SESSION EE 6-4

Evaluating R-40 Above Grade Walls for a Production Built Zero Energy House

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As part of Building America research for developing and implementing zero energy houses on a widespread basis, IBACOS conducted research on what constitutes a high performance exterior wall assembly for this level of energy-efficient construction.

Our research focused on exterior walls in a cold climate zone and considered their constructability, installation, cost, durability, and thermal performance. Our research included an examination of wall design considerations including: drying potential, thermal bridging, flashing details, and structural details. We used a variety of modeling software to obtain information, including TRNSYS, WUFI®, EnergyGauge USA, and THERM. We built some of the wall systems in a laboratory setting to better evaluate their constructability.

Here, we look at the best wall assemblies that emerged from our research and why they were chosen. This paper also covers the evaluation process used in the research, design challenges encountered, the construction details researched, the detailed costing information developed. The goal is to offer lessons learned for builders and designers who strive to achieve exceptional energy efficiency in houses.

Keywords: super-insulated wall assemblies, energy efficiency, cold climate zone, energy modeling, constructability, cost, thermal performance

Introduction

As part of Building America (BA) research for developing and implementing zero energy houses on a widespread basis, IBACOS is building a lab house in the Pittsburgh, PA region. The house is being designed to a level of energy efficiency that will result in 70% whole house energy savings according to the BA Research Benchmark Definition (Hendron 2008). The house will use only electricity, with its remaining energy needs offset by electrical generation through a photovoltaic system. As part of this work, the systems and approaches needed for building a super-energy efficient house in a mass production environment were researched. In particular, research on above grade wall systems was undertaken and resulted in an exhaustive examination of available systems and a comprehensive look at a variety of related technical issues.

Based on parametric modeling using EnergyGauge USA (version 2.8.01), we determined that a wall system within RSI 7.1$(m^2 \cdot K)/W$ [R-40 $(hr \cdot ft^2 \cdot °F/ Btu)$] nominal thermal performance would help the house design meet its overall energy efficiency goal. As a result, our research has focused on wall assemblies with that characteristic. We have summarized the findings of our research in the paper that follows to help novices, as well as more seasoned researchers, to learn from our experience.

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Evaluation of Wall Systems

In order to select the best above grade wall systems, each system or technical solution was evaluated according to criteria developed by IBACOS that provide a detailed and ranked comparison. This evaluation process ensured that the best systems were selected and no technical solutions were overlooked. The IBACOS evaluation criteria are considered either “Must Meet” or “Should Meet” (Table 1).

Table 1: Evaluation Criteria for Thermal Enclosure Systems

Technical Solutions“Must Meet” Criteria	“Should Meet” Criteria
• Minimum Energy Performance Specification • Code Acceptance • Market Availability of the Technical Solution(s) • Constructability • Trade skill set change • Functionality • Architectural Flexibility • Scalability Potential • Cost vs. Energy Savings Ratio • Durability: Moisture Management	• Homeowner Impact • Systems Integration and Elimination Potential • Environmental Responsibility • Cycle Time • Durability and Maintenance • Comfort

The evaluation process is divided into two stages—Initial Gate and Detailed Scoring. During the Initial Gate stage, the “Must Meet” criteria are evaluated using a “go/no go” decision. If a technical option is given a “no go” for any of the “Must Meet” criterion, then it does not go to the second stage of the evaluation. Any technical solutions that receive “go’s” for all “Must Meet” criteria advance to the more detailed second stage of the evaluation process.

During the Detailed Scoring stage, a technical solution is evaluated according to “Must Meet” criteria and “Should Meet” criteria. The technical solution is given a ranking depending on how well it meets the criteria requirements. Also in this stage, each criterion is assigned a weight value based on its importance. The rank of each technical solution is multiplied by this weight, resulting in a weighted ranking. The weighted rankings are totaled for each technical solution with the highest total score becoming the first system choice.

Scope of Wall Systems Research

At the beginning of our research, all above grade wall systems for single family housing went through the Initial Gate process, including non-typical production housing wall systems like straw bale, concrete sandwich panel, insulated concrete form, and steel frame. Many wall systems were eligible to advance to the more Detailed Scoring stage of the evaluation process. To further reduce the evaluation effort to a more manageable number of technical solutions, parameters for nominal thermal performance were established. Parametric modeling using EnergyGauge USA (version 2.8.01) showed that above grade wall systems that exhibited a nominal thermal performance of RSI 7.1(m^2•K)/W [R-40 (hr•ft^2•°F/ Btu)], plus or minus RSI 1.8(m^2•K)/W [R-10 (hr•ft^2•°F/ Btu)], would help achieve a 70% whole house energy savings house design. As a result, above grade wall systems meeting this range of thermal performance were chosen for further evaluation.

All of the modeling work was based on the same two-story house design that that is located in Pittsburgh, PA. The house has 201 m^2 (2160 ft^2) of floor area, three bedrooms, and a full conditioned basement. The house design features a thermal enclosure that promotes the energy efficiency level IBACOS is trying to achieve, including a RSI 1.8(m^2•K)/W [R-10 (hr•ft^2•°F/ Btu)] sub-slab insulation system, a RSI 5.8(m^2•K)/W [R-32 (hr•ft^2•°F/ Btu)] nominal foundation wall system, triple-glazed windows, RSI 10.8(m^2•K)/W [R-60 (hr•ft^2•°F/ Btu)] attic insulation, and a building airtightness level of 0.6 air changes at 50 Pa.

To control thermal bridging in wood framed wall systems, it was necessary to consider the use of exterior insulating sheathing and decide which insulating sheathing material would perform the best. In the end, extruded polystyrene (XPS) insulating sheathing was favored as the main insulating sheathing material, rather than expanded polystyrene or polyisocyanurate-based insulation products. This material was chosen because it offers a high thermal performance for its cost, its ability to act as a drainage plane, its positive performance as an insulating sheathing for a variety of claddings, and its favorable cold climate water vapor permeability characteristics for un-faced versions. The latter point was proven through WUFI® analysis, which showed that an un-faced extruded polystyrene insulating sheathing with a permeability of 46 ng/Pa•m^{2}s [0.8 ft^{2}h (in Hg)/grain] allows wet wall designs to dry quicker than insulating sheathings with a facing permeability of 17 ng/Pa•m^{2}s [0.3 ft^{2}h (in Hg)/grain].

Since most wall systems in a cold climate feature vinyl or fiber cement siding systems, it was necessary to consider their attachment requirements over wood framed walls with varying thicknesses of exterior insulating sheathing. Based on research with siding manufacturers on their fastening requirements, we found that exterior strapping is necessary for most walls with more than 25mm (1”) of insulating sheathing.

After focusing our research, we chose 17 wall systems for additional research, including unfamiliar or seldom-used wood framed wall systems like the staggered stud 2x8, the double wall (with two rows of 2x4 studs), any wall with more than 25 mm (1”) of exterior insulating sheathing, SIPS (Structural Insulated Panel System) construction, and a base wall system (representing the walls used in one of our local Building America Program prototype houses). Table 2 summarizes the characteristics of the wall systems we evaluated.

Table 2: Summary of Wall Systems in Study

Name of Wall System	Nominal Thermal Performance	System Construction Characteristics
Base wall	RSI 4.1 [(m^2•K)/W] R-23 (hr•ft^2•°F/ Btu)	2x6 wall (single stud), 19% FF[1], RSI 4.1 (R-23) blown-in fiberglass within cavities, OSB sheathing
Staggered stud 2x8 wall with R-5 insulating	RSI 6.3 [(m^2•K)/W] R-36 (hr•ft^2•°F/ Btu)	Staggered stud 2x8 wall (using staggered 2x4s)[2], RSI 5.5 (R-31) blown in fiberglass

sheathing		within cavities, RSI 0.9 (R-5) un-faced XPS insulating sheathing
Staggered stud 2x8 wall with R-10 insulating sheathing	RSI 7.2 [(m^{2}•K)/W] R-41 (hr•ft^{2}•°F/ Btu)	Staggered stud 2x8 wall (using staggered 2x4s), RSI 5.5 (R-31) blown in fiberglass within cavities, RSI 1.8 (R-10) un-faced XPS insulating sheathing, vertical strapping[3]
Staggered stud 2x8 wall with layer of closed cell spray polyurethane foam and R-10 insulating sheathing	RSI 6.9 [(m^{2}•K)/W] R-39 (hr•ft^{2}•°F/ Btu)	Staggered stud 2x8 wall (using staggered 2x4s), RSI 5.5 (R-27) blown-in fiberglass and 25mm (1") RSI 1.2 (R-6.6) closed cell spray polyurethane within cavities, RSI 0.9 (R-5) un-faced XPS insulating sheathing, vertical strapping
Double wall with R-5 insulating sheathing	RSI 6.0 [(m^{2}•K)/W] R-34 (hr•ft^{2}•°F/ Btu)	Double wall (using two rows of staggered 2x4s)[2], 178mm (7") RSI 5.1 (R-29) blown-in fiberglass within cavities, RSI 0.9 (R-5) un-faced XPS insulating sheathing, separately framed walls with 2x4 top and bottom plates
Double wall with 1” spacing and R-5 insulating sheathing	RSI 6.7 [(m^{2}•K)/W] R-38 (hr•ft^{2}•°F/ Btu)	Double wall (using two rows of staggered 2x4s) with 25mm (1") space, 203mm (8") RSI 5.8 (R-33) blown-in fiberglass within cavities, RSI 0.9 (R-5) un-faced XPS insulating sheathing, separately framed walls with 2x4 top and bottom plates
2x6 wall with closed cell spray polyurethane foam and R-5 insulating sheathing	RSI 6.7 [(m^{2}•K)/W] R-38 (hr•ft^{2}•°F/ Btu)	2x6 wall (single stud)[2], 16% FF, 127mm (5")[4] RSI 5.8 (R-33) closed cell spray polyurethane within cavities, RSI 0.9 (R-5) un-faced XPS insulating sheathing
2x6 wall with closed cell spray polyurethane foam and R-10 insulating sheathing	RSI 7.6 [(m^{2}•K)/W] R-43 (hr•ft^{2}•°F/ Btu)	2x6 wall (single stud), 16% FF, 127mm (5") RSI 5.8 (R-33) closed cell spray polyurethane within cavities, RSI 1.8 (R-10) un-faced XPS insulating sheathing, vertical strapping
Staggered stud 2x6 wall with closed cell spray polyurethane foam and R-10 insulating sheathing	RSI 7.6 [(m^{2}•K)/W] R-43 (hr•ft^{2}•°F/ Btu)	Staggered stud 2x6 wall (using staggered 2x4s)[2], 127mm (5") RSI 5.8 (R-33) spray polyurethane within cavities, RSI 0.9 (R-5) un-faced XPS insulating sheathing
2x6 wall with layer of closed cell spray polyurethane foam and R-5 insulating sheathing	RSI 5.5 [(m^{2}•K)/W] R-31 (hr•ft^{2}•°F/ Btu)	2x6 wall (single stud), 16% FF, 114mm (4½") RSI 3.3 (R-19) blown-in fiberglass and 25mm (1") RSI 1.2 (R-6.6) closed cell spray polyurethane within cavities, RSI 0.9 (R-5) un-faced XPS insulating sheathing, vertical strapping
2x6 wall with layer of closed cell spray	RSI 6.3 [(m^{2}•K)/W] R-36 (hr•ft^{2}•°F/ Btu)	2x6 wall (single stud), 16% FF, (4½") RSI 3.3 (R-19) blown-in fiberglass and 25mm

polyurethane foam and R-10 insulating sheathing		(1") RSI 1.2 (R-6.6) closed cell spray polyurethane within cavities, RSI 1.8 (R-10) un-faced XPS insulating sheathing, vertical strapping
2x6 wall with layer of closed cell spray polyurethane foam and R-15 insulating sheathing	RSI 7.2 [(m^2•K)/W] R-41 (hr•ft^2•°F/ Btu)	2x6 wall (single stud), 16% FF, (4½") RSI 3.3 (R-19) blown-in fiberglass and 25mm (1") RSI 1.2 (R-6.6) closed cell spray polyurethane within cavities, RSI 2.6 (R-15) un-faced XPS insulating sheathing, vertical strapping
2x6 wall with R-5 insulating sheathing	RSI 4.9 [(m^2•K)/W] R-28 (hr•ft^2•°F/ Btu)	2x6 wall (single stud), 16% FF, RSI 4.1 (R-23) blown in fiberglass within cavities, RSI 0.9 (R-5) un-faced XPS insulating sheathing
2x6 wall with R-10 insulating sheathing	RSI 5.8 [(m^2•K)/W] R-33 (hr•ft^2•°F/ Btu)	2x6 wall (single stud), 16% FF, RSI 4.1 (R-23) blown-in fiberglass within cavities, RSI 1.8 (R-10) un-faced XPS insulating sheathing, vertical strapping
2x6 wall with R-15 insulating sheathing	RSI 6.7 [(m^2•K)/W] R-38 (hr•ft^2•°F/ Btu)	2x6 wall (single stud), 16% FF, RSI 4.1 (R-23) blown-in fiberglass within cavities, RSI 2.6 (R-15) un-faced XPS insulating sheathing, vertical strapping
2x6 wall with R-20 insulating sheathing	RSI 7.6 [(m^2•K)/W] R-43 (hr•ft^2•°F/ Btu)	2x6 wall (single stud), 16% FF, RSI 4.1 (R-23) blown-in fiberglass within cavities, RSI 3.5 (R-20) un-faced XPS insulating sheathing, vertical strapping
SIPS 8¼" thick	RSI 5.6 [(m^2•K)/W] R-32 (hr•ft^2•°F/ Btu)	SIPS 210mm (8¼") thick (two 11mm (7/16") OSB skins with 187mm (7-3/8") EPS Core) RSI 5.6 (R-32)
SIPS 10¼" thick	RSI 7.6 [(m^2•K)/W] R-43 (hr•ft^2•°F/ Btu)	SIPS 260mm (10¼") thick (two 11mm (7/16") OSB skins with 244mm (9-5/8") EPS Core) RSI 7.6 (R-43)

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

A summary follows of the research conducted for all of "Must Meet" criteria as part of the second stage of the evaluation process. We have included details on our research findings related to comfort as well because of the importance of this "Should Meet" criterion.

Minimum Energy Performance Specification, Code Acceptance, and Market Availability of the Technical Solution(s)

As noted earlier, a parametric analysis determined that the thermal performance range for acceptable above grade walls was nominally RSI 5.3 to 8.8 (m^2•K)/W [R-30 to R-50 (hr•ft^2•°F/

Btu]. At this range, there are no issues associated with exterior walls meeting the minimum insulation specifications for any climate zone noted in the International Energy Conservation Code 2009 Table 402.1.1 (IECC 2009).

The market availability of a wall system is based largely on whether or not it has mass market availability or if it is assumed to be a niche market product; mass market availability is more favorable. Mass market products allow for competitive bidding and many regional suppliers carry equivalent versions of the product. Niche market products have limited market penetration and competitive bidding is unlikely, as only one supplier in a region may carry the product. Since each of the wood framed wall systems could be constructed on-site or in a factory without difficulty, they are considered as having mass market availability. Although SIPS assemblies are becoming more prevalent in the marketplace, in regions like Pittsburgh, they are still considered a niche product and came in less favorably for this criterion.

Constructability, Trade Skill Set Change, and Functionality

The evaluation criteria for constructability, trade skill set change, and functionality are closely related. For a wall system to achieve the highest score for constructability, its construction details must be readily available, and it must require fewer parts, steps, and trades than a base wall system. Untrained or reasonably trained skilled labor must be able to construct or install the wall system with a minimal amount of training for it to score well in the trade skill criteria. For a wall system to score well for functionality, it must provide the same level (or better) of performance/utility as the wall it is replacing without additional resources.

Of the 17 wall systems that were chosen for additional research, the majority of them are wood framing strategies that are either staggered stud 2x8 walls or 2x6 single stud wall framing. Referring to the heating and cooling annual energy usage associated with each wall system (as shown in the cost vs energy savings ratio section) and after receiving industry feedback, it was decided that the staggered stud 2x8 wall with R-10 insulating sheathing and the 2x6 wall with R-15 insulating sheathing showed promise for meeting energy efficiency goals. As a result, we decided to study them first from a constructability, trade skill set change, and functionality viewpoint. This research would be transferrable to other 2x8 and 2x6 wall systems studied.

In order to better understand the benefits and drawbacks of actually constructing these two wall assemblies, IBACOS designed and built a 1½ story mock-up structure that is constructed on one side using the staggered stud 2x8 framing and the other side with 2x6 single stud framing as shown in Figures 1 and 2. The mock-up allowed us to evaluate framing approaches and requirements, particularly for studs, top plates, and wall bracing. In addition, we were able to research the issues associated with the attachment of varying thicknesses of exterior insulating sheathings, the fastening of cladding over the sheathing, the installation of windows within the wall assembly, and the water management strategies for the wall system. Furthermore, we used the mock-up as a focal point on above grade wall system research with industry stakeholders, allowing product manufacturers, builders, and other industry experts to provide feedback on our technical designs and approaches. Due to financial considerations, construction of a mock-up to evaluate double wall systems and SIPS for constructability, trade skill set change and functionality was not possible. For these systems we would rely on our experience and feedback from builders and other industry stakeholders to complete the evaluation.

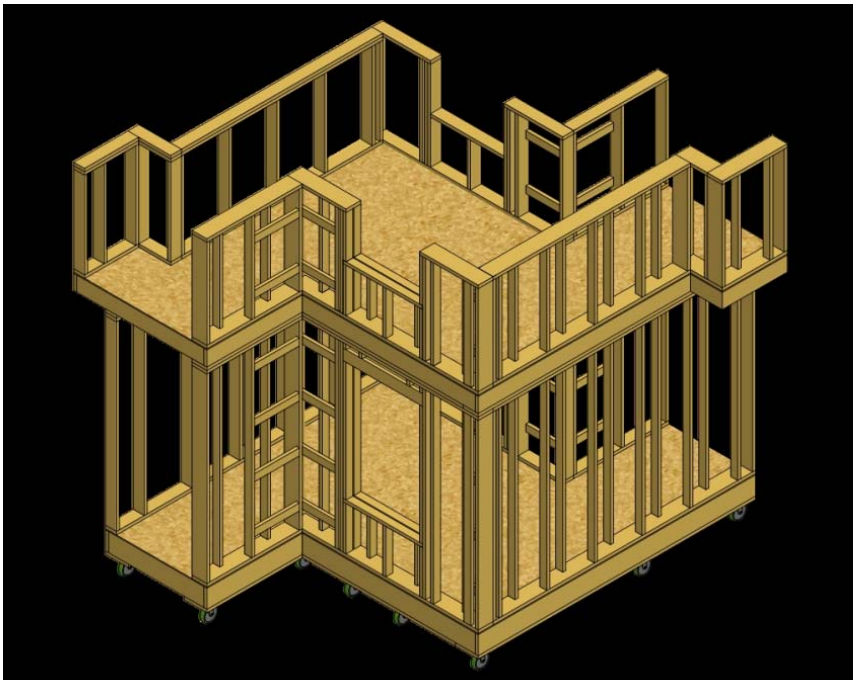

Figure 1. Schematic showing wall and floor structure for the wall mock-up. The staggered stud 2x8 wall system is in the foreground.

Figure 2. Wall mock-up constructed and sheathed. The 2x6 wall system is in the foreground.

Initially, framing research focused on the process of laying out the 2x4 staggered studs at 600 mm (24”) o.c. along the interior and exterior of the 2x8 wall system. Doing so added some time to the construction process; however; the 2x8 framing system requires only one side of each stud to be aligned with either the interior or exterior surface of the wall. In contrast, a 2x6 wall requires both sides of the stud to be aligned with both the interior and exterior wall surfaces. This allowed for 2x4 studs to be installed slightly faster, which offset some of the upfront time needed to lay out the 2x8 wall system, thereby making it slightly more flexible if it has studs with some imperfections. When taking into consideration the transportation of pre-manufactured wall panels or onsite handling and installation of wall sections, the size and weight of the framed assemblies may have an impact. Research results showed that the 2x8 wall system weighted approximately 20% more than the 2x6 wall system, putting it at a slight disadvantage because it may require additional trucks for transportation and onsite labor to handle and install the wall sections.

IBACOS had a structural engineer review detailed drawings of the 2x8 wall system to better understand the structural implications of using a single top plate, 600 mm (24”) o.c. spacing for floor and roof framing and stacking of framing members throughout the building. We determined that when using a single top plate, the roof trusses and floors joists would have to align with either all of the interior or all of the exterior wall studs. While roof trusses are commonly used at 600 mm (24”) spacing, neither the engineer nor our builder partners recommend using floor joists with that spacing for serviceability reasons, namely floor squeaks resulting from floor deflection. Instead, they recommend placing joists at a maximum spacing of 490 mm (19.2”) o.c. and using 19mm (¾”) thick sub-floor sheathing, making stack framing difficult. Furthermore, the use of double top plates would provide greater structural sufficiency and eliminate several requirements associated with the use of a single top plate. These requirements include determining which row (interior or exterior) of studs should be considered as load bearing, stacking the roof trusses and floor joists with either the interior or exterior bearing studs, aligning the joints in the top plate directly over a stud, using metal connectors at plate joints and corners, and determining where headers would need to be placed within the wall profile. In addition, modeling in TRNSYS showed that including the second top plate results in only a 10 kWh/year annual energy use penalty due to the extra framing material in the wall, an energy loss too insignificant to justify its elimination and lose the constructability advantages of using the two top plate approach.

Research on wall bracing convinced us that wood structural sheathing (either OSB or plywood) should be used as the primary strategy. Industry experience has shown that let-in bracing, and particularly metal let-in bracing, does not provide the same level of performance as wood sheathing. The let-in bracing is often used in conjunction with either a mechanical hold-down or the interior drywall to provide the structural bracing requirements. However, in order to achieve the designed lateral resistance, both the let-in bracing and drywall require specific fastening schedules, which most trades do not understand or implement correctly. Consequently, for ease of constructability, wood structural sheathing was chosen as the wall bracing strategy.

The use of insulating sheathing in greater thicknesses than typically done in production housing involved substantial research. We worked with insulating sheathing and fastener manufacturers to determine the best practices for installing varying thicknesses of insulating sheathing over wood framing. We identified five different fasteners that could be used for attaching the insulating sheathing directly to the wall framing, and they ranged in price from $.17 each to over

$.75 each. The challenge in selecting the appropriate fasteners was to find one that provided adequate length to embed at least 25mm (1”) into a solid wood base, per siding manufacturer requirements, while still having a narrow diameter that would allow for easy installation. After experimenting on the mock-up, our preferred fastener was a screw with a plastic plate designed for installation on exterior insulation and finish systems (EIFS). Following suggestions by an insulating sheathing manufacturer, in cases where the sheathing needed to be installed in multiple layers, the inner layer could be temporarily held in place while only the outermost layer would require the full fastening schedule. Additionally, at panel joints, a common fastener could be used to secure both panels directly to the stud. Doing so would help eliminate the issues of installing fasteners at angles along the edge of each foam sheet and trying to hit the 38 mm (1½”) wide stud face beneath.

A summary of the constructability advantages and disadvantages of different thicknesses of insulating sheathing is highlighted in Table 3. The main disadvantage to using insulating sheathing that is greater than 25 mm (1”) thick is that 19mm (¾”) thick, vertically–installed, wood-based wall strapping is required for the installation of siding (either vinyl or fiber cement siding), which is the most prevalent façade finish in single family housing. The attachment of strapping adds another layer of work that builders could find onerous.

Table 3: Summary of Constructability Advantages and Disadvantages of Different Thicknesses of Insulating Sheathing

Thickness of Insulating Sheathing	Advantages	Disadvantages
25 mm (1”)	• Does not require the use of exterior strapping for attachment of cladding • Most siding types can be installed directly over sheathing • Less potential for visual irregularities with cladding • Single layer can be easily attached at panel plant	• No overlapping seams in weather barrier, relies more heavily on integrity of taped joints or housewrap • Need more fasteners to attach sheathing since strapping is not used
Greater than 25 mm (1”)	• Can overlap seams in successive layers to decrease potential of direct water intrusion at panel joints • Fastening of strapping reduces amount of fasteners needed to attach insulating sheathing to wood framing	• Requires the use of strapping for attachment of exterior trim and cladding • Costs more because of strapping, longer fasteners, increased labor, and more sheathing • Creates additional window framing requirements • As sheathing thickness increases the level of difficulty for panel attachment to framing increases • Greater potential for visual

		irregularities in cladding

Regardless of the thickness of the insulating sheathing, all sheathing joints and fastener penetrations require flashing membrane and sheathing tape (respectively) to provide a good drainage plane along with sheathing. But during mock-up research, the amount of effort observed to install the tape was substantial enough for us to strongly consider using housewrap instead for the drainage plane.

We worked with several window manufacturers and builders to determine best practices for installing windows into a wall assembly that has at least 50 mm (2”) of exterior insulting sheathing. Each window manufacturer recommended mounting their window either centrally or fully recessed toward the interior of the wall assembly. The purpose is to keep the window as far away from the outdoor elements or as close to the indoor conditioned environment as possible. Each builder recommended mounting the windows on the exterior side of the foam sheathing to simplify the installation and flashing details. Recessing the window in the assembly can be done with either a replacement-type window without a nailing flange or a new construction window with a flange. For the replacement window, no additional framing requirements are typically needed. For the flanged window, the rough opening size would need to be increased in order to place a wood buck to facilitate the attachment of the nailing flange. With the window recessed in the wall, a “shelf” is created at the sill on the exterior side of the window. This “shelf” needs to be sloped to prevent water from collecting on its horizontal surface. In the exterior-mounted application, a new construction window with a nailing flange could be installed with the flange directly against the foam sheathing and secured back through the layers of insulating sheathing to the wall framing with fasteners penetrating at least 38mm (1½”) into a solid wood base. Depending on the amount of insulated sheathing on the exterior, this could require the use of screws up to 150 mm (6”) in length. To make sure a window does not bear mostly on the insulating sheathing, appropriate support at the sill and a wood base for fastening along the jambs is necessary. Our research revealed that the window rough opening should be increased by 19mm to 25mm (¾” to 1”) on each side and trimmed out with a wood sheathing material at least 19mm (¾”) thick. The sheathing should extend across the entire depth of the rough opening.

Flashing requirements for a recessed window were more onerous than if the window was placed on the exterior. This approach required more work because the window sill had to slope properly for drainage and more extensive flashing was necessary to make sure the recess was watertight, especially at the outside corners. The flashing for either window installation approach could be integrated with a housewrap drainage plane.

In summary, the staggered stud 2x8 wall with R-10 insulating sheathing and the 2x6 wall with R-15 insulating sheathing were constructible wall systems. But, they require further design details than a base wall system. In general, wall systems with more than 25 mm (1”) of insulating sheathing require wall strapping for cladding attachment; as a result, they have a lower constructability score. Similarly for the trade skill set change and functionality evaluation criteria, wall systems with 25 mm (1”) of insulating sheathing were favored over systems with thicker amounts of insulating sheathing.

Architectural Flexibility, Scalability Potential

For an above grade wall system to have a high degree of architectural flexibility it must work in a variety of housing styles and layouts within a builder's community. For a system to have a high scalability potential, it must be scalable for mass implementation, with wall systems that could be built on a national scale scoring higher than those that are climate zone specific.

Of the wall systems under examination, 2x6 wood framed wall construction is the most familiar to homebuilders. But many of the 2x6 walls we studied have the greatest thickness of insulating sheathing, up to 102 mm (4") thick. Insulating sheathing arrangements more than 25 mm (1") thick lead to non-typical cladding fastening details that require strapping and extremely long fasteners (either nails or screws) to help install the cladding (whether vinyl or fiber cement siding). In thick wall assemblies, the position of the window becomes an important decision. Exterior positioning of windows results in thick window bays on the interior, which could be considered an architectural feature or wasted space. In contrast, interior positioning of windows requires greater window flashing resources and detailing.

For these evaluation criteria, a 2x6 wall with 25mm (1") of insulating sheathing was regarded as having the greatest architectural flexibility and scalability potential because it is the closest to industry standard practice (represented in this research by the base wall system). As the wall system's amount of insulating sheathing became thicker, its evaluation rating for these criteria became less favorable.

SIPS construction is generally regarded as having less architectural flexibility than wood framing because of the structural considerations associated with them, such as panel attachment requirements and minimum panel widths. For example, wood framed wall panels between a closely aligned pair of windows can be built narrower than SIPS in order to accommodate an architectural look or interior layout. For widespread implementation of SIPS, most builders or their subcontractors would have to embark on an extensive training program to provide the labor necessary for installation work. In addition, with the potential for engineering, production, and shipping efforts to take a significant amount of time, the start-to-finish implementation time for SIPS is likely longer than a wood framed wall system, thereby downgrading its scalability score.

Durability: Climate Appropriate Moisture Management

Each wall system must provide appropriate moisture management for a cold climate location to fulfill this evaluation criterion. In general, the design of each wall system was assumed to include best practice water management techniques to prevent bulk water entry and capillary action, as well as an air barrier system at the interior drywall surface to hinder moisture movement into walls by air leakage, unless this detailing was impossible with the design (best practice water management details are standard for BA projects). Therefore, we focused on durability shortcomings inherent to the wall system's design through the use of several modeling tools.

IBACOS used WUFI®2D modeling to study moisture retention and movement within the different wall systems over the course of a year. Painted drywall was used as the vapor retarder in all modeling. Modeling results at the interior face of the exterior sheathing (at a point midway between framing members) revealed that on average, water was not accumulating in wood framed walls with cavities filled with closed cell spray polyurethane foam and in the SIPS assemblies. The dryness of the SIPS assemblies appears to be related to their lower cavity insulation thermal performance versus the other walls we studied. Due to the airtightness of the closed cell spray polyurethane foam, it appears to be good at limiting water accumulation within the stud cavity and allowing for any water to dry (Figure 2). Water did accumulate in wood framed walls with cavities insulated with blown-in fiberglass insulation, although these systems dried out after the summertime period of the modeling.

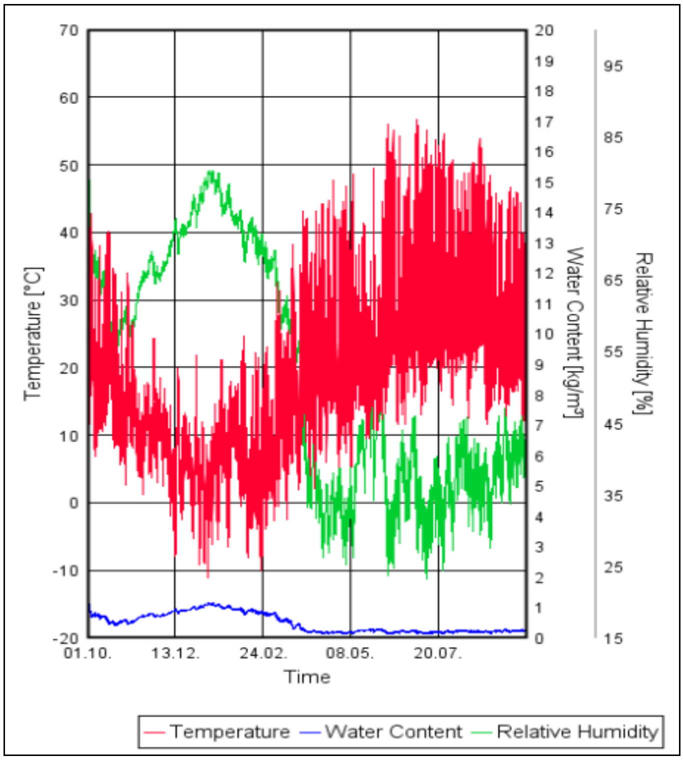

Figure 2. WUFI 2D model output displaying whole year temperature, water content, and relative humidity conditions in a 2x6 wall with closed cell spray polyurethane foam and R-10 insulating sheathing

By using WUFI Pro (version 3.3), we were better able to understand the drying capacities of different wall cavity insulation systems under wet conditions. Dense-pack fiberglass insulation (blown-in blanket system) and polyurethane spray foam insulation systems displayed the best drying potential.

We used THERM to study the condensation potential of each wall system, an important consideration for a cold climate assembly. Modeling focused on the temperature conditions at four different points in each wall system: at the wall corner at the interior face of the insulating sheathing, at the interior face of insulating sheathing within a wall cavity, at the inboard drywall face at the wall inside corner, and at the inboard drywall face intersection point with a stud. Not surprisingly, as thicker amounts of insulating sheathing were placed on a wall system, the warmer the temperature conditions became at the examination points and the risk of condensation decreased. The SIPS assemblies, since they use OSB as sheathing, exhibited the coldest sheathing temperatures. If insulating sheathing thicknesses is constant while the thermal performance of the wall cavity changes, wall cavities with lower thermal performance result in higher temperatures at the sheathing points and thereby have lower condensation potential.

The cumulative modeling results on durability indicated that wall systems with thicker amounts of insulating XPS sheathing and closed cell spray polyurethane within the wall cavities behaved the best overall (assuming best practice moisture management techniques are followed).

Cost vs. Energy Savings Ratio

We determined a cost vs. energy savings ratio for each wall system as a measure of thermal performance and cost effectiveness. Heating and cooling energy savings are in comparison to corresponding energy use values in the base case wall system. The costs associated with each wall system represent the annualized incremental cost of a wall system (with respect to the base wall) assuming the cost is amortized for 30 years at a 7% interest rate.

To determine heating and cooling, energy usage models were built in TRNSYS (version 16.01). TRNSYS modeling yields more detailed information than EnergyGauge USA on the thermal performance of wall systems within the house. TRNSYS modeling more accurately reflects the framing configurations of the different wall systems, allowing for a more precise determination of the annual energy use associated with each. This is because each wall is divided into common framing and/or insulation configurations, resulting in situations where studs that do not travel the entire width of the wall, such as in the staggered stud approach, to be modeled accurately. All other house system performance attributes were kept constant in the modeling.

Figure 3 displays the heating and cooling annual energy usage associated with each wall system. The five wall systems with the best performance are highlighted with green vertical bars and are within 100 kWh of annual heating and cooling energy usage of each other. In order of decreasing energy efficiency, the leading wall systems are:

1. 2x6 wall with R-20 insulating sheathing; 1799 kWh
2. 2x6 wall with layer of spray polyurethane foam and R-15 insulating sheathing; 1865 kWh
3. 2x6 wall with spray polyurethane foam and R-10 insulating sheathing; 1871 kWh
4. Staggered stud 2x8 wall with R-10 insulating sheathing; 1872 kWh
5. 2x6 wall with R-15 insulating sheathing; 1896 kWh

Each of the leading wall systems has a minimum of 51mm (2") un-faced XPS insulating sheathing, which provides thermal protection for the entire wall surface, particularly for the wood framing on the outboard side of the assembly.

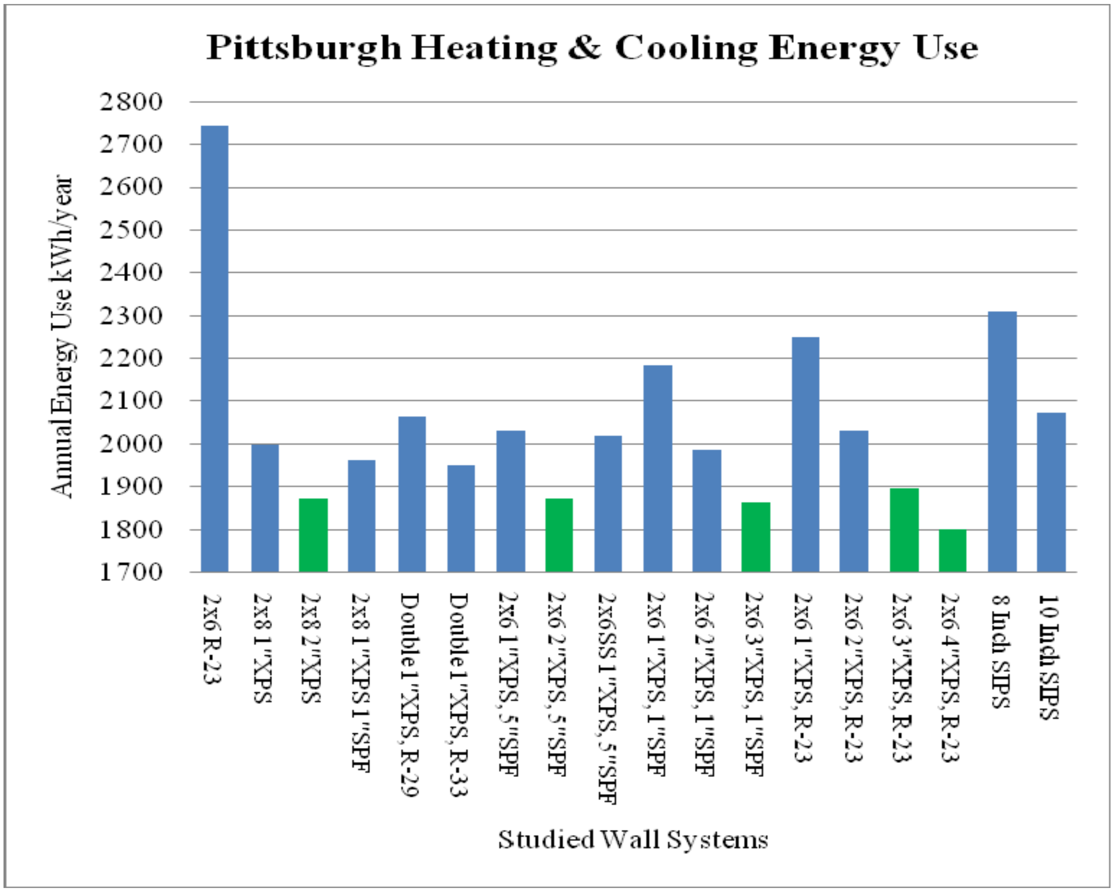

Figure 3. Annual heating and cooling energy use associated with the high performance of the above grade wall systems

A local builder’s framing subcontractor provided construction cost information for all of the wood framed wall systems in the analysis, with the exception of the blown-in fiberglass insulation component, which came made product manufacturers. The procurement and installation of items, such as the wood strapping, fasteners for the installation of insulating sheathing and strapping, and construction tape for use over sheathing joints, were accounted for in the construction costs for the wood framed wall systems (where applicable). A local SIPS manufacturer provided cost information on the two SIPS-based wall assemblies.

Figure 4 displays the incremental construction cost vs. energy savings ratio for each wall system for the Pittsburgh house design, with the five wall systems that were leaders in energy efficiency shown as green vertical bars. Each wall is compared to the base wall system. Based on this criterion, new leading wall systems emerged. In order of increasing cost vs. energy savings ratio, the leading wall systems are:

1. 2x6 wall with R-5 insulating sheathing; $0.17/kwh
2. Staggered stud 2x8 wall with R-5 insulating sheathing; $0.40/kwh
3. Double wall with 1” spacing and R-5 insulating sheathing; $0.42/kwh
4. Double wall with R-5 insulating sheathing; $0.45/kwh

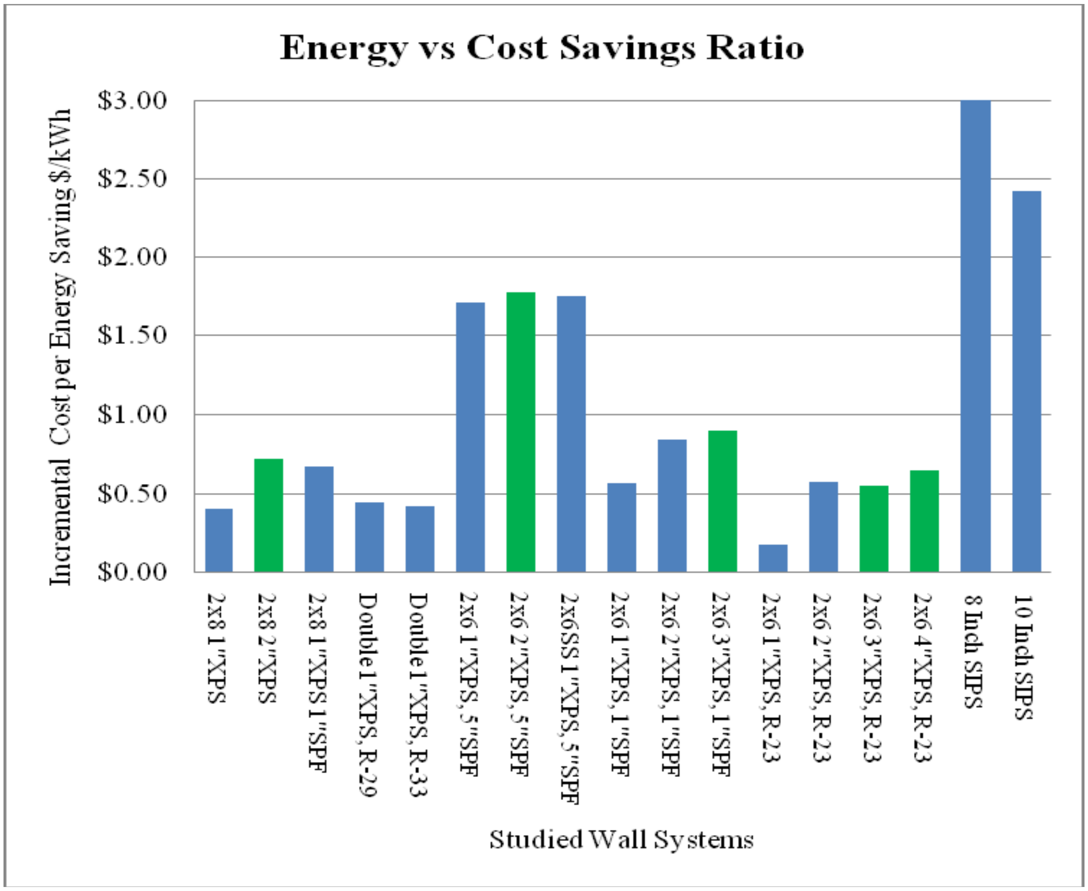

Figure 4. Additional cost increment per annual energy savings for the high performance above grade wall systems with respect to the base wall

The wall with the lowest construction cost vs. energy savings ratio, a 2x6 wall with R-5 insulating sheathing with RSI 4.9 (R-28) nominal performance, has 254 kWh greater energy consumption than the next most cost effective wall system, which is the staggered stud 2x8 wall with R-5 insulating sheathing with RSI 6.3 (R-36) nominal thermal performance. Based on estimated energy consumption for the house design, 254 kWh of energy use equates to 2.6% of all energy use for the house design, a significant amount of energy for a house design attempting to achieve 70% whole house energy savings. As a result, even though this wall system is very cost effective, it will not provide enough energy savings for the whole house energy savings goal to be realized. So, from a cost vs. energy savings ratio perspective, the most favored wall system is the staggered stud 2x8 wall with R-5 insulating sheathing with RSI 6.3 (R-36) nominal thermal performance although the two double wall systems we studied deserve favorable consideration as well.

Comfort

Although occupant comfort is a “Should Meet” criterion, its importance warrants some discussion. Determining the comfort conditions associated with each wall system was included in the TRNSYS modeling protocol. Indoor comfort conditions for each house design zone were generated for each wall system, allowing for comparisons according to the Thermal Comfort Performance Index (TCPI) parameter.

Figure 5 displays the whole house TCPI results derived from the TRNSYS modeling for each wall system. The five wall systems that were leaders in energy efficiency were also leaders in the TCPI value and are displayed as green vertical bars. Overall, there is a correlation between a wall system's energy efficiency and its TCPI value. The TCPI compares the predicted mean vote (PMV) against predetermined neutral comfort criteria at each simulation time step. The TCPI value is calculated by dividing the number of values that meet the criteria by the total number of values calculated with a value of 1.0 representing perfectly acceptable comfort. In the evaluation criteria for comfort, a TCPI value between 98 and 100 is considered to be the best situation. In each model, the air balancing strategy was held constant so this factor would not influence the TCPI value.

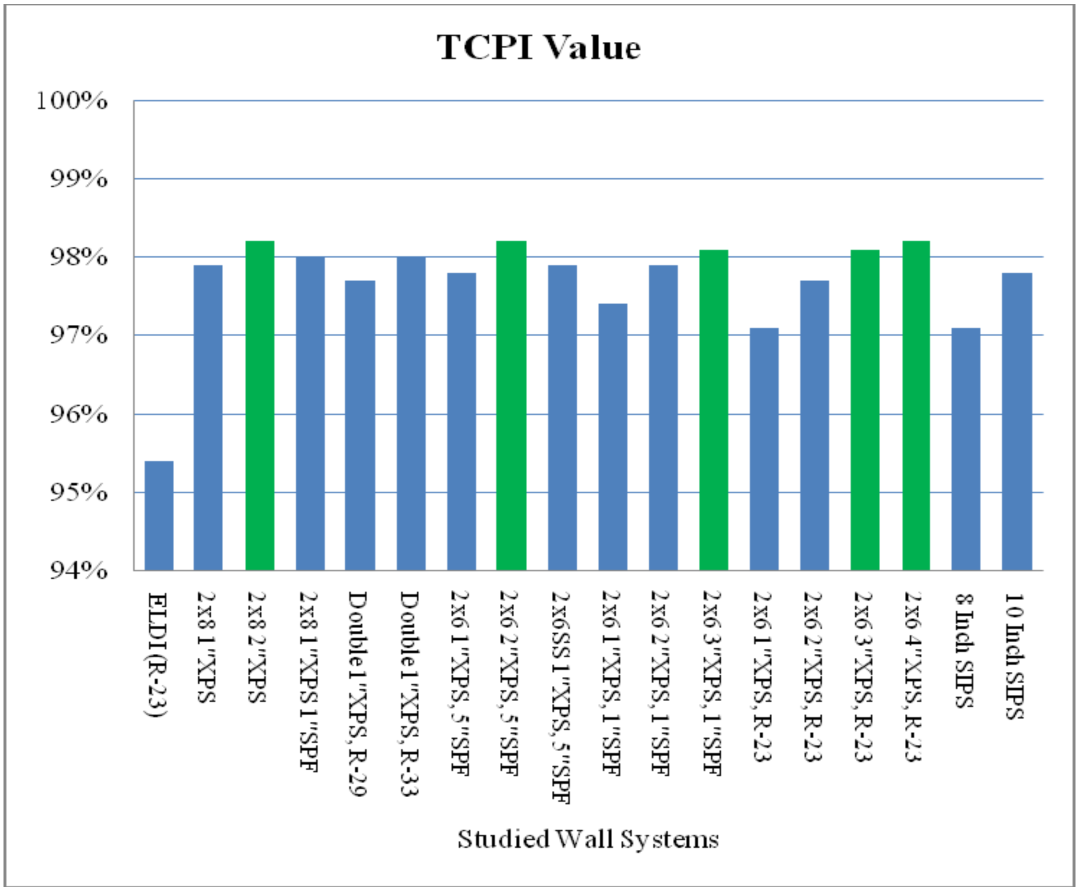

Figure 5. TCPI for the high performance above grade wall systems

Conclusions

The total evaluation score of each wall system we studied, which includes the score of all "Must Meet" and "Should Meet" criteria, is shown in Table 4.

Table 4: Summary of Wall System Scoring

Wall Systems Name	Total Points
Staggered stud 2x8 wall with R-5 insulating sheathing	2420
Staggered stud 2x8 wall with R-10 insulating sheathing	2485
Staggered stud 2x8 wall with layer of closed cell spray polyurethane foam and R-10 insulating sheathing	2395
Double wall with R-5 insulating sheathing	2420
Double wall with 1” spacing and R-5 insulating sheathing	2395
2x6 wall with closed cell spray polyurethane foam and R-5 insulating sheathing	2385
2x6 wall with closed cell spray polyurethane foam and R-10 insulating sheathing	2315
Staggered stud 2x6 wall with closed cell spray polyurethane foam and R-10 insulating sheathing	2335
2x6 wall with layer of closed cell spray polyurethane foam and R-5 insulating sheathing	2510
2x6 wall with layer of closed cell spray polyurethane foam and R-10 insulating sheathing	2340
2x6 wall with layer of closed cell spray polyurethane foam and R-15 insulating sheathing	2385
2x6 wall with R-5 insulating sheathing	2520
2x6 wall with R-10 insulating sheathing	2440
2x6 wall with R-15 insulating sheathing	2410
2x6 wall with R-20 insulating sheathing	2285
SIPS 8¼” thick	2135
SIPS 10¼” thick	2210

The 2x6 wall system with R-5 insulating sheathing scored the best, followed by the 2x6 wall system with a layer of closed cell spray polyurethane foam and R-5 insulating sheathing, and then followed by the staggered stud 2x8 wall with R-10 insulating sheathing. The two highest scoring walls rose to the top because of their high rating they achieved for constructability and construction cost vs. energy savings ratio. Of these three, the staggered stud 2x8 wall with R-10 insulating sheathing offers the greatest amount of energy savings for the whole house, saving an additional 379 kWh/yr in energy use than the first wall and 313 kWh/yr more than the second wall. Since our goal was to build a house to a level of energy efficiency that would result in 70% whole house energy savings according to the BA Research Benchmark Definition, the staggered stud 2x8 wall with R-10 insulating sheathing appears to be the best choice in meeting this target, even though it scored third in the evaluation process. Considering that the comparative energy savings between wall systems was not a distinct part of the evaluation process (although it was accounted for in the cost vs. energy savings ratio criteria), but can be an important factor in choosing a leading wall system for a zero energy house, that criterion should be developed and included in the next version of the wall evaluation process.

Acknowledgments

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