (76 mm) thick R-19.5 (RSI 3.5) polyisocyanurate board insulation, a special order thickness, to insulate the interior and provide a code-approved thermal barrier. Joints in the board will be taped to prevent moisture accumulation at the concrete foundation wall interior surface.

To assist with constructability research on foundation wall and above-grade wall system integration and detailing at the brick portion of the foundation, we built a mock-up of the front corner of the house, including the porch. The mock-up features a portion of the above-grade wall system, which is represented by a wood framed wall system with insulating sheathing. From this research, we determined that:

- A sill sealer product placed under the sill plate with the ability to flash above and below it at the exterior would provide good airtightness and termite control. The above-grade wall's housewrap layer will be extended over the band joist and taped to the exterior insulation board on the foundation wall to complete the air barrier detailing.

- The use of a through-wall flashing material with a flexible membrane will facilitate drainage through the brick façade (at grade) as shown in Figure 2. A polypropylene net material product will facilitate drainage behind the brick to the weeps.
- The porch foundation, because it extends out from the main foundation wall and will rise above grade, cannot be cost effectively insulated on its outboard side. This leaves a small area of the main foundation wall where the two foundations meet un-insulated on the exterior (but this area will be insulated on the interior).

Figure 2. Foundation Wall Mock-up Highlighting Integration with Above-Grade Wall and Through-wall Flashing and Polypropylene Net Material Product at Brick Detail

Above-Grade Walls

The design challenges for above-grade wall systems mirror those for the general thermal enclosure design but with a greater emphasis on component selection, particularly structural and insulating systems. At the beginning of our research, an extensive number of above-grade wall systems suitable for single-family housing were assessed, including non-typical production housing wall systems like straw bale, concrete sandwich panel, insulated concrete form, and steel frame. These non-typical wall systems were not given further consideration because of low constructability or high cost considerations in a production homebuilding environment. As a result, several production housing-ready wall systems were chosen for further research. To reduce the evaluation effort to a more manageable number of technical solutions, IBACOS conducted parametric modeling using EnergyGauge USA version 2.8.01 (Parker et. al. 1999).

This modeling showed that above-grade wall systems that exhibited a nominal thermal performance of R-40 (RSI 7.0) plus or minus R-10 (RSI 1.8) would help the house design achieve 70% whole-house energy savings. Then, we began a detailed evaluation process to select an above-grade wall system. In the end, there were 17 leading wall systems worth evaluating that represented four main wall system approaches, including staggered 2x8 studs, 2x6 studs with multiple layers of XPS sheathing, double wall construction, and SIPS construction.

TRNSYS was used to conduct detailed modeling to characterize the energy usage associated with each wall system, because the software had a greater ability to accurately reflect the framing configurations of the different wall systems. In addition, TRNSYS provided indoor comfort condition information associated with each wall system, allowing for comparisons according to the Thermal Comfort Performance Index (TCPI) parameter (Rittelmann 2008). Modeling results indicated that the three wall systems with the lowest level of energy use are (estimated annual heating and cooling energy usage is noted):

1. Single stud 2x6 wall, framing at 24" (600 mm) spacing, R-23 (RSI 4.1) blown-in fiberglass insulation in wall cavities, R-20 (RSI 3.5) un-faced XPS insulating sheathing; 1,952 kWh/yr
2. Single stud 2x6 wall, framing at 24" (600 mm) spacing, R-19 (RSI 3.3) blown-in fiberglass insulation in wall cavities, R-6.6 (RSI 1.2) 1” (25 mm) layer spray polyurethane, R-15 (RSI 2.6) un-faced XPS insulating sheathing; 1,983 kWh/yr
3. Staggered stud 2x8 wall (using staggered 2x4s), framing at 24" (600 mm) spacing, R-31 (RSI 5.5) blown-in fiberglass insulation in wall cavities, R-10 (RSI 1.8) un-faced XPS insulating sheathing, vertical strapping at 24"; 2,006 kWh/yr

The three wall systems that were leaders in energy efficiency were also leaders in comfort, since they have TCPI values of 99.0% or greater. The TCPI compares the modeling results against predetermined neutral comfort criteria at each simulation time step. A TCPI value over 98% is considered very good, and a value at or over 99% is considered excellent.

By using TRNSYS modeling results for energy use and obtaining construction cost information from the builder, its trade partners, and product manufacturers, a measure of cost effectiveness was determined for each wall. The measure is the result of the annualized incremental construction cost divided by the annual heating and cooling energy savings for each wall system design. Each wall is compared to a base wall with R-23 (RSI 4.1) nominal performance. Table 1 displays the most cost effective wall systems.

The most cost effective wall, the 2x6 wall with R-28 (RSI 4.9) nominal performance, uses 210 kWh/yr more space conditioning energy than the next most cost effective wall system, a level that would not aid in meeting energy savings targets for net zero energy construction.

Through our work in the Building America program, we were familiar with standard 2x6, double wall, and SIPS wall system construction. But to evaluate the constructability, durability, structural requirements, and performance of a staggered stud 2x8 wall system and any wall with more than 1” of insulating sheathing, IBACOS constructed a house mock-up in its facility based on the staggered stud 2x8 and the 2x6 (single stud) wall systems. The house mock-up allowed us to evaluate the installation protocols for attaching different types of exterior cladding over varying thicknesses of insulating sheathing up to 4” (102mm). The mock-up also facilitated an examination of window placement strategies within “thick” wall systems. IBACOS called on outside industry professionals—builders, trade partners, and product manufacturers—at various stages of construction to provide feedback on critical constructability details.

Table 1. Most Cost Effective Wall Systems

Wall System	Construction	Incremental Construction Cost per Unit of Energy Saved
Single stud 2x6 wall with R-5 insulating sheathing	Studs at 24" spacing, R-23 (RSI 4.1) blown-in fiberglass in cavities, R-5 (RSI 0.9) un-faced XPS insulating sheathing	\$0.15/kWh/yr
Single stud 2x6 wall with R-10 insulating sheathing	Studs at 24" spacing, R-23 (RSI 4.1) blown-in fiberglass in cavities, R-10 (RSI 1.8) un-faced XPS insulating sheathing	\$0.41/kWh/yr
Staggered stud 2x8 wall with R-5 insulating sheathing	Staggered 2x4 studs at 24” spacing, R-31 (RSI 5.5) blown-in fiberglass, R-5 (RSI 0.9) un-faced XPS insulating sheathing	\$0.42/kWh/yr
Double wall with 1" space between rows of framing	Two rows of separately framed 2x4 stud walls with 1" space, R-33 (RSI 5.8) blown-in fiberglass in cavities, R-5 (RSI 0.9) un-faced XPS insulating sheathing	\$0.42/kWh/yr
Double wall with no space between rows of framing	Two rows of separately framed 2x4 stud walls, R-29 (RSI 5.1) blown-in fiberglass, R-5 (RSI 0.9) un-faced XPS insulating sheathing	\$0.42/kWh/yr

Framing research was conducted first using the house mock-up. We reviewed the process of laying out the 2x4 staggered studs at 600 mm (24”) spacing along the interior and exterior of the 2x8 wall system. Doing so added some time to the construction process; however; the 2x8 framing system required only one side of each stud to be aligned with either the interior or exterior surface of the wall. In contrast, the 2x6 wall required both sides of the stud to be aligned with the interior and exterior wall surfaces. As a result, 2x4 studs can be installed slightly faster, offsetting some of the upfront time needed to lay out the 2x8 wall system and making the 2x8 wall system slightly more flexible if it has studs with some imperfections.

IBACOS reviewed the structural implications of using a single top plate with 24” (600 mm) spacing for floor and roof framing members. In this situation, the roof trusses and floors joists have to align with either the interior or exterior row of wall studs. This spacing for floor joists could cause serviceability issues, namely floor squeaks resulting from floor deflection. Furthermore, the use of double top plates could provide greater structural sufficiency and eliminate the need to precisely stack roof trusses and floor joists. In addition, modeling in TRNSYS showed that including the second top plate results in only a 10 kWh/yr energy use penalty due to the extra framing in the wall, an energy loss too insignificant to justify using a single top plate and lose the constructability advantages of using the double top plate approach.

We then used the house mock-up to research the constructability of exterior insulating sheathing systems of at least 2” (51 mm) in thickness. For insulating sheathing attachment, a fastener, which can be outfitted with a button head and is long enough to embed into stud framing at least 1” (25 mm), exhibited good attachment characteristics. The insulating sheathing manufacturer suggested that in situations where multiple layers of insulating sheathing are installed on a wall, there is no need to install the inner layer as rigorously as the outer layer (which would have to meet the attachment requirements posted by the manufacturer), since strapping can be used to help attach it to the assembly. In addition, the insulating sheathing manufacturer suggested using one fastener at common panel joints to secure both panels. On the mock-up, screws varying in length according to insulating sheathing thickness were needed to install furring strips over insulating sheathing 2” (51 mm) or greater in thickness. As the screws became longer, their cost increased dramatically, and it was harder for us to embed them sufficiently into the stud framing since they were prone to drifting, resulting in increased installation time and some poorly attached screws. While installing sheathing tape and flashing membrane over the fasteners and sheathing panel joints respectively, we concluded that this approach was time consuming enough for us consider using housewrap instead for the wall drainage plane.

During our investigation of exterior insulating sheathing products, an insulating sheathing product that is normally used in basements came to light. This product has recessed channels that allow the installer to attach ¾”x3” (19 mm x 76 mm) furring strips with 3¼” (86 mm) nails, resulting in a uniform, flush surface without protrusions as shown in Figure 3. The use of nails instead of screws to fasten furring strips made this sheathing system more cost effective than non-recessed insulating sheathing (of the same thickness). Additional recessed channels for installing furring strips at corners and around window and door openings could be prepared easily in this insulating sheathing product by using a hot knife cutter. Determining the location of the furring strips required careful planning initially, but after the first wall orientation was prepared, the others went more smoothly. The uniform surface offered by the wall system provided continuous support for vinyl siding, a requirement advocated by product manufacturers. Both vinyl and fiber cement cladding systems were successfully installed on this wall system. Furthermore, there were no constructability issues with fastening the vinyl siding at 24” (600 mm) spacing directly to the wall system studs, even though it is commonly installed at 16” (400 mm) spacing. The vinyl siding could also be fastened to the OSB sheathing layer in the wall, if additional structural support is required. We preferred using furring strips cut from OSB panels, because they exhibited better dimensional consistency and were more cost effective than lumber.

IBACOS’ investigation of insulation for the above-grade wall cavities found blown-in fibrous insulation systems to be leading options because of their ability to provide a virtually zero-defect cavity fill and good thermal performance at a cost competitive to other systems. We worked with one manufacturer of this insulation to determine the product’s drying time when installed in the 2x8 wall cavities of our mock-up. A WUFI® analysis of the house’s location indicated that in a worst-case scenario, the insulation needs a maximum of 34 to 64 hours after installation for drying. When the insulation was installed within the 2x8 walls of the house mock-up, we observed that it was not always effectively contained within the staggered stud wall cavity, and a small pocket of the wall, which was behind a framing member for interior wall attachment, did not have full insulation coverage because the framing member obstructed the area. These installation issues are expected to be remedied with additional installation practice.

Figure 3. Furring Strips Installed in Recessed Channels of Insulating Sheathing

Taking into consideration all modeling and constructability research, we completed our evaluation of the wall systems. The evaluation indicated that the 2x6 wall system with R-5 (RSI 0.9) insulating sheathing scored the best, followed by the 2x6 wall system with a layer of closed cell spray polyurethane foam and R-5 (RSI 0.9) insulating sheathing, and followed by the staggered stud 2x8 wall with R-10 (RSI 1.8) insulating sheathing. The two highest scoring walls rose to the top because of the high rating they received in the constructability and construction cost vs. energy savings ratio categories. Of the top three walls, the staggered stud 2x8 wall with R-10 (RSI 1.8) insulating sheathing offers the greatest amount of energy savings for the whole house, saving an additional 317 kWh/yr in energy use than the first wall and 197 kWh/yr more than the second wall. The 2x6 wall systems with 3” (76 mm) and 4” (102 mm) of insulating sheathing were energy efficient and had good cost effectiveness values, but were rated low in the constructability category due to challenges associated with installing such thick panels of sheathing. Since IBACOS’ goal was to build a house to meet the 70% level of whole house energy savings, the staggered stud 2x8 wall with R-10 (RSI 1.8) insulating sheathing was our favored choice because of its high overall evaluation score and the amount of energy savings it offered.

Windows and Exterior Doors

The design challenges faced in windows and exterior doors system selection was related mostly to thermal performance, water management, and installation details. Initial modeling using EnergyGauge USA determined that the optimized window should have a U-value around 0.20 BTU/hr•°F•ft^2 (1.1 W/m²•K). This analysis allowed IBACOS to identify for detailed evaluation the final group of high performance window systems, all of which were characterized by U-values close to the optimal level. How each window faired according to constructability, construction cost, and comfort would set them apart during the selection process.

To determine the energy savings associated with different window systems as accurately as possible, TRNSYS was used since it allowed for detailed window performance characteristics to be incorporated in the modeling. To facilitate modeling accuracy, TRNSYS requires performance maps derived from the WINDOW 5.2 computer program from Lawrence Berkley National Laboratory. The performance maps provide very detailed information on the center glazing performance characteristics of a window. Modeling of each window system was very accurate when combined with detailed thermal performance information on its glazing spacer and framing, which was determined for each size of window. Five high performance window types were modeled in TRNSYS according to the super energy efficient house design. Table 2 provides performance information obtained from the National Fenestration Rating Council, TRNSYS modeling results, and Pittsburgh-based material cost information for each window system.

Table 2. Summary of Window Products in Study

Window Product	Description	U-Value*	SHGC* and VT*	Space Energy Usage**	TCPI Value	Material Cost
A	Double-glazed with argon and krypton gas fill, low emissivity coatings, vinyl frame	0.22 BTU/hr•°F•ft^2 (1.2 W/m²•K)	0.33; 0.47	1,946 kWh/yr	98.8	\$21/ft^2 (\$226/m^2)
B	Triple-glazed with suspended film, krypton and air gas fill, low emissivity coatings, fiberglass frame	0.19 BTU/hr•°F•ft^2 (1.1 W/m²•K)	0.22; 0.40	1,816 kWh/yr	99.7	\$44/ft^2 (\$474/m^2)
C	Triple-glazed, krypton gas fill, two low emissivity coatings, fiberglass-reinforced vinyl frame	0.17 BTU/hr•°F•ft^2 (1.0 W/m²•K)	0.16; 0.36	1,832 kWh/yr	99.7	\$24/ft^2 (\$258/m^2)
D	Triple-glazed, krypton-enhanced argon gas fill, vinyl frame	0.21 BTU/hr•°F•ft^2 (1.2 W/m²•K)	0.47; 0.40	2,008 kWh/yr	96.5	\$36/ft^2 (\$388/m^2)
E	Double-glazed, krypton gas fill, two low emissivity coatings, vinyl frame	0.25 BTU/hr•°F•ft^2 (1.4 W/m²•K)	0.27; 0.44	2,006 kWh/yr	99.0	\$20/ft^2 (\$215/m^2)
* Total window unit value						
** Annual heating and cooling energy usage associated with Window product						

Overall, Window B provided the lowest heating and cooling energy usage, and Window C provided the best comfort, offering equivalent comfort while using only16 kWh/yr more in space conditioning energy. With respect to product cost, Window B was the most expensive, while Window C had one of the lower material costs. With 306 square feet (28.4 m^2) of window area in the lab house, the cost difference between procuring Window B over Window C would be significant for the builder at $6,120. But Window C has a visual transmittance value of 0.36, which is quite low, and when a sample of the unit was reviewed, the glazing for the window was noticeably darker than other windows. This situation gave us the impetus to explore the potential impacts of installing a window with a low visual transmittance (VT) value on homeowners in a cold climate location. Feedback from industry experts indicated that for a window with a VT rating below 0.40, and particularly in colder, cloudier climates (e.g. Pittsburgh), the reduced visibility and reduction of natural sunlight in the home may be very unappealing to occupants. As a result, in spite of Window C's leading performance characteristics, we felt that consumers of production houses would not be satisfied with the appearance of its glazing.

Windows A and E are in the next highest tier of windows in terms of comfort and energy use performance and both have reasonable VT values, material costs, and comfort characteristics. Window A has a lower overall TCPI value than Window E, since modeling revealed a greater number of instances of overheating occurring when it was installed in a south-facing room. Using Window E over Window B would result in190 kWh/yr more space conditioning energy use. Although a window with a low U-value is important in a cold climate, if it has a high SHGC as exhibited by Window D, TRNSYS modeling showed that overheating will result particularly during the shoulder seasons, lowering overall comfort for the house design. Since Window D also had the highest space conditioning energy usage, it was not favored.

Of the final group of windows, Window E scored high for constructability due to its continuous nailing fin and integral J-channel, installation features important for production homebuilding that none of the other high performance windows matched. The other windows studied are marketed as a replacement product only, with some offering new construction options, such as snap-on nailing fins (which have drawbacks) that allow them to be installed in new houses. This high level of constructability, a critical attribute for a homebuilder, resulted in Window E being considered as the most suitable window for the project in spite of other windows offering greater energy savings.

A consideration for all window systems was their positioning within wall systems that measured up to 10" (254 mm) wide. IBACOS observed that installing a recessed window within a 2x6 or 2x8 wall system with 2" (51 mm) or more of exterior insulating sheathing required more detailing work than if the window was in an exterior location. More work is required because the insulating sheathing has to be carefully installed at the recessed (inset) portion of the wall over additional rough framing. In addition, the window sill has to be properly sloped for drainage, and extensive flashing is necessary to make sure the recess is watertight, especially at outside corners. We also observed that with thick insulating sheathing, windows need to be adequately attached to framing members beneath the insulating sheathing layers, window flanges are necessary for installation, attachments (eg furring strips) for siding and brick work and trim work are needed around windows, the window rough opening height needs to be increased to accommodate the use of OSB or plywood to act as support for a cantilevered window sill, and water management/flashing installation details are similar to any window applied over exterior insulation sheathing.

Exterior door research determined that the most appropriate type of door to use for the house design would be a polyurethane insulated fiberglass door. This door balances high insulation and durability, while maintaining a traditional wood appearance. Its typical thermal performance ranges from R-4 (RSI 0.7) to R-8 (RSI 1.4). Although not favored for the project, energy efficient doors with glazing are in the marketplace. For example, doors with ¼ unit glazing options are available with U-factors as low as 0.18 BTU/hr•°F•ft2 (1.1 W/m²•K). The house mock-up was used to examine the most appropriate way to install an exterior door with a 9" wide threshold in an exterior wall over 10" wide without affecting wall durability. The best approach for installing the door was to position it toward the exterior and install a modified plastic flashing pan underneath the threshold to manage water penetration and drainage. The door threshold is wide enough where minimal changes to the interior drywall and trim work will allow the door to operate properly to facilitate adequate clearances for the door latch, door handle, and door jamb (without reducing the overall thermal performance of the wall system).

Summary

The thermal enclosure design challenges associated with building a cold climate net zero energy house in a production housing environment were overcome by conducting a comprehensive evaluation of each system area to aid in system selection. The evaluation focused on determining a system's energy use and comfort implications through very accurate modeling, by obtaining local costing information, and by thoroughly assessing constructability and durability. The systems that were selected showed that net zero energy production houses can be built durably with existing products and new strategies and that the constructability characteristics of a system can rate as highly as its energy efficiency.

For the house design, R-10 sub-slab insulation was determined to be the optimum choice. IBACOS favored a poured concrete foundation wall with exterior and interior insulation systems, as well as finished and unfinished basement versions, with its nominal thermal performance ranging from R-22.5 (RSI 4.0) to R-28 (RSI 4.9). For above-grade walls, a staggered stud 2x8 wall with R-10 (RSI 1.8) insulating sheathing and blown-in fiberglass cavity wall insulation was chosen because it scored highly for energy efficiency, cost effectiveness, and constructability, although it did not score the highest in any of these criteria. A window with a U-value of 0.25 BTU/hr•°F•ft^2 (1.4 W/m²•K) and SHGC of 0.27 was selected, because it was the one most ready for production housing out of the high performance windows studied while still being acceptable to homeowners. A polyurethane insulated fiberglass door that balances high insulation and durability while maintaining a traditional wood appearance was selected for the design.

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