U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

# Modular Zero Energy: BrightBuilt Home

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*Consortium for Advanced Residential Buildings*

March 2016

Building America
U.S. Department of Energy

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Prepared for:

The National Renewable Energy Laboratory

On behalf of the U.S. Department of Energy's Building America Program

Office of Energy Efficiency and Renewable Energy

15013 Denver West Parkway

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NREL Contract No. DE-AC36-08GO28308

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Prepared under Subcontract No. KNDJ-0-40342-05

March 2016

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The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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# Acknowledgments

This work was funded through the Building America Program of the U.S. Department of Energy Building Technologies Office, and the Consortium for Advanced Residential Buildings is very appreciative of support from the National Renewable Energy Laboratory. The authors are also grateful for the support and participation of Kaplan Thompson Architects, BrightBuilt Home, Keiser Homes, and Black Bros. Builders.

## Definitions

| | |
|---|---|
| ACH | Air Changes per Hour |
| ASHP | Air-Source Heat Pump |
| Btu | British Thermal Unit |
| BBH | BrightBuilt Home |
| CARB | Consortium for Advanced Residential Buildings |
| CFM | Cubic Feet per Minute |
| EPS | Expanded Polystyrene |
| GWP | Global Warming Potential |
| HERS | Home Energy Rating System |
| HPWH | Heat Pump Water Heater |
| HRV | Heat Recovery Ventilator |
| HVAC | Heating, Ventilating, and Air Conditioning |
| ICF | Insulated Concrete Form |
| kW | Kilowatt |
| NAHB | National Association of Home Builders |
| NMHC | National Modular Housing Council |
| OSB | Oriented Strand Board |
| PV | Photovoltaic |
| R- | Thermal Resistance, Typical Units: $ft^2h°F/Btu$ |
| U- | Thermal Conductance, Typical Units: $Btu/ft^2h°F$ |
| UA | Thermal Conductance Times Area, Typical Units: Btu/h°F |
| XPS | Extruded Polystyrene |
| ZERH | Zero Energy Ready Home |

# Executive Summary

In mid-2013, Kaplan Thompson Architects in Portland, Maine, launched the BrightBuilt Home (BBH) brand—a line of high-performance, modular homes designed to attain zero net energy consumption with 5–10 kilowatt (kW) photovoltaic (PV) systems. Kaplan Thompson Architects had designed several custom, zero net energy homes for clients in the Northeast, but they were eager to make zero energy homes more affordable and available to a wider range of clients.

Although modular homes certainly offer more savings than site-built homes, there are some additional challenges associated with modular construction—especially with high-performance homes. Optimizing the BBH wall system, for example, involved not only achieving desired R-values (at least 35 $ft^2h°F/Btu$) and durability at reasonable costs, but also the wall systems needed to be resilient during shipment. In addition, wall construction at the factory could not be allowed to slow the modular production line.

With funding from the Building America Program, part of the U.S. Department of Energy Building Technologies Office, the Consortium for Advanced Residential Buildings (CARB) worked with BBH to evaluate and optimize building systems. CARB's work focused on a home built by Black Bros. Builders in Lincolnville, Maine (International Energy Conservation Code Climate Zone 6). As with most BBH projects to date, modular boxes were built by Keiser Homes in Oxford, Maine.

**Figure 1. The BrightBuilt Home built by Black Bros. Builders in Lincolnville, Maine**

Modeling showed that the home in Lincolnville achieved 41% source energy savings without PV and 77% with PV. Modeling also showed $2,400 in annual energy savings compared to the Building America benchmark. In brief, BBH systems include:

- R-19 minimum foundation insulation—details may be determined by the builder; the Lincolnville home used R-20 insulated concrete forms (ICFs).
- Double, 2x4 walls with staggered studs built on 2x8 plates with dense cellulose; 2 in. of rigid foam is installed outside of the oriented strand board sheathing.
- R-60 ceiling/roofs, which are challenging to achieve with insulated roofs. The Lincolnville home uses 4 in. of extruded polystyrene (XPS) above the deck and 2x6 rafters packed with cellulose (R-42).
- Triple-pane windows (U-values from 0.18–0.25 Btu/ft$^2$h°F)
- Heating and cooling provided by inverter-driven, air-source heat pumps; different homes use different combinations of single-zone, multi-zone, ductless, and ducted heat pumps.
- A heat recovery ventilator that provides whole-building ventilation. Local ventilation strategies vary; the Lincolnville home used the heat recovery ventilator for bathroom exhaust but used a dedicated kitchen exhaust hood.

Especially during the first few projects, BBH experienced challenges related to quality control. Communication among clients, designers, modular builders, and site builders was not always clear, which sometimes led to added costs or performance problems. To help improve quality control and recognize superior performance, CARB suggested ENERGY STAR® and/or Zero Energy Ready Home certification for BBH homes. Beginning in January 2015, BBH started meeting Home Energy Rating System (HERS) ratings and ENERGY STAR certification standards for their homes.

During the first two years, BBH showed that there is demand for more affordable, zero energy homes. Between its launch in mid-2013 and the writing of this report in mid-2015, BBH completed 25 homes, had 16 under construction or under contract, and had customer interest for dozens more homes. Homes have been built in seven states, and BBH has agreements with modular manufacturers in New Hampshire and Pennsylvania that will expand BBH's geographical range. For projects completed to date, BBH has seen construction costs of $164–$195/ft$^2$.

# 1 Background

Kaplan Thompson Architects has specialized in sustainable, energy-efficient buildings, and they have designed several custom, zero energy homes in New England. These zero energy projects have generally been high-end, custom homes with budgets that could accommodate advanced energy systems. In an attempt to make zero energy homes more affordable and accessible to a larger demographic, Kaplan Thompson Architects explored modular construction as way to provide high-quality homes at lower costs. In mid-2013, Kaplan Thompson Architects formalized this concept when they launched BrightBuilt Home (BBH). The BBH mission is to offer "a line of architect-designed, high-performance homes that are priced to offer substantial savings off the lifetime cost of a typical home and can be delivered in less time."

BBH architects have designed nine modular homes ranging in size from 960–2,240 $ft^2$. The homes are very efficient, use no fossil fuels, and are designed to attain zero net energy performance with 5–10 kilowatt (kW) photovoltaic (PV) systems. Since the BBH launch two years ago, 20 homes have been completed, and BBH reports construction costs between \$164–\$195/$ft^2$. For the past two years, the Consortium for Advanced Residential Buildings (CARB) has worked with BBH and Keiser Homes (the primary modular manufacturer for BBH) to discuss challenges related to wall systems; heating, ventilating, and air conditioning (HVAC); and quality control. In spring of 2014, CARB and BBH began looking in detail at a home to be built in Lincolnville, Maine (Climate Zone 6) by Black Bros. Builders. Black Bros. has specialized in high-performance homes in mid-coast Maine, but this was their first modular project.

One of the challenges BBH had identified was consistency and quality control throughout the design and construction process. In a few early projects, some gaps in communication led to inconsistent construction details. Rating the homes for compliance with the U.S. Environmental Protection Agency's ENERGY STAR® and the U.S. Department of Energy's Zero Energy Ready Home (ZERH) programs seemed like an excellent way to provide quality control as well as recognition for superior energy performance.

CARB inspected boxes in the factory several times, the foundation, and air sealing and HVAC rough-in at the site and performed preliminary blower door testing. Unfortunately, completion of the home was substantially delayed, so final testing has yet to be performed. Although one of the appealing factors of modular homes is shorter construction times, the purchasers of this home were not on a tight timeline, and they have been very deliberate in selecting materials and finishes after the home was set.

In working with BBH, Black Bros., and Keiser Homes, CARB sought to assess the overall approach to constructing modular, zero energy homes, specifically:

- What are the most practical envelope systems for these modular ZERHs?
- What HVAC systems are most practical for BBH homes?
- Is there market demand for these modular ZERH?

# 2 Building Systems

## 2.1 Foundation and Slab

As with typical modular homes, the site builder is responsible for providing the appropriate foundation. BBH's standard foundation wall detail includes a monolithic concrete wall insulated on the inside with 3 in. of polyisocyanurate (R-18–20 $ft^2h°F/Btu$). This is not dramatically higher than the current code requirements; both the 2012 and 2015 International Energy Conservation Codes (ICC 2011, ICC 2014a) specify minimum continuous R-values of 13, 15, and 19 $ft^2h°F/Btu$ in climate zones 5, 6, and 7 respectively. Beneath basement slabs, BBH specifies a minimum of R-16 insulation (4 in. of expanded polystyrene [EPS] foam).

The home evaluated in Lincolnville, Maine, used insulated concrete forms (ICFs), which include 2.5 in. of EPS foam on each side of the concrete (providing an R-value of approximately 20, see Figure 2). Beneath the slab, Black Bros. installed 2 in. of extruded polystyrene (XPS) foam providing approximately R-10 rather than the standard R-16.

**Figure 2. The ICF foundation in Lincolnville.** ***Image from Black Bros. Builders***

## 2.2 Above-Grade Walls

### *2.2.1 Framing and Insulation*

Determining the best wall system involved balancing concerns about R-value, material cost, practicality in a factory setting, workable air-barrier details, durability in module transport, ease of finishing the boxes on site, and other environmental factors. Global warming potential (GWP) of foam and blowing agents was a significant concern for BBH when selecting wall systems. Where assemblies include rigid foam insulation, polyisocyanurate is often specified because of its relatively high R-value (per thickness) and relatively low GWP. While EPS has lower R-values, it is preferred over XPS because of its lower GWP. An analysis of common blowing agents shows that HFC-134a (the common blowing agent in XPS) has GWP approximately 150 times higher than the GWP of pentane (the common blowing agent in EPS and polyisocyanurate). When normalized by the amount of blowing agent needed to achieve equivalent R-values, XPS still has 40–50 times greater GWP than EPS or polyisocyanurate (Wilson 2010). These factors were key considerations in BBH insulation systems.

In early discussions, wall systems considered included:

1. 2x6 framed walls with cellulose, 4 in. of exterior foam
2. Double-framed walls (two 2x4 walls, 10–12 in. total cavity width) filled with dense cellulose
3. 2x8 framed walls with 2 in. of exterior foam.

All of these have the potential to deliver R-values near 40 $ft^2$hr°F/Btu, but each of these had significant drawbacks. One key drawback of system 1 was the cost of the rigid foam. While not a standard product, the factory obtained pricing for 4 in. polyisocyanurate boards (preferred for its high R-value and low GWP). The cost of this was prohibitive—several times the cost of two layers of 2-in. polyisocyanurate board. While installing two layers of foam insulation would reduce material costs, this proved to be prohibitive from a time and labor perspective. The factory felt that installing two layers of foam would slow the line unacceptably. In addition, protecting this thick layer of foam during shipment would be challenging, as would finishing the homes at the site. The long fasteners needed to attach siding through 4 in. of foam can be very costly.

The thick double-wall system (2) did not have any of the costs associated with foam, but building a second frame wall can be very time consuming (Aldrich, Arena, and Zoeller 2010). CARB suspected that the time required for extra framing would make option 2 untenable in a modular production line, but the modular factory was more concerned with the settling of cellulose insulation during transport in such a large wall cavity.

The 2x8 framing members in option 3 would likely have been cost prohibitive, but it is a variation of this system that is now used by BBH. Each wall uses 2x8 bottom and top plates, but staggered 2x4 stud walls are constructed on the inside and outside of these plates (see Figure 3 and Figure 4).

After the framing method was agreed upon, discussions on the type of foam to use continued. Designers preferred to use polyisocyanurate primarily because of its low GWP; the factory preferred XPS because of its durability during transportation. For the Lincolnville home, XPS was ultimately used.

**Figure 3. A 2x8 bottom plate with staggered 2x4 studs in the factory. The gypsum board is visible through the vapor retarder.**

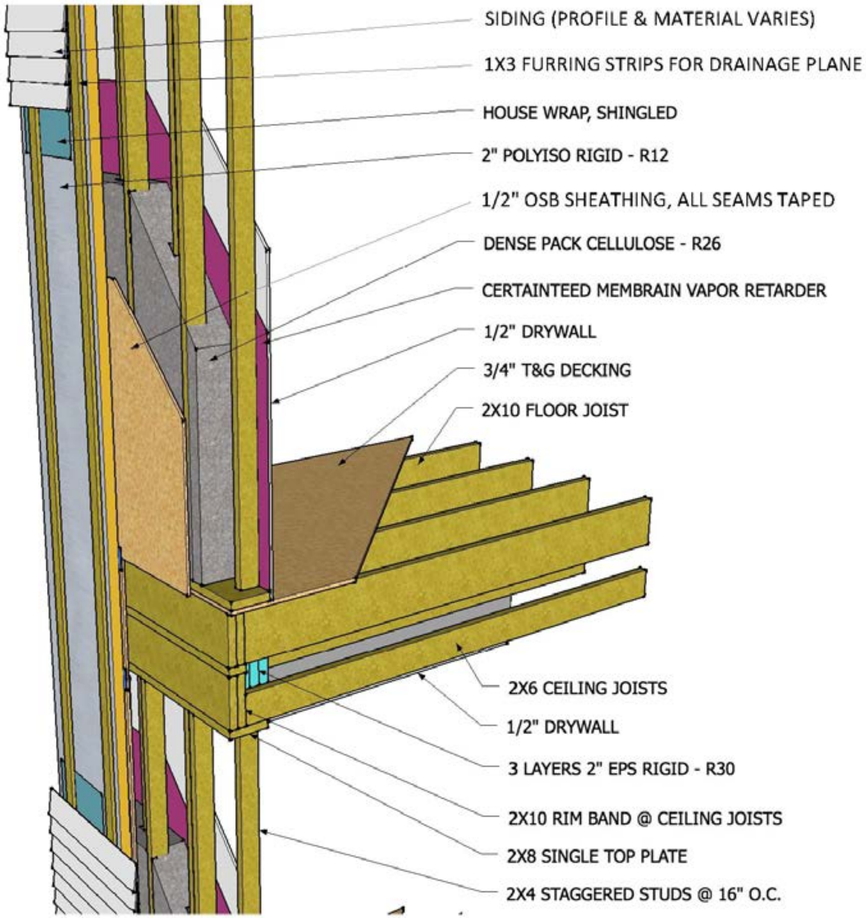

**Figure 4. Cutaway of typical BrightBuilt Home wall system. The type of foam and location of house wrap differed in Lincolnville home.** ***Image from BrightBuilt Home***

### *2.2.2 Moisture Management*

In the standard BBH wall system, house wrap serves as a secondary drainage plane (after the siding) outside of the rigid polyisocyanurate insulation. Pictures of the Lincolnville home after set (Figure 5) show two key discrepancies with the detail:

- XPS was used instead of polyisocyanurate
- The house wrap is inside of the foam insulation.

Installing a secondary drainage plane directly against the Oriented Strand Board (OSB) sheathing was the factory's standard practice. While others have used this detail, BBH and CARB believe keeping moisture further outside carries lower risks, especially at windows and doors when water must be directed out and around these obstructions. In future BBH homes (such as the one in Figure 6), the factory has made adjustments to accommodate this system, and house wrap is outside of the foam insulation.

The reason XPS was used rather than polyisocyanurate was simply because of an incorrect order. The factory ordered XPS for the home (which was their standard when using exterior foam sheathing). Ordering polyisocyanurate would have resulted in unacceptable delays to the factory's production line.

**Figure 5. The Lincolnville home soon after set**

**Figure 6. A later BrightBuilt Home in which house wrap was installed outside of the foam insulation**

To prevent moisture problems associated with air infiltration and exfiltration, BBH's standard wall system calls for meticulous air sealing at the OSB sheathing with appropriate tape (see the dashed red line in Figure 7). After the set, builders sealed the marriage walls and band joist areas using gaskets, tape, foam, and blocking as appropriate. Air sealing details and preliminary blower door test results are discussed in more detail in section 2.5.

Interior vapor retarders can be useful in very cold climates to prevent interior moisture from entering the wall system and condensing on cold, exterior sheathing. Such vapor retarders are required by many codes (e.g., 2015 International Residential Code, ICC 2014b). At the same time, interior vapor retarders can reduce the ability of wall assemblies to dry, especially when there is a vapor retarder on the outside of the wall system (e.g., OSB and/or rigid foam). To reduce moisture risks, BBH uses a “smart” vapor barrier (Certainteed’s MemBrain) that changes permeance depending on the relative humidity. During the winter when conditions are very dry, the vapor retarder’s permeance is less than 1 perm (Certainteed 2012), meeting code requirements. Under more humid, summer conditions, the permeance increases to more than 10 perms. In a past study, side-by-side tests of this product in cold-climate homes showed that the “smart” vapor retarder resulted in drier wall cavities than conventional vapor retarders (Zuluaga 2006). In BBH homes, the vapor retarder is installed in the factory between the drywall and the interior framing (visible in previous images of wall framing, Figure 3 and Figure 4).

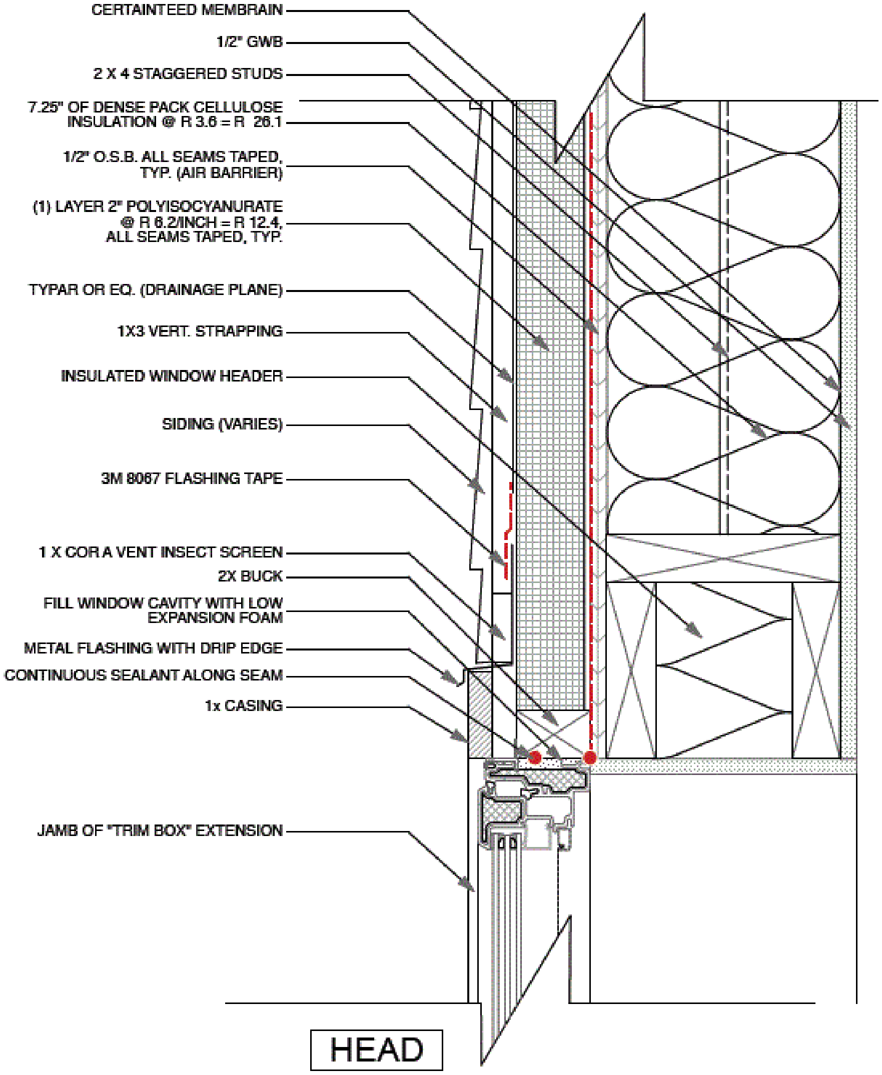

**Figure 7. Typical window header detail for BrightBuilt Home. The home in Lincolnville differs because the house wrap is inside of the rigid foam.** ***Image from BrightBuilt Home***

### *2.2.3 Siding*

The type of siding used in BrightBuilt Homes varies, but the fiber cement clapboards used in the Lincolnville home are common (see Figure 8). Furring strips are aligned with studs and attached with screws. The furring provides an air gap that can improve drainage and lower moisture-related risks. This is especially beneficial with fiber cement siding, which can absorb a significant amount of moisture (Straube and Smegal 2009). The fiber cement clapboards are nailed to the furring strips. At the bottom and top courses of siding, rigid vent material with insect screens allows drying without giving pests access to the wall assembly.

**Figure 8. Fiber cement clapboard siding installed on furring strips**

## 2.3 Windows

Triple pane, vinyl-framed windows from Paradigm are standard in BrightBuilt Homes. These windows typically have U-values of 0.18-0.25 Btu/ft$^2$h°F. Where tempered windows are required (such as in bathrooms), windows are double pane with U-values of 0.27 Btu/ft$^2$h°F. Most windows are installed in the factory. Only basement windows or gable windows are installed on site.

Because the factory installed the house wrap behind the rigid foam, the window detail for the Lincolnville home did not match the standard detail (as in the window header shown in Figure 7). The installation of the windows in the Lincolnville home is outlined below.

- In the factory, house wrap was installed over the OSB sheathing, slit diagonally at the window openings, and wrapped inside.
- Window bucks were installed over the house wrap on the sides and bottom and under the house wrap at the top.
- Window flanges were attached to bucks (with caulk on all sides, standard practice for the modular plant).
- The top flap of the house wrap was laid over the buck and window flange.

- Flexible window flashing tape sealed the window flange to the house wrap on all sides.
- Rigid foam board was installed over the house wrap to the edge of the window bucks.

### 2.4 Roof and Attic

Ceilings and/or roofs of modular homes are typically not insulated at the factory. The most common practice is a “tilt-up” rafter assembly. This assembly lies flat for shipping with a hinge located at the eaves. At the site, hinged roof sections are lifted (with a crane) and secured in place. For the home in Lincolnville, the top section of the roof and the large gable dormer were assembled in the factory separately. After the lower sections of the roof were tilted up and secured, these other factory-built pieces were set in place and secured (Figure 9). When asphalt shingles are used, they are typically installed on the lower, tilt-up section of the roofs in the factory. As a standing-seam metal roof was used in Lincolnville, all roofing was installed at the site.

**Figure 9. The tilt-up roof (left) and factory-assembled dormer (right)**

BBH’s standard details for vented attics call for R-60 loose fill cellulose (approximately 21 in.). In models with cathedral ceilings and insulated roofs, the target R-value is still 60 $ft^2h°F/Btu$. In the Lincolnville home, this target was not achieved. Black Bros. installed two layers of 2-in. XPS above the roof deck (Figure 10). Above this foam, another deck was installed for attaching the standing seam metal roofing. The 2x6 rafter bays were then filled with dense cellulose. The overall R-value achieved (approximately 42 $ft^2hr°F/Btu$) is less than the minimum specified by the 2012 and 2015 International Energy Conservation Code (R-49), but the overall UA (the product of thermal conductance and area) of the home is 35% below the overall code maximum (Max UA: 332 Btu/h°F, as-built UA: 217 Btu/h°F). Black Bros. opted for this approach because of the additional cost and dimensions required for attaining the R-60 cathedral assembly; this challenge is addressed further in the Discussion section below.

**Figure 10. Four inches of XPS were installed above the first roof deck. A second deck, paper, and asphalt roofing were installed above the foam.**

## 2.5 Air Sealing

Building homes in a factory allows for excellent quality control in many air sealing details. With many modular homes, however, there can be great inconsistency in air sealing performed on site. When marriage walls and vertical transitions are not meticulously sealed, modular homes can be extremely leaky. CARB inspected the Lincolnville home a week after it was set, and there were striking gaps (Figure 11). Several weeks later, however, these gaps appeared to be well sealed with blocking and/or foam (Figure 12).

A preliminary blower door test was conducted in March 2015. This was well before the home was finished—electrical plates were not installed, plumbing was not finished, and HVAC was not completed. Still, the blower door tests showed infiltration of 440 cubic feet per minute (CFM) when tested at 50 pascals, or approximately 0.97 air changes per hour (ACH). This is expected to drop further when fixtures and finishes are completed.

**Figure 11. Gaps soon after set. Clockwise from top left: large gap in gable wall; daylight seen through marriage wall between bedrooms; damaged gasket between boxes on first floor; gaps at tilt-up roof.**

Figure 12. Gable wall and roof gaps appeared well sealed with foam and blocking.

## 2.6 Heating and Cooling

For any home, selecting the most appropriate heating and cooling system usually involves balancing several factors, including:

- Comfort throughout the home
- Operating cost (efficiency)
- First cost
- Integration of equipment and distribution systems.

The efficiency of the envelopes in BrightBuilt Homes means that heating and cooling costs would be quite low for most HVAC systems, but many conventional HVAC systems have capacities that are much larger than necessary to meet the modest loads. In the $3,100\text{-ft}^2$ Lincolnville home (gross area including a conditioned basement and finished loft), the design heating load is 24,600 Btu/h; the total design cooling load is 10,300 Btu/h. To match these modest loads, most BrightBuilt Homes use inverter-driven air-source heat pumps (ASHPs). In addition to matching the loads, ASHPs can be powered by on-site PV systems, making zero net energy equations more straightforward. The types of ASHPs used in each home, however, vary depending on the desires of BBH clients.

### *2.6.1 Ductless Heat Pumps*

Some of the simplest heating and cooling systems in BBH homes use a single, ductless fan coil located in a central space on the first floor. Past Building America research (Ueno and Loomis 2014; Prahl et al. 2007; Stecher, Allison, and Prahl 2012; Aldrich 2010) has shown that such point-source heating systems can provide comfort in low-load homes during the winter, but upstairs spaces can be uncomfortably warm during the summer. In a climate such as Maine's, however, inconsistent cooling upstairs may be acceptable to some homebuyers, especially when considering the added cost of more complex systems. Costs for single-zone, ductless heat pumps can vary, but some published data show that installed costs may average $3,500–$4,000 in the Northeast (NEEP 2014).

Quite recently, residential multi-zone or "multi-split" systems have become available with efficient performance at colder outdoor temperatures. These systems use a single outdoor unit connected to several (sometimes up to eight) indoor fan coils. While these products were not available when the Lincolnville home began construction, one such system was installed in a more recent BBH home in Falmouth, Maine (Figure 13). The 3.5-ton outdoor unit is tied to five ductless fan coils.

**Figure 13. The heat pump outdoor unit in this BBH home under construction connects through a branch box to five ductless fan coils.**

This multi-zone approach provides heating and cooling to each space in the home, but the smallest fan coil has a capacity of 6,000 Btu/h—three times the design load of many bedrooms. It's not clear that such oversizing would lead to comfort problems, but these systems may be fairly costly to install. CARB is not aware of any surveys on the cost of these systems, but a few anecdotal accounts indicate that the cost per fan coil of these multi-zone systems is on par with the same number of single-zone ductless heat pumps ($3,500–$4,000 per fan coil). As these products are fairly new, it's possible these anecdotal accounts are somewhat inflated, and prices may come down as contractors gain experience and volume increases.

### 2.6.2 *Small, Ducted Heat Pumps*

Many manufacturers of ductless ASHPs also manufacture small, ducted heat pumps of similar capacity (9,000–18,000 Btu/h). These "slim" fan coils may be ducted to several spaces, but they often operate at very low static pressures, so duct runs must often be short with few restrictions. Even with the 0.2 in. of static pressure, ducts with 6–8 in. diameters are appropriate for many BBH bedrooms because of the low design loads.

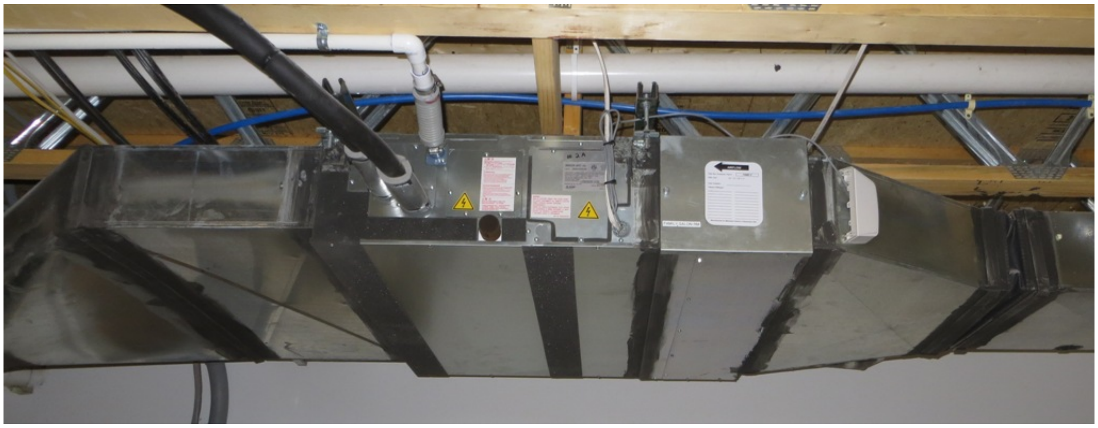

**Figure 14. A "slim" ducted heat pump fan coil**

As with multi-zone heat pumps, CARB is not aware of studies that document typical installed costs of these systems. Conversations with some contractors indicate that installed costs may be twice those of a ductless ASHP of similar capacity.

### 2.6.3 *Heating and Cooling Systems in Lincolnville Home*

For the home in Lincolnville, CARB provided recommendations on heating and cooling systems to meet the loads efficiently and effectively. These home buyers desired a fair amount of temperature control, including one bedroom that could be controlled independently of all other parts of the home. The heating and cooling system ultimately consisted of:

- One ductless heat pump on the first floor (12,000 Btu/h nominal capacity)
- One ducted heat pump serving most of the second floor and the loft (12,000 Btu/h nominal capacity)
- One ductless heat pump serving one bedroom (9,000 Btu/h nominal capacity).

Many contractors installing heat pumps in northern climates are mindful of protecting outdoor units from snow and ice. Covers for ASHP outdoor units such as those shown in Figure 15 have become standard for many contractors. Outdoor units are also located well above snow level.

**Figure 15. To ensure better winter performance, heat pumps are located well above snow level and covered to protect them from snow and ice.**

The purchasers of this home also opted to include a wood stove. While most wood stoves are natural draft appliances (i.e., they use air from the surrounding space for combustion and draft), wood stoves in BBH homes must have dedicated outdoor air ducts. The stove in this home has an outdoor air inlet directly behind the stove and a very short duct run. Figure 16 shows the wood stove (covered during construction) and the first-floor heat pump fan coil.

Figure 16. First-floor heat pump fan coil and wood stove

## 2.7 Ventilation

As with heating and cooling, approaches to ventilation vary in BBH projects. While few BBH homes are certified Passive Houses, the design of the homes is strongly influenced by Passive House standards. Many homes use a single Heat Recovery Ventilator (HRV) for all ventilation needs—whole-building ventilation as well as local exhaust. This is standard in many Passive Houses, and Passive House standards mandate that all ventilation pass through efficient heat recovery; no dedicated exhaust ventilation is allowed (O'Leary et al. 2015). Many other U.S. codes and efficiency programs, on the other hand, require higher levels of exhaust ventilation in bathrooms and kitchens. Table 1 summarizes the ventilation required in the Lincolnville home for ENERGY STAR (also ZERH) and Passive House programs. It's striking that whole-building ventilation requirements are higher for Passive House, but exhaust ventilation requirements are 2–3 times lower (though with some continuous exhaust required). In addition, Building America research at Lawrence Berkeley National Laboratory has led to recommendations that kitchen ventilation rates be higher than ENERGY STAR minimums—at least 200 CFM using a hood that effectively captures contaminants from cooking (Chao 2013).

Table 1. Minimum Program Ventilation Requirements for Lincolnville Home

| Program | Whole Building | Bathroom | Kitchen |
|---|---|---|---|
| **ENERGY STAR/ZERH** | 62 CFM continuous | 20 CFM continuous or 50 CFM intermittent | 100 CFM intermittent |
| **Passive House** | 85 CFM continuous | 24 CFM intermittent | 35 CFM continuous |

As the Lincolnville home is participating in the ZERH program and not Passive House, ENERGY STAR levels had to be achieved. The homeowner and builder chose to achieve these levels by using the HRV to exhaust from the bathrooms (at least 20 CFM continuously) and a hood over the range rated at 200 CFM.

## 2.8 Water Heating

As fossil fuels are not allowed (or strongly discouraged) in BBH homes, water heaters are electric. Heat pump water heaters (HPWHs) are strongly recommended, but some homeowners have complained that HPWHs make basements uncomfortably cold. In these cases, well-insulated resistance tanks are often used.

The Lincolnville home has an 80-gallon HPWH with a 2.33 energy factor in the basement. To meet the ZERH hot water delivery requirements, the Lincolnville home uses an electric on-demand water heater for the second-floor bathrooms. These heaters are thermostatically controlled so that resistance heat turns off when hot water from the HPWH arrives. Supplemental on-demand heaters are not standard for BBH, but they are an option for homes targeting ZERH certification. As plumbing fixtures were not all installed at the time of this writing, hot water delivery times have not yet been tested.

## 2.9 Photovoltaic Systems

During the design phase of each project, BBH assesses likely electricity loads using the Passive House Planning Package, and PV systems are sized to meet these loads. Typical PV capacities are 5–10 kW. The Lincolnville home has 7 kW of PV installed on a detached garage. Because few BBH homes have been occupied for a full year, there is not yet data available on how often the zero energy target was achieved. Tracking this information is certainly of interest moving forward.

# 3 Predicted Energy Performance

Building America seeks to reduce source energy use by 30–50% in new construction when compared to the Building America benchmark home (Wilson et al. 2014). Using BEopt v. 2.3 with Energy Plus, CARB modeled three permutations of the Lincolnville home:

- Reference home (benchmark specifications)
- As-built without PV
- As-built with PV.

Modeling shows that the Lincolnville home will require 77% less source energy annually and energy costs will be 76% lower (savings of $2,400 per year, see Table 2). Annualized energy-related costs are meant to approximate increased mortgage payments from the advanced energy features as well as the annual utility savings. CARB was unable to get actual, incremental costs for all systems in the home, so these costs are based on standard BEopt values. Cost is discussed more in the next section. Source energy consumption of each case is also presented in Figure 17.

**Table 2. Energy Cost and Savings Summary of BEopt Results**

| Home | Source Energy Savings | Annual Energy Costs | Annualized Energy-Related Costs |
|---|---|---|---|
| **Reference** | NA | $3,206 | $3,206 |
| **Lincolnville Home (no PV)** | 41% | $1,870 | $2,527 |
| **Lincolnville Home (7 kW PV)** | 77% | $770 | $2,689 |

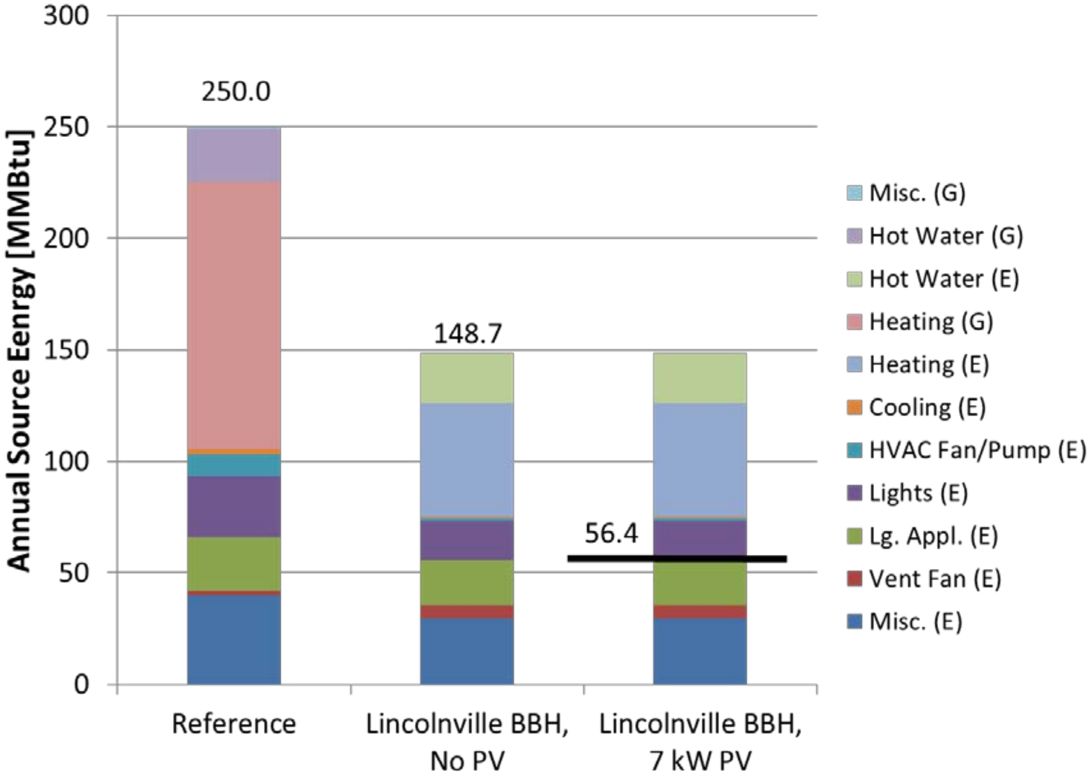

Figure 17. Summary of modeled source energy consumption in the Lincolnville home

# 4 Discussion

## 4.1 Cost

BBH's goal is to deliver zero energy homes at more affordable prices. Lower costs achieved with modular construction allow for zero energy homes at costs near those of custom, site-built homes that only meet current energy codes. Construction costs change with many variables, but BBH and Black Bros. were able to provide approximate factory cost premiums, total construction costs, as well as finished home pricing.

From their modular partners, BBH has collected cost premiums associated with their high-performance systems. Compared to standard, code-compliant modular homes, BBH performance specifications typically increase costs of boxes from the factory by \$11–\$15/ft$^2$ of floor area. Approximately 50% of this premium is associated with the wall system, and 40% is associated with windows. The remaining 10% comes from additional air sealing, mechanical chases, and other details.

Black Bros. only works on high-performance homes, so they were not able to provide similar premiums compared with typical construction. Black Bros. did, however, provide standard "turn-key" prices for BBH homes (Table 3).

**Table 3. Costs from Black Bros Builders to Deliver BrightBuilt Homes (Spring 2015)**

| | | Total Price | | Price per ft$^2$ | |
|---|---|---|---|---|---|
| **Model** | Finished Floor Area [ft$^2$] | Base Finishes | Architectural Finishes | Base Finishes | Architectural Finishes |
| **Foxbird** | 1,680 | $282,000 | $345,000 | $168 | $205 |
| **Little Diamond** | 1,515 | $285,000 | $340,000 | $188 | $224 |
| **Appledore** | 1,750 | $295,000 | $355,000 | $169 | $203 |
| **Great Diamond** | 1,680 | $310,000 | $370,000 | $185 | $220 |
| **Cushing** | 1,975 | $337,000 | $405,000 | $171 | $205 |
| **Vinalhaven** | 2,240 | $355,000 | $425,000 | $158 | $190 |
| **Average** | 1,807 | $310,700 | $373,300 | $173 | $208 |

These costs do not include land or PV systems (a 5-kW PV system typically adds approximately \$15,000–\$20,000), but prices *do* include allowances for permits, well, septic system, electric utility connection, excavation and foundation, basic landscaping (loam and lawn seeding), a short driveway, and a Home Energy Rating System (HERS) rating. The prices also include BBH design allowances for reconfiguration of the floor plans (within the confines of the footprint and volume for each model). Table 3 shows a significant premium (approximately 20%) for "architectural" finishes. These finishes include siding, flooring, plumbing fixtures, lighting, etc.

Base level finishes are the standard modular factory finishes—for example, laminate countertops, carpeted stairs, and vinyl siding. Architectural finishes include features such as solid-surface countertops; maple stairs and banisters; and fiber cement clapboard siding.

Comparing the construction cost per area to costs of "typical" new construction in the area is challenging—CARB has not found similar data compiled in a meaningful way. In an attempt to put BBH construction costs in some perspective, however, the authors followed these steps:

- CARB performed an online search of new home listings in southern Maine recording listing price, home floor area, and lot size. These homes appeared to be single speculation homes or part of larger new home developments.
- CARB performed a similar search of building lot listings recording listing price and lot size.
- The typical cost of land (found to average near $40,000 per acre) was subtracted from the listing price of each home, and the remaining home costs were divided by finished floor area.

This analysis showed costs per floor area of $\$110$–$\$200/\text{ft}^2$ with an average near $\$175/\text{ft}^2$. While this is a very unsophisticated analysis, it does indicate that first costs for BBH homes from Black Bros. are similar to costs for new speculation homes. BBH also works with builders to track construction costs of their homes, and they have found that costs have typically ranged from $\$164$ to $\$195/\text{ft}^2$. These costs also do not include PV and are consistent with Black Bros' "turn-key" costs (which include additional items such as driveway, well, septic, etc.).

### 4.2 Modular Savings and Construction Time

Modular homes represent a small but growing segment of residential new construction in the United States. According to the National Modular Housing Council (NMHC), 13,836 modular homes were delivered in 2014 (NMHC 2015). This represents 3.2% of total new homes sold according to the National Association of Home Builders (NAHB) (NAHB 2015). Over the past 15 years, CARB has worked with many modular builders across the country, and the two benefits of modular that builders most often cite are lower cost and faster construction time compared with site-built homes. Some builders also cite better quality control than is possible with site-built homes.

These benefits are important to BBH. The lower costs possible with factory-built homes are key to the overall market strategy—delivering zero energy homes for prices comparable to custom, site-built homes built to local codes. For site builders, the speed of enclosure and construction is also compelling. Black Bros. Builders specializes in zero energy homes, and the Lincolnville home was their first modular project. While the completion of the home has been significantly delayed by customization of interior systems and finishes, the building was fully enclosed within four weeks of the set. In the 12 months since this home was set (August 2014), Black Bros. has begun twelve more modular BBH projects. Modular has allowed them to significantly increase their production volume.

When CARB first interviewed Black Bros. on the site soon after the Lincolnville home was set, they expressed concern about the lack of control of building details. Construction details (especially air sealing) are critical for Black Bros.' zero energy projects, and they initially had concerns about attaining the same level of performance without full control of the construction process. Preliminary blower door tests showed less than 1 ACH when tested at 50 pascals (with further reductions expected), so Black Bros. clearly is able to achieve very good air sealing in these modular homes.

The speed of enclosure has added benefits in a cold, wet climate such as that of northern New England. Exterior work can be very challenging in winter months, and the amount of exterior work required with modular construction is significantly reduced. In addition, framing, sheathing, and other construction materials are far less exposed to the elements than in site-built homes.

### 4.3 Modular Coordination and Planning

Some of the challenges with BBH projects stem from the number of parties involved in the design and construction process. BBH serves as the architect and initial point of contact for many customers, but these customers ultimately also contract with a builder (such as Black Bros.), and the builder then contracts with the modular factory. With more parties involved, there is more potential for miscommunication and quality control gaps. Some builders are not as committed to the premium energy performance as Black Bros. and BBH, and many homeowners are not educated about the value of energy systems. One builder, for example, offered a customer savings by eliminating the foam insulation on the home's walls. BBH discovered this only after the boxes were on the line. While this did reduce modular construction costs, HVAC systems and PV system size needed to be adjusted to provide adequate comfort and achieve the zero energy goal. Learning from these early challenges, BBH has continuously improved communication and quality control of the entire design and construction process.

During design of the Lincolnville home, BBH architects specified the location of the heat pumps. Outdoor units were to be located on the west side of the home, mounted on the house 3–4 feet above the ground, and covered by a site-built shed roof to prevent accumulation of snow and ice. The Keiser factory was provided heat pump layouts, and Black Bros. coordinated with Keiser on the chases needed for line sets, condensate drains, and ducts (for the one ducted system).

After the set, the homeowners decided that they wanted the heat pump outdoor units located elsewhere. Black Bros.' HVAC contractor was able to accommodate the change, but it required at least one new chase and a longer line set for one heat pump. With modular construction, this type of change order can be more challenging than with custom, site-built homes. Careful planning and coordination of mechanical and plumbing systems before the boxes go on the line can streamline site work tremendously. BBH now has an approval and cross-check system in place to avoid similar situations.

In the factory itself, however, coordinating details is sometimes made easier because many parties involved are beneath one roof. Most trades (framers, insulators, electricians, plumbers, roofers, etc.) are usually at the factory, and this can be very useful when working out integration of new systems and details. For example, the windows and exterior foam details for the Lincolnville home were finalized in the factory with the architect, rater, factory supervisor, and key contractors. Getting all of these people to a construction site at the same time can be more challenging.

To help reduce gaps in communication and quality control, BBH made HERS ratings and ENERGY STAR certification standard at the beginning of 2015. Raters review plans and specifications, inspect boxes in the factory and conditions at the site, and test the completed homes. BBH believes this can reduce gaps in performance.

## 4.4 Envelope Systems

As with many high-performance homes, determining the best wall system involved maximizing energy performance and durability while minimizing cost. In modular homes, there are additional challenges:

- The time needed to build the wall cannot slow the production line.
- The wall must maintain its integrity during shipment and set.

During discussions with BBH and the Keiser factory, using multiple layers of exterior foam was dismissed for the first reason, and using 12-in. wall cavities insulated with cellulose was dismissed for the second (because of concerns about insulation settling). The current system seems to be practical and meets cost and performance requirements:

- Double-stud wall with staggered 2x4 studs built on 2x8 plates
- Certainteed smart vapor retarder on inside of studs
- Stud cavities insulated with dense cellulose
- ½-in. OSB sheathing meticulously air sealed
- 2-in. exterior foam (polyisocyanurate or XPS)
- House wrap providing a secondary drainage plane
- Vented siding attached to furring strips aligned to studs (installed on site).

Once the wall system and window bucks were determined (see window head detail in Figure 7), installation of triple-pane windows was very similar to installation in typical homes.

Achieving target levels of roof insulation (R-60 $ft^2h°F/Btu$) is challenging in homes without a vented attic. The tilt-up roof system typical for these modular homes uses 2x6 rafters. Filling these rafters with closed-cell spray foam would result in approximately R-30. In the Lincolnville home, Black Bros. added 4 in. of XPS above the roof deck and insulated the rafter bays with dense-blown cellulose, but this still missed the R-60 target (at approximately R-42). One of BBH's specifications for insulated roofs calls for constructing a dropped ceiling with gussets to create a cavity that can accommodate 9 in. of closed-cell spray foam (Figure 18). This is a costly detail, and it results in lower ceiling heights in spaces that may already have limited useful floor areas. With an 8/12 roof pitch, for example, sloped ceiling height would be lowered more than 5 in. It's understandable that builders have explored other insulation strategies, and this is a system BBH is working to improve.

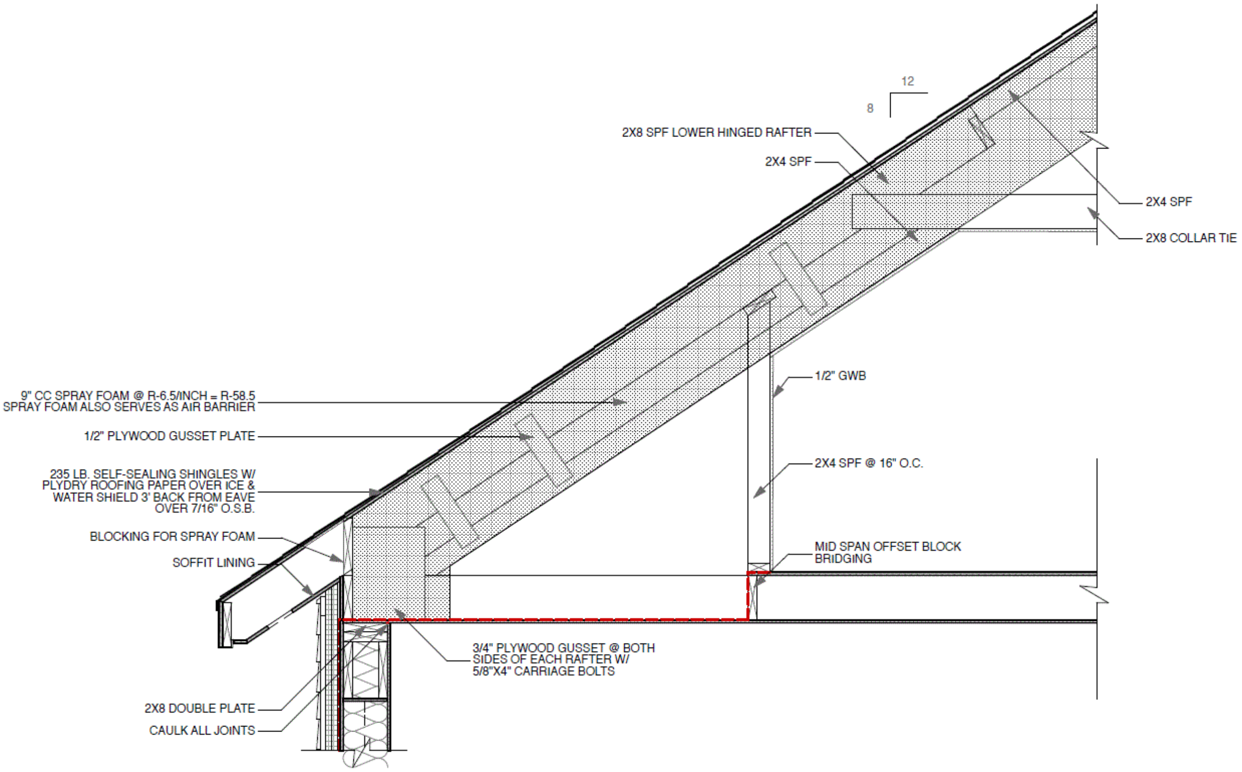

**Figure 18. Standard BrightBuilt Home detail for insulated roofs—gussets create a cavity for 9 in. of closed-cell spray foam.** ***Image from BrightBuilt Home***

## 4.5 Heating, Ventilating, and Air Conditioning

While ASHPs have been standard in BBH projects, there has been a wide range in equipment and system configuration (e.g., one or two ductless heat pumps, ductless heat pumps in every room, mix of ducted and ductless heat pumps). One reason for the variability is that customers have different desires with respect to zoning and control. Another key reason is that there is not yet a good understanding in the industry about what level of heating and cooling distribution is required to provide comfort in such low-load homes with low-capacity heating and cooling systems.

One last reason that BBH heating and cooling systems are not more standardized is that heat pump products in the United States are rapidly evolving. More manufacturers are providing products that work efficiently at low temperatures, some manufacturers are improving efficiencies, and some manufacturers are offering different configurations (e.g., ducted and ductless, single-zone and multi-zone). This has led to some unusual approaches. At the Lincolnville home, for example, the builder had a good relationship with a Mitsubishi distributor, and the ductless heat pumps are both Mitsubishi products. The ducted heat pump on the second floor, however, is a Fujitsu product because Mitsubishi did not have a single-zone, ducted system with published performance and low temperatures (below 0°F).

As described above, approaches to ventilation also vary widely. HRVs are used for whole-building ventilation in many homes, but solutions to local ventilation vary with preferences of customers and builders. When a single HRV provides ventilation to all parts of a home, planning for duct runs and outdoor air terminations are critical before the modular boxes go on the line. Ducted systems may require:

- Designing chase locations so duct runs can be site installed
- Factory installed ducts that are connected when boxes are set on site.

Either approach requires planning and attention to duct sealing in the factory and access to necessary ducts at the site.

# 5 Conclusions

Keiser Homes and BBH worked through a few iterations before settling on the 7.25-in. double 2x4 wall with cellulose insulation and 2 in. of rigid exterior foam. This system provides the desired R-value (approximately 35 $ft^2h°F/Btu$), is durable and affordable, and does not slow the modular production line. It is more challenging for builders to achieve target R-values for insulated roofs (R-60). Attaining R-60 in vented attics with loose-fill cellulose is straightforward, but these modular roofs have 2x6 rafters. Even with closed-cell spray foam, rafter cavity insulation is limited to approximately R-30. Builders need to extend the roof dimensions either upward (with rigid, insulating foam as in the Lincolnville home) or downward (with gussets and much deeper cavity insulation). This system is being refined as BBH and builders gain more experience with different strategies.

The BBH HVAC strategy has two core systems:

- ASHPs for heating and cooling
- Heat recovery ventilation for whole-building ventilation.

The types of systems and the way they are used vary significantly, however, depending on desires of the client, builder preferences, budget, etc. The simplest heating and cooling systems may have one or two ductless heat pumps; more complex systems have ducted heat pumps or a fan coil in every room. For ventilation, sometimes the HRV is used to provide local exhaust ventilation as well as whole-building ventilation. In other situations, clients and builders choose to install local exhaust ventilation in bathrooms and/or kitchens. It's likely that HVAC strategies will continue to evolve as BBH and their builders gain more experience and receive more feedback from customers. The growing diversity of ASHP and energy recovery ventilation and HRV products available in the United States will also play a role in HVAC strategies moving forward.

Since launching the product line in mid-2013, 25 BBH homes have been completed, 16 are currently under construction or under contract, and BBH has additional customer interest for dozens more. To date, homes have been completed in Maine, New Hampshire, Massachusetts, and Vermont. In addition to Keiser Homes, BBH now has agreements with modular manufacturers in New Hampshire and Pennsylvania to expand the geographical range of the homes. Although few data are available yet to determine how many homes are achieving zero net energy consumption, Building Energy Optimization modeling showed 41% source energy savings without PV and 77% savings with PV. Modeling shows that the Lincolnville home will save $2,400/year in energy costs. Although these homes carry a premium compared to standard, code-compliant modular homes, data show that turnkey costs of BBH homes are similar to costs of more conventional, stick-built speculation homes. The BBH paradigm—providing ZERHs at the affordable prices allowed by modular construction—has market appeal, and BBH has seen steady growth in demand during their first two years.

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DOE/GO-102016-4800 ▪ March 2016