BUILDING TECHNOLOGIES OFFICE

Transformations, Inc.: Partnering To Build Net-Zero Energy Houses in Massachusetts

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Building Science Corporation

September 2013

U.S. Department of Energy

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Transformations, Inc.: Partnering To Build Net-Zero Energy Houses in Massachusetts

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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

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Unless otherwise noted, all figures were created by Building Science Corporation.

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Definitions

ACH	Air changes per hour
ACP	alternative compliance payment
ADA	airtight drywall approach
ASHP	Air source heat pump
BSC	Building Science Corporation
Btu	British thermal unit
ccSPF	Closed-cell spray polyurethane foam
CFM	Cubic feet per minute
COP	Coefficient of performance
DOE	U.S. Department of Energy
DOER	Massachusetts Department of Energy Resources
ft^2	Square foot, square feet
HDD	Heating degree day
MC	Moisture content
NREL	National Renewable Energy Laboratory
ocSPF	Open-cell spray polyurethane foam
o.c.	On center
OSB	Oriented strand board
PCF	Pounds per cubic foot
PV	Photovoltaic
RH	Relative humidity
RPS	Renewable Portfolio Standard
SEER	Seasonal energy efficiency ratio
SHGC	Solar heat gain coefficient
SREC	Solar Renewable Energy Certificate
T/RH sensor	Temperature/relative humidity sensor
Wh	Watt-hour
XPS	Extruded polystyrene

Executive Summary

Transformations, Inc. is a residential development and building company that has partnered with Building Science Corporation (BSC) to build new construction net-zero energy houses in Massachusetts under the Building America program.

There are three communities that are being constructed through this partnership: Devens Sustainable Housing ("Devens"), The Homes at Easthampton Meadow ("Easthampton"), and Phase II of the Coppersmith Way Development ("Townsend"). This report covers all of the single-family new construction homes that have been completed to date.

The houses built in these developments are net-zero energy capable homes built in a cold climate. The set of measures offered by the developer exceeds the 30% energy saving goals set by the Building America program for new homes in the cold climate for 2013. The houses will contribute to developing solutions and addressing gaps in enclosures and space conditioning research; specific topics included the following:

- To determine the range of temperatures experienced in bedrooms of homes heated by point sources, data loggers were installed at two unoccupied and two occupied houses. The first year of data from the unoccupied homes show that under favorable conditions, mini-split heat pumps can provide thermal comfort and uniformity equal to conventional forced-air systems.
- The homebuyers' perception of ductless mini-split heat pumps' performance was examined using surveys that were distributed to the homeowners in all three developments. The occupants have reported high levels of comfort, consistent with the measured temperature uniformity. Most occupants seem to accept the concept of keeping bedroom doors open most of the time, facilitating thermal distribution and thus enhancing comfort.
- The moisture risks of 12-in. thick double-stud walls insulated with cellulose or open-cell spray foam were researched with moisture monitoring experiment at one of the houses in Devens. Eight months of data have been collected and analyzed to date (from December 2011 through July 2012) in unoccupied conditions. The first winter showed sheathing moisture contents high enough to cause concern in the double-stud cellulose wall, but acceptable conditions in the remaining walls. However, all walls dried to safe ranges in the summer. In addition, it is possible that the cellulose wall can withstand high moisture content levels without damage due to borate preservatives and moisture storage. BSC is continuing to collect data (currently August 2013); further analysis will be contained in future BSC reports. The first winter measured data without occupancy (and thus interior moisture generation); the upcoming winter will demonstrate the effect of higher interior humidity levels.
- Hygrothermal modeling was not performed at this time, with eight months' of data. The planned process is to only perform hygrothermal modeling (for comparison with monitored results) after the collection of at least one year of data, and preferably more (to account for the initial year's unoccupied conditions).

- BSC worked with Transformations, Inc. to evaluate the options that are available to homeowners for obtaining photovoltaic systems. The developer has put substantial research and effort into developing affordable and viable alternatives. Local incentives—as well as state and federal tax credits—contribute to making the residential photovoltaic systems financially attractive. BSC explored the financing models provided by the developer and looked at each available option in detail. Cost values and payback time were analyzed and compared to evaluate what each of those options has to offer. Incentive programs differ substantially in each state; therefore, a number of resources were provided to homebuyers to learn the details about the available options.
- To determine the relative costs of additional above-grade space and basement space, BSC worked with the developer to compare a number of options available to the homebuyers. The cost analysis began by comparing the per square foot cost data for constructing a basement and a slab-on-grade foundation. The difference between the two approaches was found to be $12 with the basement cost at $39 and the slab-on-grade cost at $27. Several options for adding above-grade space, including unfinished and finished space above the garage, and building a one-story addition, were also explored and were found to range between $1.30–$125/ft^2.

1 Introduction

Transformations, Inc. is a residential development and building company that has partnered with Building Science Corporation (BSC) to build new construction net-zero energy houses in Massachusetts under the Building America program.

There are three communities that are being constructed through this partnership: Devens Sustainable Housing ("Devens"), The Homes at Easthampton Meadow ("Easthampton") and Phase II of the Coppersmith Way Development ("Townsend"). This report covers all of the single-family new construction homes that have been completed to date in Devens and Easthampton, as well as three homes in Phase II in Townsend. Currently, there are six houses that have been completed in the Devens development, seven houses in the Easthampton community, and three houses in the Townsend development.

Transformations, Inc. completed one community development and multiple custom homes prior to partnering with BSC. Since 2006, the developer has been developing strategies for cost-effective super-insulated homes in the New England market. Several construction methods for walls, roofs, basements, as well as mechanical and ventilation systems have been tested by the developer. After years of using various construction techniques, Transformations, Inc. has developed a specific set of assemblies that is implemented in the houses in all three developments. These assemblies exceed the requirements of current building codes and are financially viable for the developer.

The houses built in these developments are net-zero energy capable homes built in a cold climate and contribute to research on topics including high R-value double-stud walls, high efficiency ductless air source heat pump (ASHP) systems ("mini-splits"), including occupant satisfaction and feedback; financing of photovoltaic (PV) systems; and basements versus slab-on-grade construction. The research questions were as follows:

- What range of temperatures is experienced in bedrooms of homes heated by point sources?
- How do buyers perceive the performance of the ductless mini-split heat pumps? Are the room-to-room temperature differences in homes with ductless heat pumps apparent to the residents?
- Does the use of open cell spray foam (ocSPF), rather than cellulose, in the wall cavities of double-stud walls change the moisture content of the wall assembly? Does this change the risk assessment for this construction approach?
- Do results of hygrothermal analysis correlate with field-measured moisture contents, in terms of risks of wintertime moisture accumulation in wood-based sheathings?
- How can a PV array sufficient for net-zero performance be financed with no or minimal increase in annualized energy-related cost to the homeowner, through Solar Renewable Energy Certificates (SRECs) and novel finance agreements? How can this model be applied to regions outside of Massachusetts?

- Basements are a common feature of cold climate construction, but they present special challenges for insulation and water management. How does the per square foot cost of basements compare to adding above-grade space?

With the high efficiency features used in the construction of these homes, the houses meet the requirements of the U.S. Department of Energy's (DOE) Version 2 of the Builders Challenge program—the DOE Challenge Home—under the prescriptive path. The program requires that the homes are 40%–50% more energy efficient than a typical new home and are certified through a third-party company. The program requirements are as follows:

- Fulfill the requirements of the ENERGY STAR® for Homes Version 3.
- Comply with the requirements of the U.S. Environmental Protection Agency's (EPA) Indoor airPLUS checklist.
- Use ENERGY STAR-qualified appliances.
- Use high performance windows that meet ENERGY STAR requirements.
- Use insulation levels that meet 2012 International Energy Conservation Code.
- Install ducts in conditioned space.
- Use highly energy efficiency hot water equipment.
- Install solar systems that follow requirements of EPA Renewable Energy Ready Home (in climates with significant solar insolation).

1.1 Devens Sustainable Housing

The Devens development is a net-zero energy community located in Fort Devens, Massachusetts, where the developer was awarded the contract to build eight one- or two-story single-family houses of 1,064–1,820 ft^2.

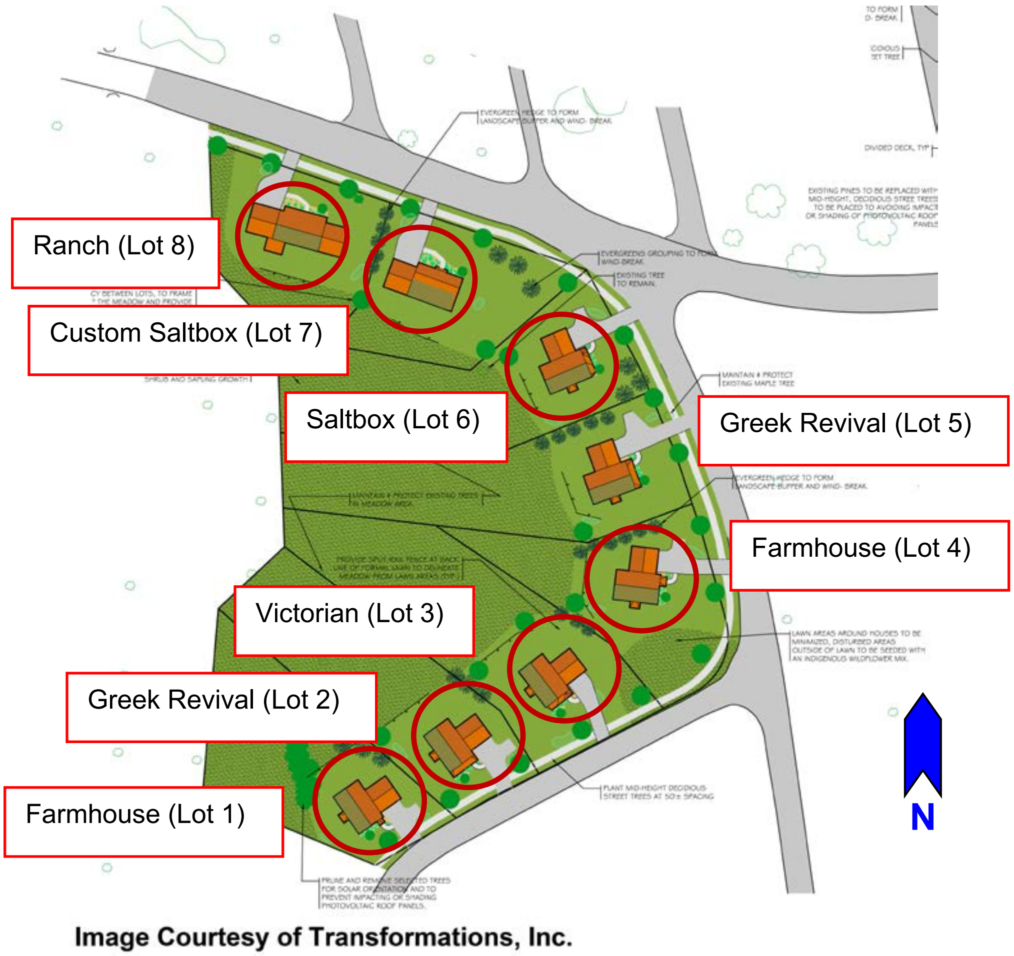

Figure 1. Devens sustainable housing site plan

As of August 2013 all of the homes in the development have been completed and occupied.

Figure 2. (L) Farmhouse (Lot 1); (R) Greek Revival (Lot 2)

Figure 3. (L) Victorian (Lot 3); (R) Farmhouse (Lot 4)

Figure 4. (L) Greek Revival (Lot 5); (R) Saltbox (Lot 6)

Figure 5. (L) Custom Saltbox (Lot 7); (R) Ranch (Lot 8)

The houses feature three or four bedrooms as well as an optional basement. The construction of the houses is shown in Figure 6. The enclosure characteristics include full basements with 2 in. of extruded polystyrene (XPS) rigid insulation (R-10) under the slab and 3½ in. of closed cell spray foam (ccSPF) insulation (R-20) at the basement walls, a double-stud wall with 12 in. of ocSPF (0.5 per cubic foot [PCF]) insulation (R-46 nominal) and 18 in. of cellulose insulation in the attic (R-63). The mechanical system consists of two single-head mini-split units, a ventilation unit, as well as a tankless propane water heater. A PV array is also part of the house package.

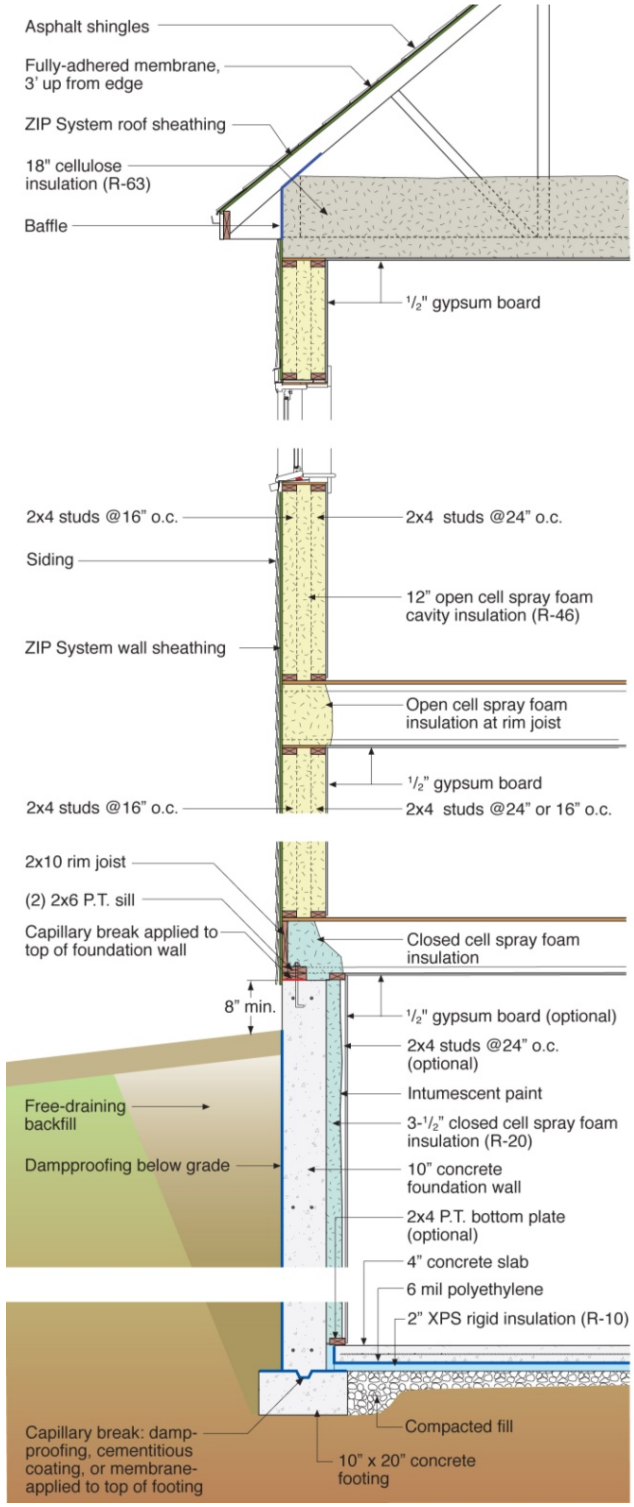

Figure 6. Wall section with basement

The work performed in the Devens development that will be discussed in this report includes moisture monitoring of the double-stud walls and heat pump monitoring in the Victorian (Lot 3), feedback from the homeowners on the heat pump performance, and air leakage testing results from all of the houses built to date.

1.2 The Homes at Easthampton Meadow

The Easthampton development is a net-zero energy capable community located in Easthampton, Massachusetts. Transformations, Inc. partnered with Beacon Communities LLC (a Boston-based development company) to build 33 one- or two-story, single-family houses of 1,064–2,365 ft^2 (Figure 7). The houses feature two, three, or four bedrooms; the development includes market-rate as well as affordable units.

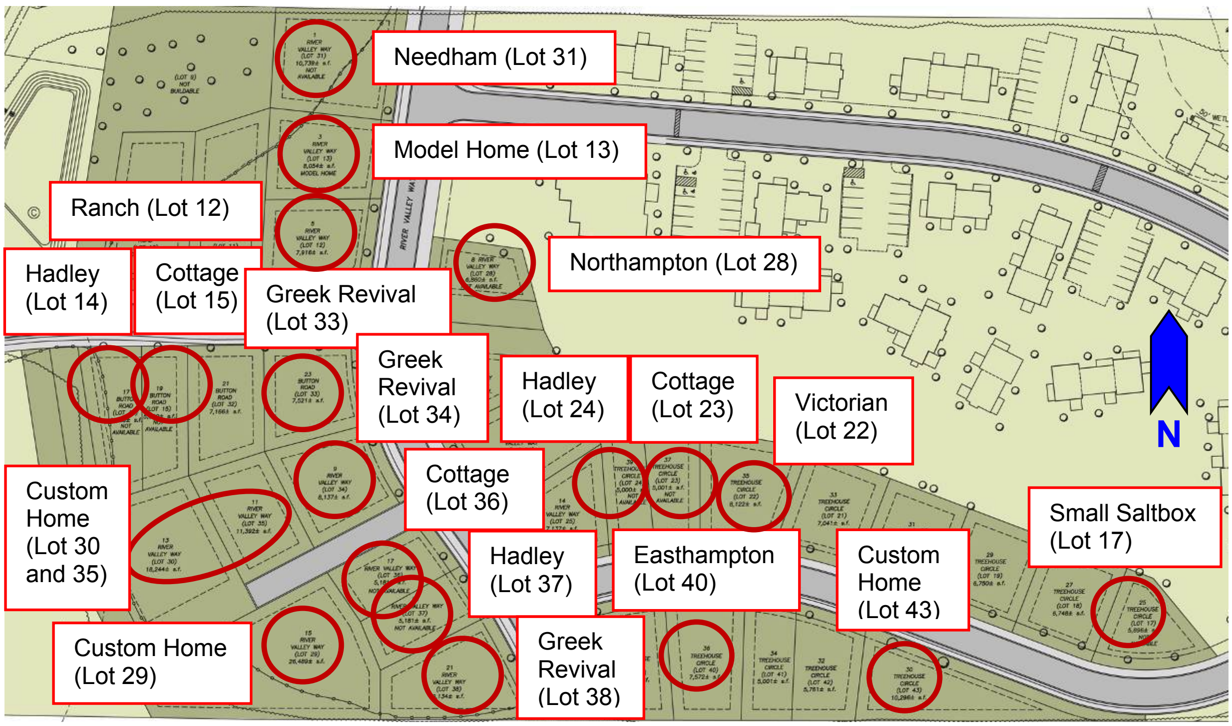

Figure 7. The homes at Easthampton Meadow site plan

Seven houses have been completed at the Easthampton community (Figure 8 through Figure 11):

- The Model Home (Lot 13)
- Four market-rate homes: Custom Home (Lot 29), Custom Home (Lot 30 and 35), Custom Home (Lot 43) and Easthampton (Lot 40)
- Five affordable homes: Small Saltbox (Lot 17), Cottage (Lot 23), Hadley (Lot 24), Northampton (Lot 28) and Needham (Lot 31).

The following houses are currently under construction:

- Market-rate homes: Ranch (Lot 12), Victorian (Lot 22), Victorian (Lot 26), Greek Revival (Lot 33), Greek Revival (Lot 34), Greek Revival (Lot 38)
- Four affordable homes: Hadley (Lot 14), Cottage (Lot 15), Cottage (36) and Hadley (Lot 37).

Figure 8. (L) Model Home (Lot 13); (R) Custom Home (Lot 30)

Figure 9. (L) Custom Home (Lot 43); (R) Easthampton (Lot 40)

Figure 10. (L) Northampton (Lot 28); (R) Needham (Lot 31)

Figure 11. (L) Cottage (Lot 23) and Hadley (Lot 24); (R) Small Saltbox (Lot 17)

The slab-on-grade foundations include 6 in. of XPS rigid insulation (R-30) under the slab and 4 in. of XPS rigid insulation (R-20) at the edge of the slab (Figure 12, left). Half-height and full-height basements are optional if the particular lot is amendable, given local water and soil conditions. Walls are 12-in. double-stud walls with 12 in. of ocSPF (0.5 PCF) insulation (R-46 nominal); the vented attics are insulated with 18 in. of cellulose insulation (R-63). The mechanical system consists of one or two single-head mini-split units, a ventilation unit, and a tankless gas water heater. A PV array is offered to the homebuyers for either purchase or lease.

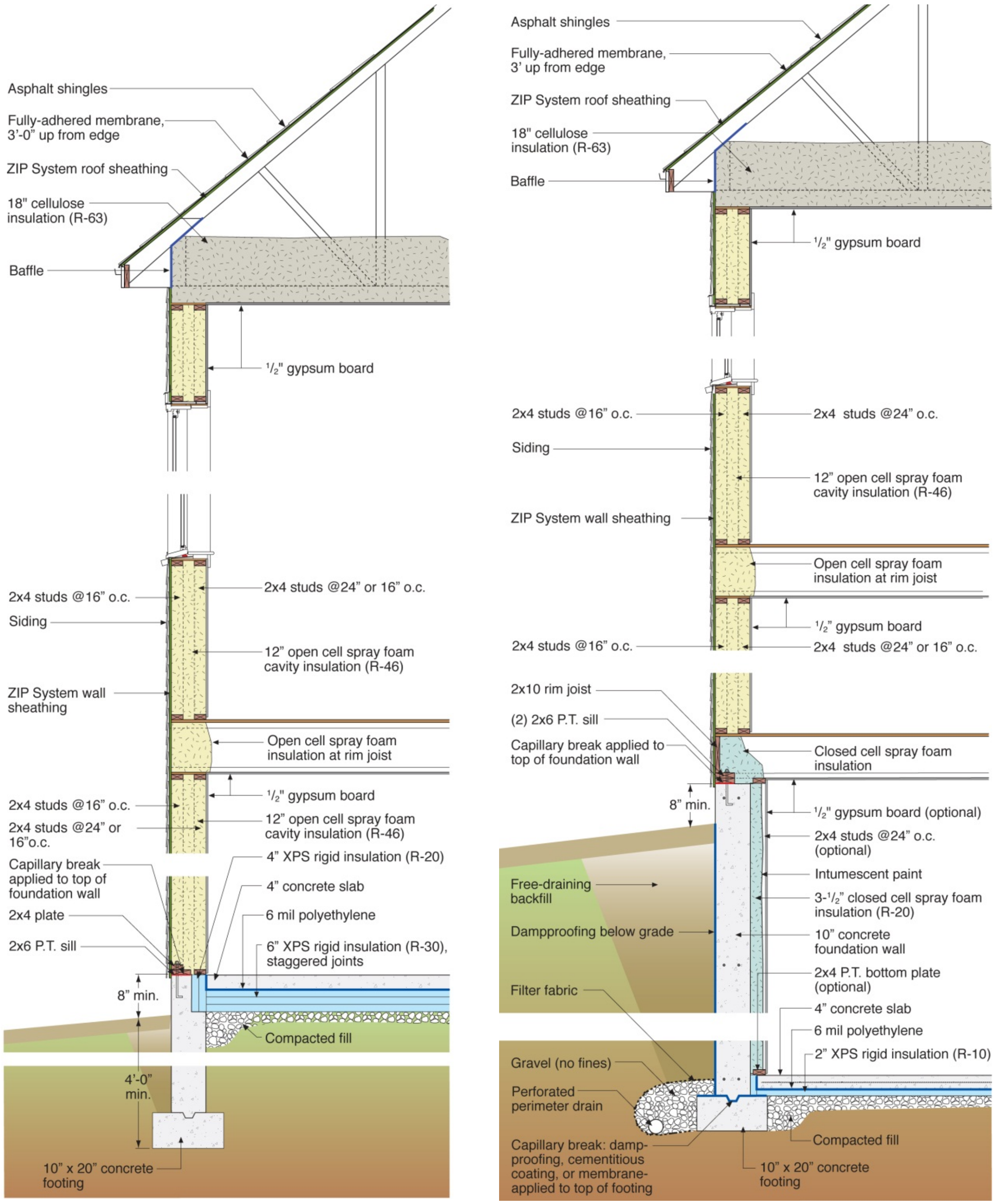

Figure 12. (L) Wall section with slab-on-grade; (R) basement

The work performed in the Easthampton development that will be discussed in this report includes heat pump monitoring at the Model Home (Lot 13), the Small Saltbox (Lot 17) and the Cottage (Lot 37). The research also covers feedback from the homeowners on the heat pump performance, and air leakage testing results from all of the houses built to date.

1.3 Coppersmith Way Development

The Townsend development is located in Townsend, Massachusetts and is made up of 41 single- and multifamily homes and has been divided into three phases (Figure 13). Phase I of the project consisted of 15 units with 13 units that were built by Transformations, Inc., and one lot and one existing house that were sold. It began in January of 2006 and was completed in August of 2008. Phase II with 15 homes is currently under way and Phase III of the project, which consists of 11 homes, is planned for the future. The houses in Phase II of the project are one to two stories tall and feature two, three, or four bedrooms.

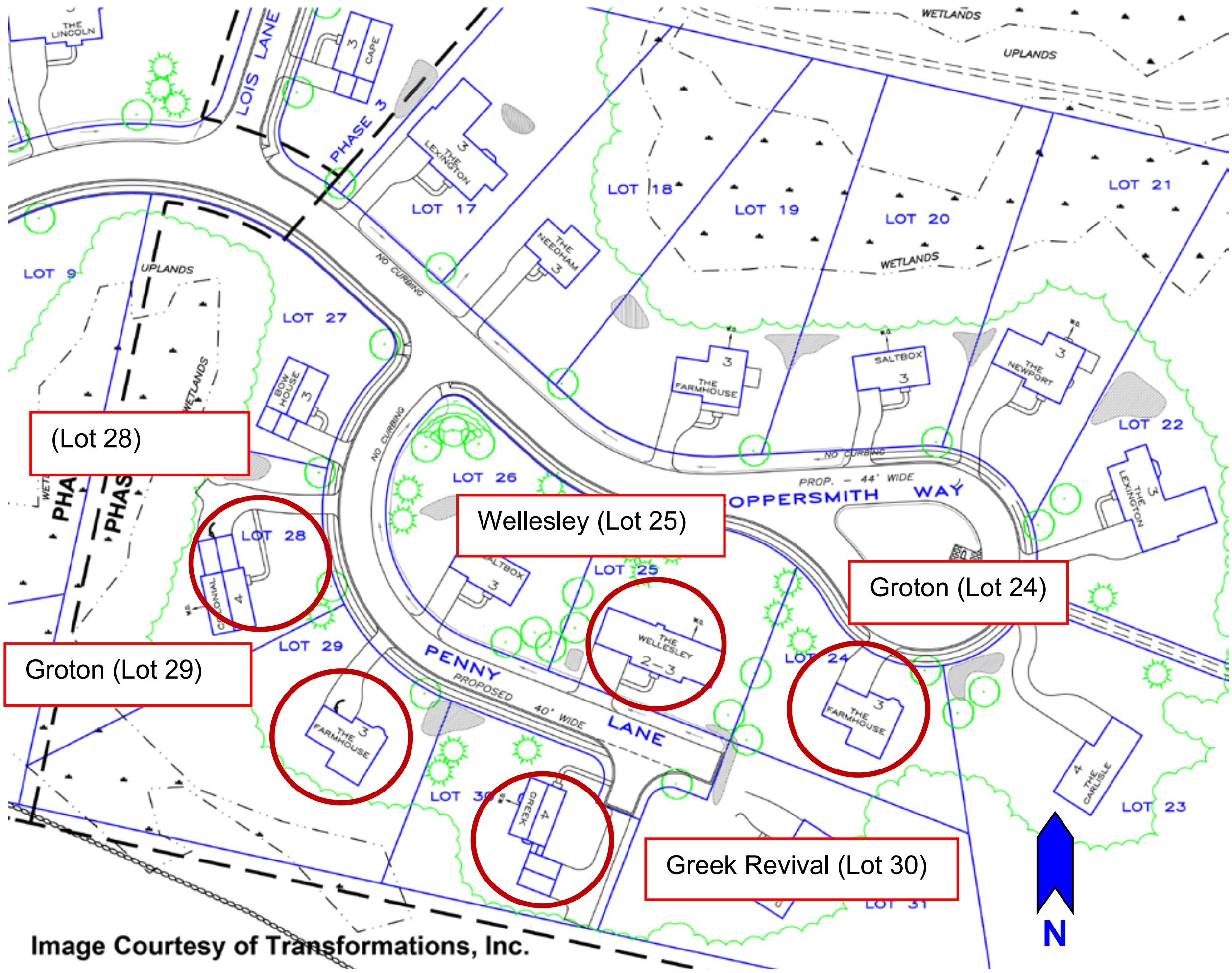

Figure 13. Coppersmith Way development site plan

Transformations, Inc. had completed several homes in Phase II of the Townsend development prior to working with BSC. The team collaborated on three homes: Groton (Lot 24), Wellesley (Lot 25), and Groton (Lot 29) (see Figure 14 and Figure 15.). As of July 2013, one additional house has been completed, the Greek Revival located on Lot 30, and one additional house is under construction, lot 28.

Figure 14. (L) Groton (Lot 24); (R) Wellesley (Lot 25)

Figure 15. (L) Groton (Lot 29); (R) Greek Revival (Lot 30)

The construction of the houses is similar to the houses in the Devens development with the exception of using natural gas for the tankless water heater in the Groton (Lot 24) (Figure 14).

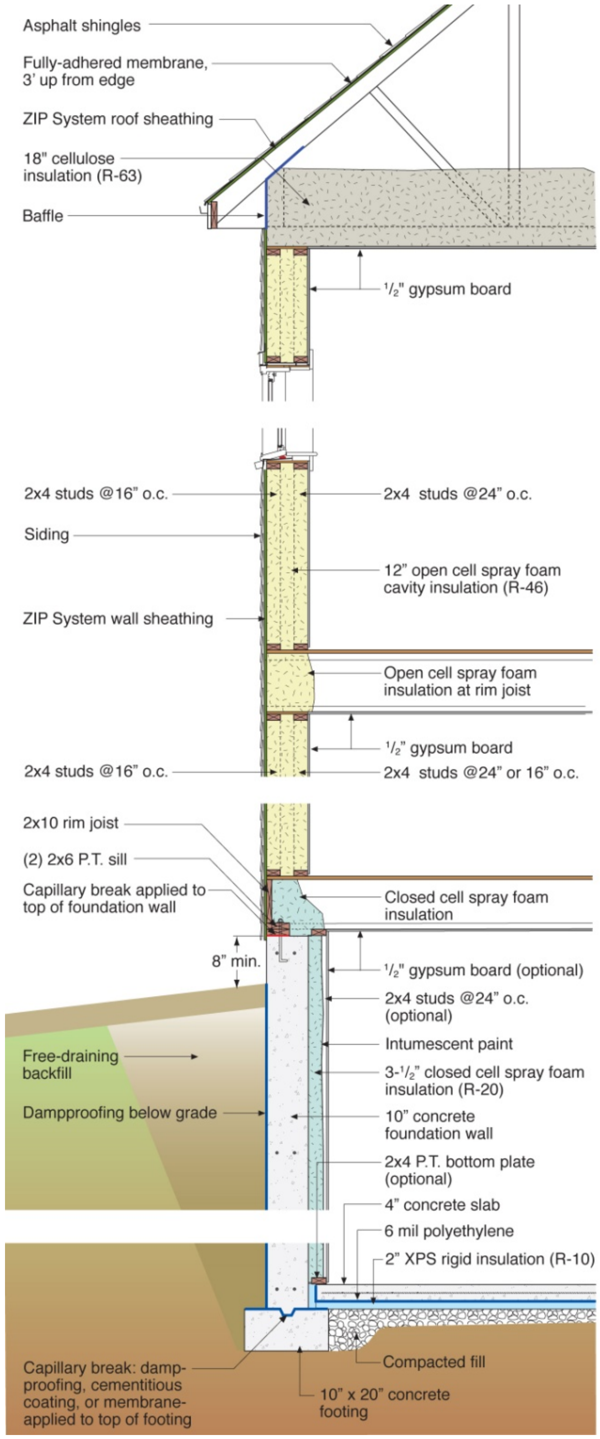

Figure 16. Wall section with basement

The work performed in the Townsend development that will be discussed in this report includes heat pump monitoring over the winter of 2010–2011 at the Groton (Lot 24), as well as feedback from the homeowners on the heat pump performance and air leakage testing results from all three houses.

2 Air Leakage Testing

A multipoint air leakage (blower door) test was performed at all of the homes built to date in all three developments. This was done for the purposes of quality control and continuing improvement. The testing was performed by BSC as well as third-party raters that work directly with the developer. The test results are listed in Table 1 through Table 3.

Table 1. Air Leakage Test Results in the Devens Sustainable Housing Development

House	House Name	CFM50	ACH50	Square Inch Leak/ 100 ft^2	CFM50/ Square Foot Enclosure
Lot 2	Greek Revival	450	1.4	1.1	0.10
Lot 3	Victorian	579	1.9	1.4	0.13
Lot 6	Saltbox	425	1.2	1.0	0.09
Lot 7	Custom Saltbox	481	1.1	0.9	0.09

Table 2. Air Leakage Test Results in the Homes at Easthampton Meadow Development

House	House Name	CFM50	ACH50	Square Inch Leak/ 100 ft^2	CFM50/ Square Foot Enclosure
Lot 13	Model Home	363	1.3	0.9	0.08
Lot 30	Custom Home	304	0.8	0.6	0.06
Lot 43	Custom Home	400	1.5	1.0	0.10
Lot 17	Small Saltbox	160	1.0	0.6	0.06
Lot 23	Cottage	156	1.0	0.5	0.05
Lot 24	Hadley	150	0.7	0.5	0.05
Lot 40	Easthampton	186	0.9	0.7	0.07

Table 3. Air Leakage Test Results in the Coppersmith Way Development

House	House Name	CFM50	ACH50	Square Inch Leak/ 100 ft^2	CFM50/ Square Foot Enclosure
Lot 24	Groton	430	1.1	0.7	0.07
Lot 25	Ranch	439	1.2	0.8	0.08
Lot 29	Groton	320	0.8	0.6	0.05

BSC performed the blower door test in the Model Home (Lot 13) in Easthampton after the interior finishes were in place but prior to the installation of the mechanical systems. The testing equipment was set up in the side door to the garage (Figure 17) and the test was performed after sealing off the exposed appliance connections, such as the PV inverter connection and the not-yet-connected tankless water heater intake and exhaust vents, as shown in Figure 18.

Figure 17. (L) Model home garage side; (R) house side

Figure 18. (L) PV inverter connection; (R) tankless water heater intake and exhaust vent

The results are presented in terms of CFM (cubic feet per minute) at 50 Pascals (Pa) test pressure, air changes per hour (ACH) at 50 Pa, square inches (EqLA) per 100 feet surface area leakage ratio, and CFM50/ft^2 of enclosure area (all six sides).

The Greek Revival (Lot 2) in the Devens development was the first house to be constructed and initially had the highest CFM50 result—682. This was due to several penetrations, such as sprinklers and a second-floor top plate that were not sealed properly. Also, the airtight drywall approach (ADA, or the use of interior gypsum board with air sealing details as an air barrier; see Lstiburek 1983, Lstiburek 2000, Lstiburek 2005, Holladay 2010) was not utilized on this project. After the final test was performed, the builder returned to the house to air seal the penetrations, which resulted in the improvement of 232 CFM50.

The Model Home (Lot 13) in Easthampton was the first house to be built in that development. The ADA was implemented in this house and all penetrations were sealed using caulk.

In the Townsend development, the two Groton houses built on lot 24 and 29 have the same footprint, but there is a noticeable difference between the CFM50 results in those homes. The ADA was utilized in the Groton on Lot 29.

Typical range for Building America infiltration benchmark for the houses is 8.8–10.4 ACH50. The DOE Challenge Home infiltration benchmark for climate zone 5 is 2 ACH50. All houses in all three developments meet these requirements.

3 Construction Cost and Energy Modeling

3.1 Construction Cost

The following table includes information regarding the cost of material and labor for the various energy-efficient building components based on the developer's previous projects. Incremental costs can be determined by subtracting upgraded option costs from the provided basic options. The mechanical system costs are installed costs.

Table 4. Construction Costs

Component	Option	Cost
Attic Insulation	Blown-in cellulose (R-63), ccSFP flash and seal[a]	$3.50/ft^2$
Wall Framing	2 × 6 @ 24 o.c.[a]	$0.80/ft^2$
Wall Framing	Double-stud wall, 2 × 4 @ 16 in. inside and outside[a]	$1.05/ft^2$
Wall Framing	Double-stud wall, 2 × 6 @ 16 in. outside, @ 24 in. inside[a]	$1.07/ft^2$
Wall Insulation	1-in. polyisocyanurate (R-6.5), 5½-in. cellulose (R-20)[a]	$2.85/sf
Wall Insulation	2-in. XPS (R-10), 9-in. cellulose (R-33)[a]	$4.50/ft^2$
Wall Insulation	4-in. polyisocyanurate (R-26), 3-in. ccSPF (R-18), 8½-in. cellulose (R-31), zip wall system[a]	$10.55/ft^2$
Wall Insulation	12-in. cellulose (R-45)	$3.60/ft^2$[b]
Wall Insulation	12-in. ocSPF (R-46)	$3.60/ft^2$[b]
Basement Ceiling Insulation	3-in. ccSPF (R-18), fiberglass (R-30)[a]	$4.40/ft^2$
Basement Ceiling Insulation	Fiberglass (R-38)[a]	$1.50/ft^2$
Basement Wall Insulation	2-in. polyisocyanurate (R-13)	$3.12/ft^2$
Basement Wall Insulation	(2) layers of 1½-in. rigid foam (R-20)	$5.00/ft^2$
Basement Wall Insulation	3–3½ in. of ccSPF with intumescent paint (R-20)	$3.97/ft^2$
Basement Slab	2-in. EPS (R-8)[a]	$1.23/ft^2$
Basement Slab	6-in. XPS (R-30)	$3.58/ft^2$
Windows	Paradigm, vinyl, triple-pane (R-5)[a]	$412.53 each
Windows	Harvey, vinyl, triple-pane (R-5)	$240.00 each
Air Sealing Water Management	Airtight drywall approach (ADA) ZIP system wall sheathing, material cost only	$250/house $0.49/ft^2$[c]
Heating/Cooling	Mitsubishi mini-split ductless heat pump (one head per floor) Per MSZ-FE12NA/MUZ-FE12NA	$2,950/head
DHW	Navien tankless instantaneous water heater (NR-180 (NG))	$1,900
Ventilation	Panasonic 30 cfm exhaust only fan with boost option, two fans ("basic requirement")	$250 each
Ventilation	Panasonic ERV, spot open location 20–40 CFM, plus a bath fan, add to "basic requirement"	$800 each
Ventilation	Fantech 704 HRV, exhaust one bathroom, supply one location, add to "basic requirement"	$1,500 each

Component	Option	Cost
Ventilation	Fantech 1504 HRV in closet near bathroom, exhaust three bathrooms, supply one location, add to “basic requirement”	$1,600 each
Ventilation	Fantech 1504 HRV in basement, exhaust three bathrooms, supply one location, add to “basic requirement”	$2,400 each
Ventilation	Fantech 1504 HRV in basement, exhaust three bathrooms, supply three bedrooms, add to “basic requirement”	$3,000 each
Ventilation	LifeBreath HRV in basement, exhaust three bathrooms, supply three bedrooms, add to “basic requirement”	$3,500 each
Lighting	Compact fluorescent lamps provided by ENERGY STAR/utility	$0
Appliances	ENERGY STAR refrigerator, dishwasher, clothes washer and dryer	Market
Photovoltaics	Net in Massachusetts after incentives	$1.80/Watt$_p$

[a] Not used in current construction.
[b] As noted previously in the report, the equivalent pricing between 12 in. of cellulose and ocSPF is the current pricing offered by the insulation subcontractor, and may not necessarily be representative of market conditions.
[c] Material cost only.

3.2 Energy Modeling and Cost Effectiveness of Energy Efficient Measures

The goal of the Building America program for new homes in the cold climate is to achieve a 30% reduction in energy use by 2013 and 50% by 2017.

The energy and cost-effectiveness analyses for the “Farmhouse” model were performed using BEopt (Christensen and Anderson 2006), the Building America performance analysis tool. This tool includes an optimization capability that uses user-supplied cost data and energy use information for a specified set of energy-saving measures to determine combinations of measures that are optimal or near optimal in terms of cost effectiveness. On a graph that plots the average source energy savings per year against the annualized energy-related costs, the optimal packages are those that form the lower bound of the plotted data points. BEopt uses a sequential searching technique so that not every possible combination of options is simulated.

For the BEopt optimization prepared for this report, the cost values listed in Table 4, which were provided by the developer, were used in combination with the default cost values for new construction.

The BEopt optimization of the enclosure compared 12 in. of ocSPF insulation (R-46) and 12 in. of cellulose insulation (R-45) installed in the above-grade double-stud walls. Different R-value levels of cellulose insulation at the attic floor were also compared: R-63, R-49, and R-38. For the basement wall insulation, three options were selected: R-20 ccSPF, R-20 rigid insulation, and R-10 rigid insulation. Window types compared in the optimization were Harvey low-e, triple-glazed units (U = 0.19; solar heat gain coefficient [SHGC] = 0.21), and standard low-e, double-glazed windows (U = 0.34; SHGC = 0.30).

Two space conditioning options for the heat pump were included for the optimization: mini-split ductless heat pump with seasonal energy efficiency ratio (SEER) 23/heating season performance factor 10.6 and mini-split ductless heat pump with SEER 16/heating season performance factor 8.6. Enclosure airtightness options included: "Tightest" (1.7 ACH50) and "Tighter" (3.3 ACH 50).

The BEopt optimization simulated the combinations of options for the Farmhouse model and an optimization curve was created (Figure 19). The selected point represents the measures implemented in the homes in all three developments. The measures include R-46 walls with ocSPF insulation, R-63 of cellulose insulation in the attic, R-20 rigid insulation for the basement walls, and Harvey triple-glazed windows. The SEER 23 ASHP was selected for space conditioning, with the "Tightest" infiltration rate for the enclosure. The difference in source energy use between the "B10 Benchmark" and "Maximum Savings" projected by BEopt was 110.7 MBtu/yr, or a 44.9% reduction (Figure 19).

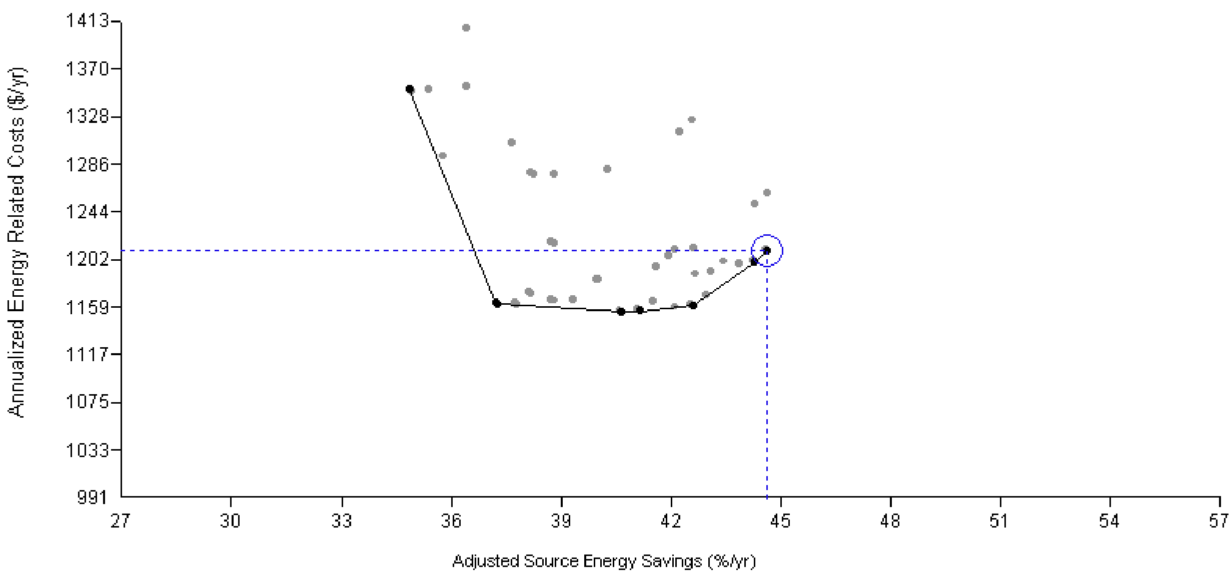

Figure 19. Farmhouse BEopt optimization results—cost versus energy use

The most optimal design in terms of annual energy related cost savings and source energy savings yields a 37.5% reduction, or 93.2 MBtu/yr (Figure 20). The measures for this option include R-45 walls with cellulose insulation, R-38 of cellulose insulation in the attic, R-10 rigid insulation for the basement walls, and Harvey triple-glazed windows. The SEER 16 ASHP was selected for space conditioning, with the "Tightest" infiltration rate for the enclosure.

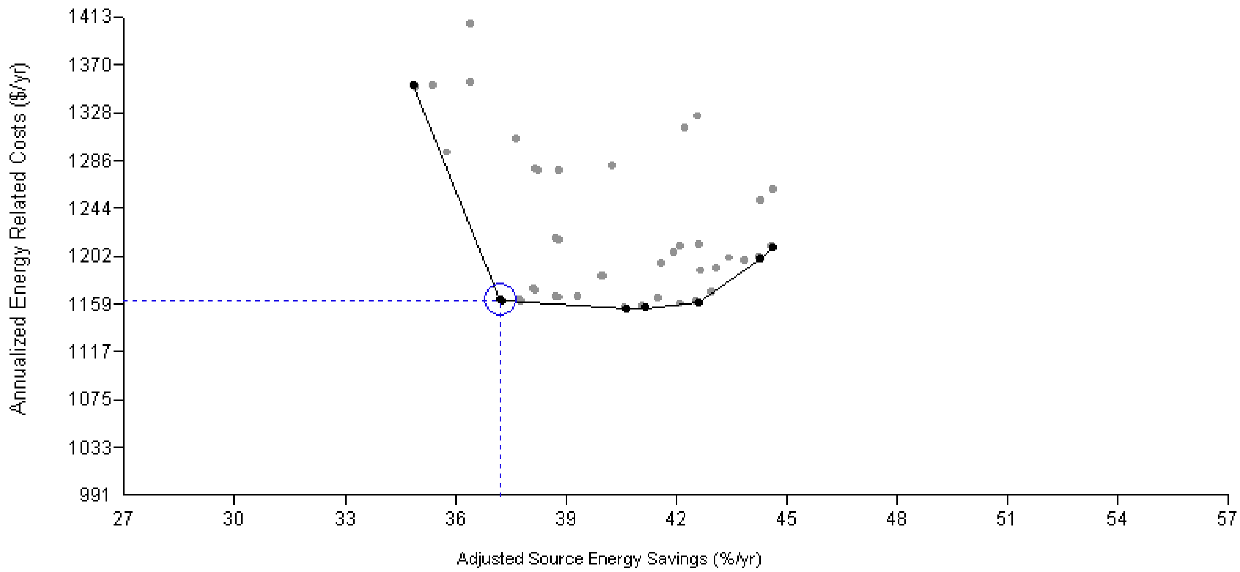

Figure 20. Farmhouse BEopt optimization results—cost versus energy use

The set of measures offered by the developer for the houses in the Devens, Easthampton, and Townsend developments exceeds the 30% energy savings goal set by the Building America program for new homes in the cold climate for 2013. With the high efficiency components these homes are very close to achieving the 50% reduction in energy use set for 2017.

3.3 Performance Data

The estimated annual energy cost for the Model Home (Lot 13) was obtained from the Home Energy Rating Certificate and is projected to be $88 (see Appendix B). The cost was determined by the REM/*Rate* software package, which was created by Architectural Energy Corporation.

The developer indicated that the incremental cost for energy efficiency measures implemented in the house as compared to a house built to 2012 International Residential Code is $\$3/ft^2$.

4 Mini-Split Heat Pump Performance and Thermal Distribution

4.1 Background

Conventional furnaces and split-system air conditioners are an awkward fit to high efficiency homes being built today. It is common for such homes to have design loads below 1.5 tons, which is the smallest size of split cooling system generally available. High SEER systems are often unavailable below 2 tons. For furnaces, 40 kBtu/h (3.3 tons-equivalent) is the smallest common size. For reference, the houses analyzed in this report have cooling loads below 1 ton, and heating loads of less than 1.5 tons. Holladay (2011) discusses the problem of selecting space conditioning equipment for low-load houses, and proposes various solutions.

Reduced mechanical system cost is often given as one of the benefits of increased building insulation and airtightness. Unfortunately, the upfront savings from reducing capacity with a conventional split system or furnace by 1 ton (to the smallest available) are modest, as most of the cost is in the labor of installation.

As annual energy demand for space heating drops, the cost of installing and maintaining gas distribution becomes harder to justify. When monthly service charges and increased mortgage cost are counted as part of the heating cost, heat pumps and additional PV can be more cost effective than a gas furnace. This is true even in cold climates (e.g., Massachusetts), and even when the furnace would use somewhat less energy on a source (primary) basis.

Ductless split-system heat pumps (“mini-splits”) offer a tempting answer to all of these problems. They are available in sizes from 0.75 tons to 1.5 tons. Transformations, Inc. has found the installed cost to be about $3000 less than a fully ducted conventional system. Similar prices are reported in other areas where local convention is to use sheet metal ducts for space conditioning distribution. Many mini-splits have a rated coefficient of performance (COP) above the best ducted heat pumps available, and variable-speed compressors, which render them even more efficient at off-peak conditions. Recently, mini-splits have come to market that maintain high heat output at 5°F or below, making them viable for cold climates. The remaining—and substantial—challenge for wider deployment of mini-splits is the uncertainty surrounding thermal comfort in houses without distribution of hot and cold air to every room.

The energy consumed by an ASHP depends on the building load and the outdoor temperature. For heat pumps with variable-speed compressors (including the mini-splits studied in this project), the COP depends strongly on both of these variables. This is in contrast to the efficiency of combustion systems, which are only weakly dependent on duty cycle and essentially independent of outdoor temperature.

Air sealing and super-insulation of buildings changes not only the total annual loads, but the distribution of those loads over time. With the exception of lighting, energy-efficient houses are assumed to have the same internal heat gains as existing or built-to-code houses. These internal gains reduce the heating load (or increase cooling load) at all times. When this is combined with the reduced enclosure load, the average outdoor temperature during heating is lower than otherwise.

4.2 Experimental Design and Sensor Installation

BSC's initial monitoring in Townsend (Bergey and Ueno 2011) informed the design of the present research. The current research is divided into two phases: houses constructed and instrumented in 2011 (for which a winter's worth of data are available), and houses instrumented in the summer of 2012 (from which data have not yet been collected).

4.2.1 Townsend (2010–2011)

Over the winter of 2010–2011, one of the houses in the Townsend development, the Groton (Lot 24), was monitored in order to measure the performance of the mini-split ductless heat pumps. One of the desired outcomes was direct measurement of the heating and cooling balance points of the house—the outdoor temperatures above or below which no space conditioning is required. The initial monitoring failed to answer this question for two reasons.

In the initially monitored house, the occupant used deep thermostat setbacks and setups. As a result, there are many cold hours when no heating is required, as the house cools to set point, and many relatively warm hours when the heat pump works at maximum output to recover from setback. During these cooling-off and warming-up periods, there are large room-to-room differences. The occupants report being quite comfortable, although the house does not meet standard targets for thermal comfort. However, we are reluctant to extrapolate this satisfaction to other occupants.

Fewer than 20% of households nationally use setbacks, although anecdotal evidence suggests they are more common in New England (EIA 2005). The authors expect that many buyers of low-load homes will stop using setbacks due to the perception that the house is efficient without compromising on comfort. Further, we expect that occupants who find some rooms too cold will stop using setbacks.

Setbacks are poorly suited to these homes for several reasons. The low air leakage and high enclosure R-values mean that indoor temperature drops slowly even without heating. This reduces the energy savings available from an overnight or daytime setback. Variable-capacity heat pumps are most efficient when delivering a low output over a long period. Delivering the same total heat over a shorter period uses substantially more energy. Winkler (2011) reports COP at high, medium, and low compressor output for two models of mini-split heat pumps, including the Mitsubishi FE12NA used by Transformations, Inc. Operating at a steady set point also reduces peak electricity demand, avoids the capacity limitations of the heat pump, and likely improves comfort.

A second problem with the Townsend monitoring resulted from the mini-split heat pump's very low minimum output, and correspondingly low power draw in this state. A simple current switch is sufficient to indicate when a single-stage heat pump is running or not running, and runtime fraction can be calculated for any chosen interval. However, with variable-speed equipment, the switch suffers many false negatives when the power draw is below the cutout current. Because the unit under test is designed to run continuously and modulate refrigerant flow according to demand, the collected data do not distinguish between high output operation and the lowest output: both states are registered as on time.

4.2.2 Unoccupied Homes (2011–Present)

In 2011 BSC instrumented two unoccupied houses, the Victorian (Lot 3) in Devens and the Model Home (Lot 13) in Easthampton. Unoccupied houses were chosen to obtain clean baseline data without the setback issues described above. The Easthampton house is acting as the model home for the development, while the Devens home was sold in June 2012. Some sensors in the Devens house are shared with the wall moisture research described in Section 5, so the sensor packages in the two houses are slightly different.

Figure 21. (L) Exterior of houses at Devens; (R) Easthampton

In each house, temperature is measured in each bedroom, in a central part of the first floor, and in the second-floor hallway. In Devens, outdoor temperature is measured on site (Figure 53, left), while in Easthampton, outdoor conditions are taken from the weather station at Westfield, Barnes Municipal Airport (KBAF). Table 5 and Table 6 provide more details of the sensors used.

Table 5. Devens Sensor Package

Location	Property	Interval	Notes
Master Bedroom (South)	Temperature, relative humidity (RH)	1 h	± 0.1°C NTC thermistor ± 2% capacitive sensor
North Bedroom	Temperature, RH	1 h	± 0.1°C NTC thermistor ± 2% capacitive sensor
West Bedroom	Temperature, RH	1 h	HOBO U10-003
Second-Floor Hall	Temperature, RH	1 h	HOBO U10-003
First Floor	Temperature, RH	1 h	HOBO U10-003
Breaker Box	Electrical power	5 min	Leviton Mini Meter HOBO Pulse Logger

Table 6. Easthampton Sensor Package

Location	Property	Interval	Notes
Master Bedroom (South)	Temperature, RH	1 h	HOBO U10-003
North Bedroom	Temperature, RH	1 h	HOBO U10-003
West Bedroom	Temperature, RH	1 h	HOBO U10-003
Second-Floor Hall	Temperature, RH	1 h	HOBO U10-003
First Floor	Temperature, RH	1 h	HOBO U10-003
Breaker Box	Electrical Power	5 min	Leviton Mini Meter HOBO Pulse Logger

Each of these houses has a 12,000-Btu/h mini-split serving the first floor, and an identical unit serving the second floor (Figure 22). These are monitored independently, with a resolution of 5 Wh (0.005 kWh). The data logger recorded energy consumption in each 5-min interval. For this report, the Wh measurements were aggregated to the 1-h interval of the temperature data.

Figure 22. (L) Upstairs mini-split at Easthampton; (R) Watt-hour meter at Devens

4.2.3 Occupied Homes (2012–Present)

In May of 2012, BSC installed sensors in two smaller (two-bedroom) occupied houses in Easthampton, the Small Saltbox (Lot 17) and the Cottage (Lot 23). At the time of installation, these two-story houses had only a single mini-split delivering air centrally on the first floor. Load calculations and anecdotal evidence from prior houses suggested this experiment to the developer. By the end of the summer, the developer had decided to install a mini-split on the second floor of each house, as is standard in the three-bedroom Easthampton houses. It appears that thermally driven buoyancy is effective in distributing heat from a first-floor mini-split head in winter, but causes discomfort in summer.

Figure 23. (L) Small Saltbox (Lot 17); (R) Cottage (Lot 23)

The sensor packages in these two houses are similar to that in the Easthampton model home. Because they are occupied, we have added a HOBO State Logger to each bedroom door. A magnet on the door frame triggers a reed switch in the sensor, providing at least a rough idea of when and how long the door is shut.

No data have yet been downloaded from the sensors in these two houses. The data over the winter of 2012–2013 will be compared to the data from unoccupied houses. Occupied houses are expected to have bedroom doors closed some (but not all) of the time, increasing temperature differences between rooms. Heat gains within closed rooms also affect the temperature distribution. Internal gains are expected to move the balance point toward colder weather, and simultaneously decrease energy used for heating.

4.3 Results

4.3.1 Data Overview/Boundary Conditions

4.3.1.1 Easthampton

Monitoring of the Easthampton house began in July 2011. Data were last downloaded in May 2012 (Figure 24). The house in Easthampton lost power for two days, October 29–31, 2011, due to a record-setting snowstorm (red highlighted rectangle). The weather station data are also unavailable during this period. The house dropped from 68°F to a low of 60°F during this period, recovering somewhat during daytime hours.

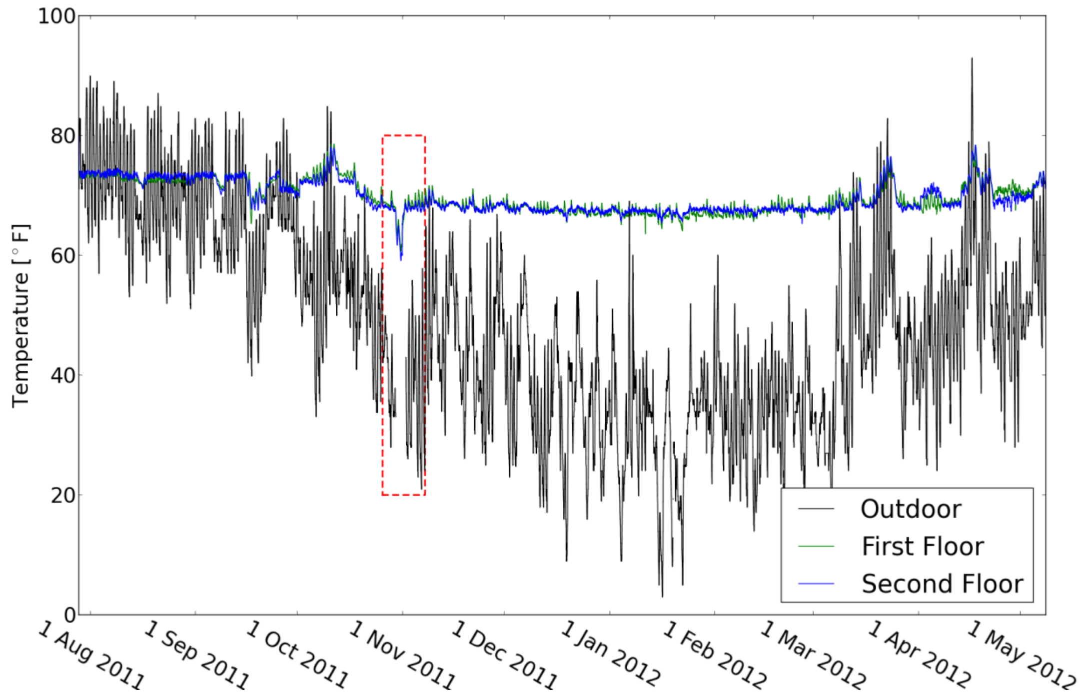

Figure 24. Indoor and outdoor temperatures at Easthampton

4.3.1.2 Devens

Data collection at Devens began in December 2011, and data from HOBOs were last downloaded in May 2012, at the same time as the Easthampton loggers. Data from the Devens Campbell logger can be downloaded without entering the building and so were collected again in July 2012 (Figure 25).

Both Devens mini-splits were turned off on March 10, 2012. On the April 14, the second floor unit was turned on again, while the first floor unit remained off until April 24 (red highlighted rectangle). This two-week period is omitted from all further analysis, since it is quite different from typical operating conditions.

Prior to February 17, 2012, the basement at Devens was uninsulated. A large spike in the basement temperature occurs on the day basement wall ccSPF insulation was installed (gray arrow; exothermic reaction).

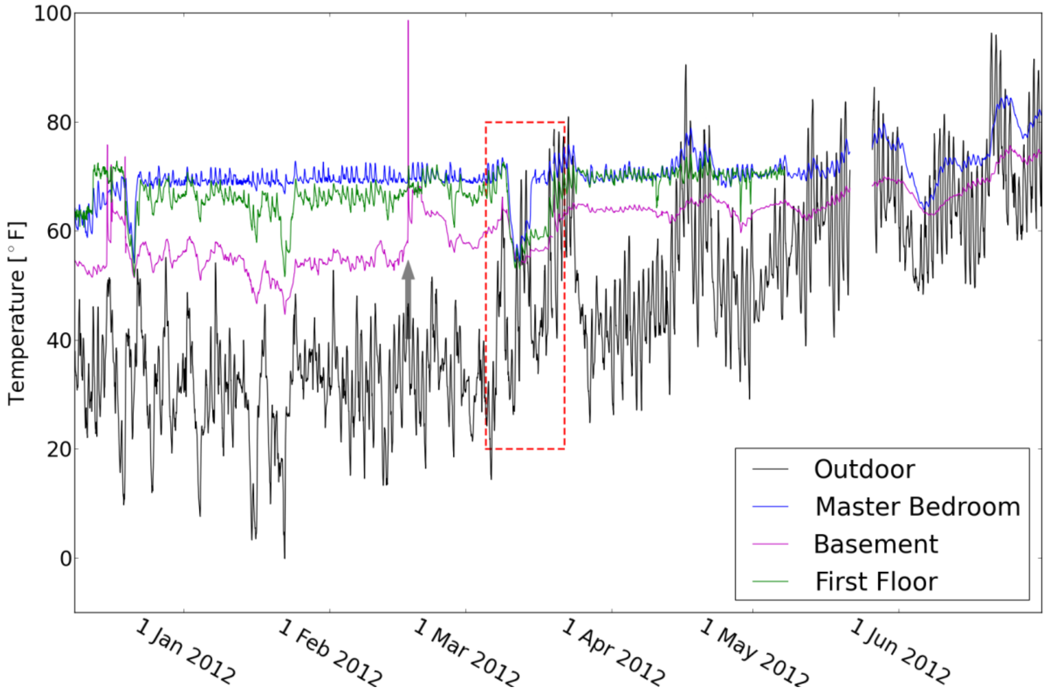

Figure 25. Indoor and outdoor temperatures at Devens

After insulation, both basement and first-floor temperatures are substantially warmer, given similar outdoor conditions (Figure 26 and Figure 27). Unfortunately, the later period (with the house fully insulated) also has much warmer weather. Since extremely cold weather presents the greatest challenge to heat pump performance, and the greatest chance of large temperature differences within the building, the earlier data are especially important. The two periods were therefore pooled for most of the further analysis. In particular, since second-floor temperatures and mini-split energy use were similar in both periods (Figure 37), pooling these measurements seems reasonable.

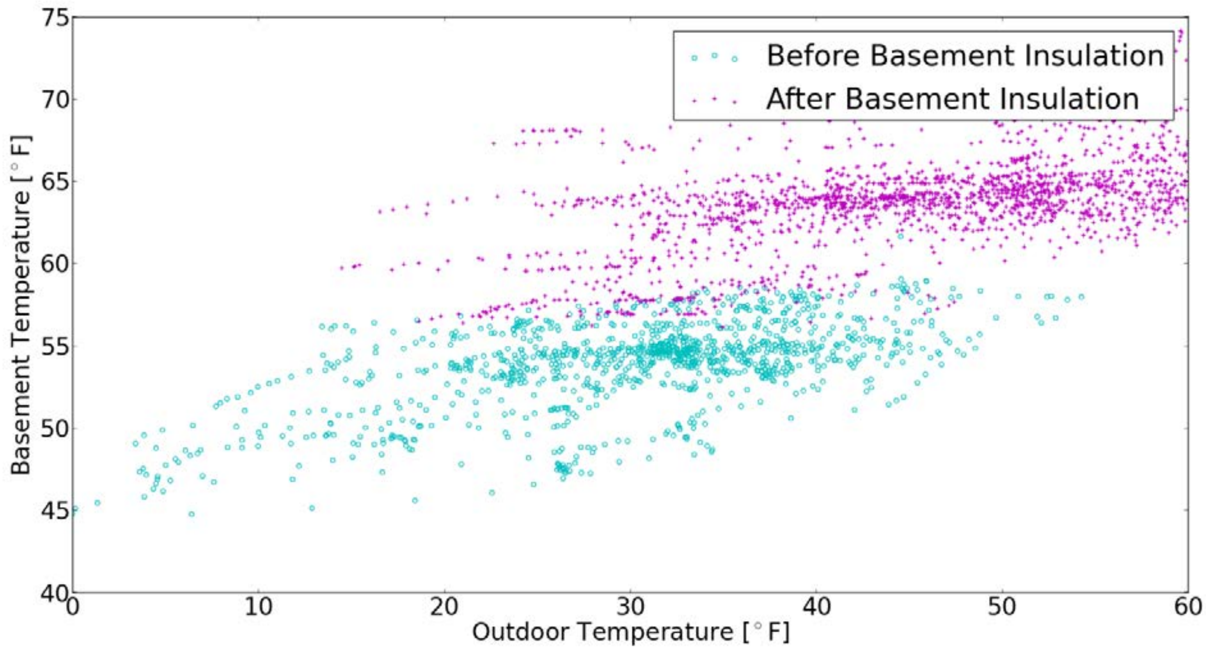

Figure 26. Devens basement temperature before and after basement insulation

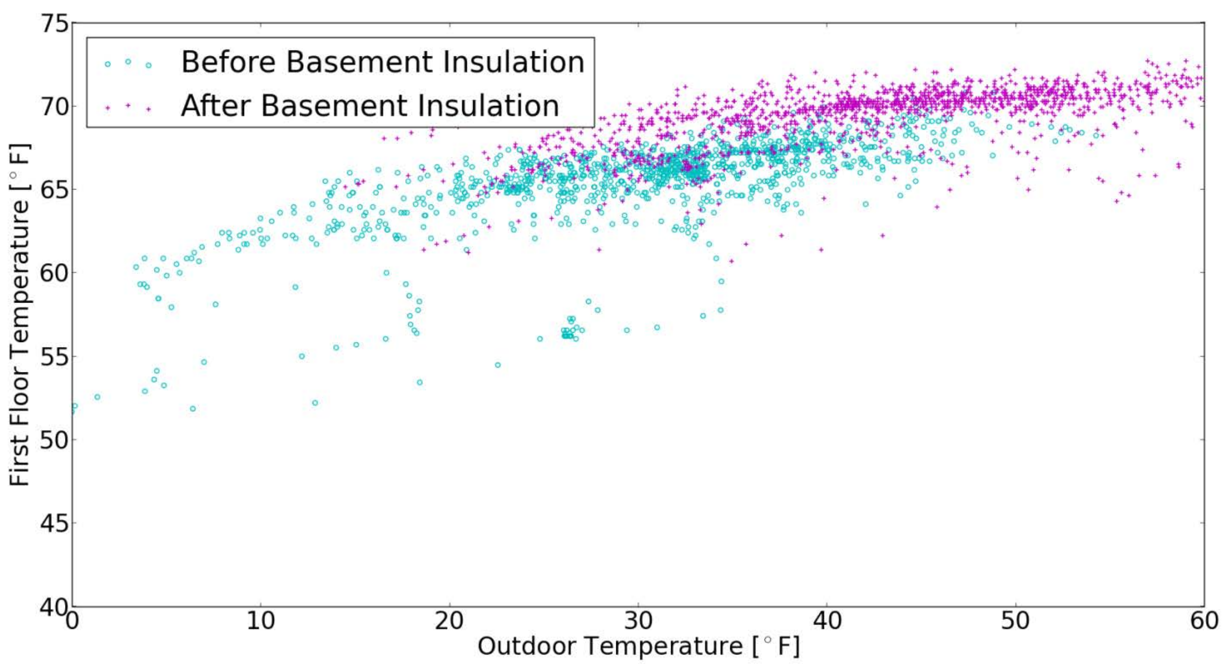

Figure 27. Devens first-floor temperature before and after basement insulation

4.3.2 Distribution

Concerns about thermal comfort in homes without forced distribution largely focus on bedrooms. Residents spend long periods in bedrooms; bedroom doors are closed for long periods for privacy reasons; and even with doors open, airflow to bedrooms is more restricted than to spaces on the first floors of these houses.

4.3.2.1 Easthampton

Figure 28 plots temperatures in several rooms in Easthampton against those in the second-floor hallway during the heating season. The heating season was taken to be the months of November through February, inclusive, as outdoor temperature was always below indoor temperature during these months. The thermostat is in the hallway, and it is presumed that the second-floor set point will be adjusted to maintain comfort in bedrooms.

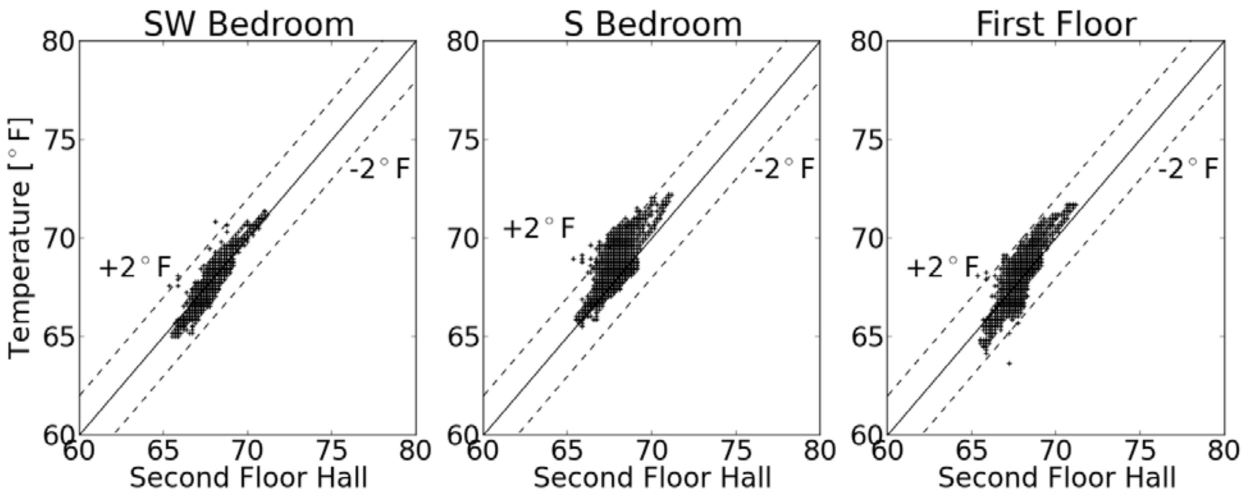

Figure 28. Easthampton temperature variations

All rooms of the house are within ± 2°F of each other nearly all of the time. The variance within each room over time is larger than the variation between rooms at the same time. Figure 29 and Figure 30 show the distributions of temperatures in each room, and the distributions of the temperature differences relative to the second-floor hallway. The southwest bedroom is within ± 1°F of the hallway more than 90% of the time. The south bedroom is never more than 1°F cooler than the hall, but spends nearly 20% of the time more than 1°F warmer.

This solar gain is consistent with prior observations. The windows on these houses have SHGCs of 0.2, and U-values also around 0.2. Even with this relatively low SHGC, it is peak solar heating, rather than the coldest conditions of the year, that presents the greatest challenge for uniform space conditioning.

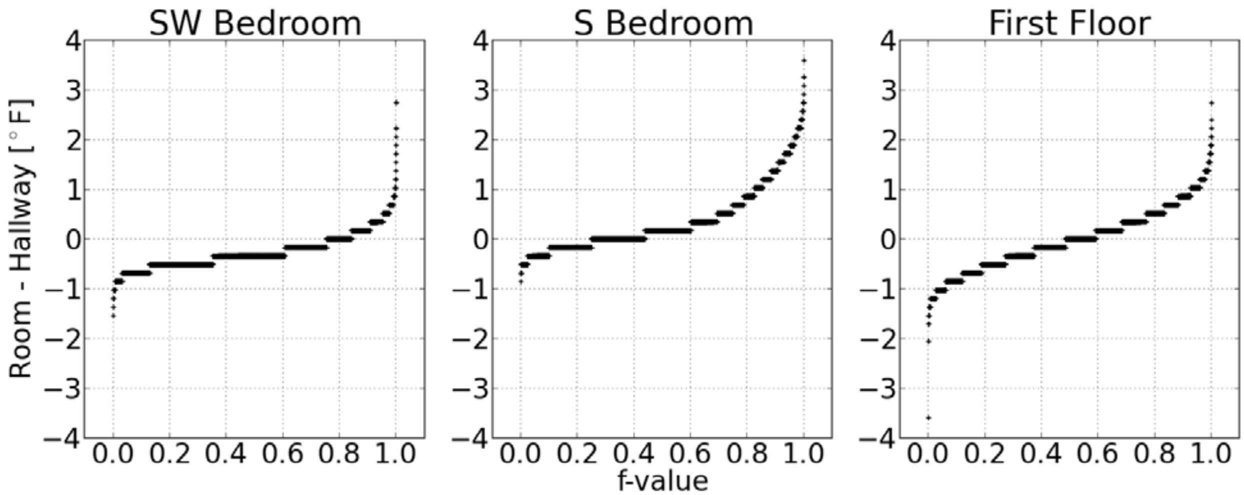

Figure 29. Easthampton frequency distribution of temperature differences

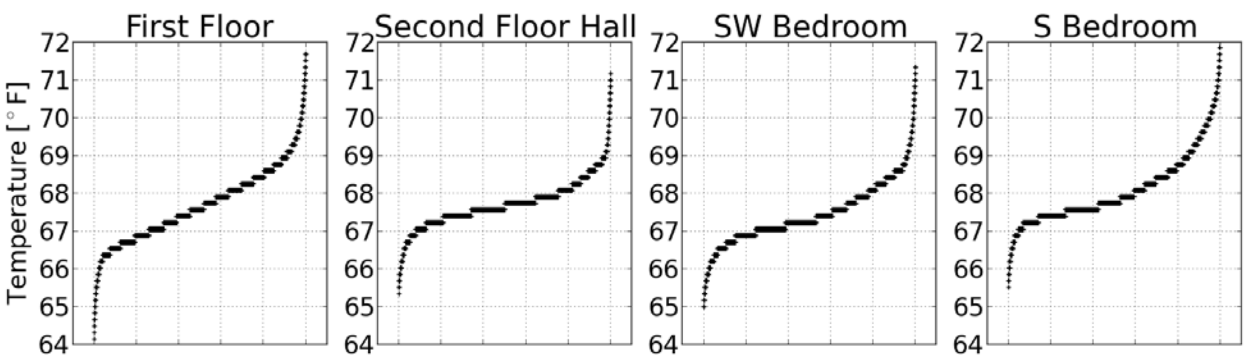

Figure 30. Easthampton frequency distribution of temperatures

While wintertime overheating can be a problem in houses with higher SHGCs and glazing ratios, it seems unlikely that the observed temperatures here would be a cause for complaint. The peak temperature in the south bedroom is only 72°F. Even if the hallway were kept at a more generous set point (for example, 72°F), the 3°F difference, resulting in a 75°F bedroom, is unlikely to be perceived as uncomfortable.

4.3.2.2 Devens

In Devens, the bedrooms consistently ran cooler than the hallway, often by more than 2°F. The south bedroom is warmer than the hallway only 10% of the time, and even less often for the other bedrooms (see Figure 31 through Figure 34). The west bedroom is 2°F or more below the hallway 20% of the time, but for the other bedrooms 60% and 80% of the time. Note, however, that the bedrooms are warmer than those in Easthampton. The hallway at Devens was maintained around 72°F, while Easthampton was kept between 67°F and 68°F.

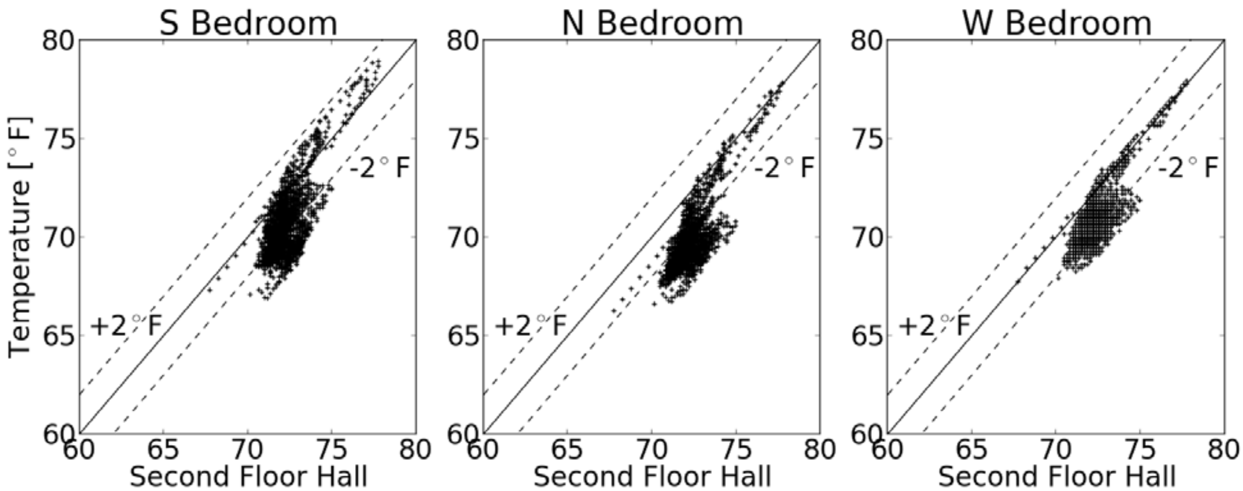

Figure 31. Devens temperature variations

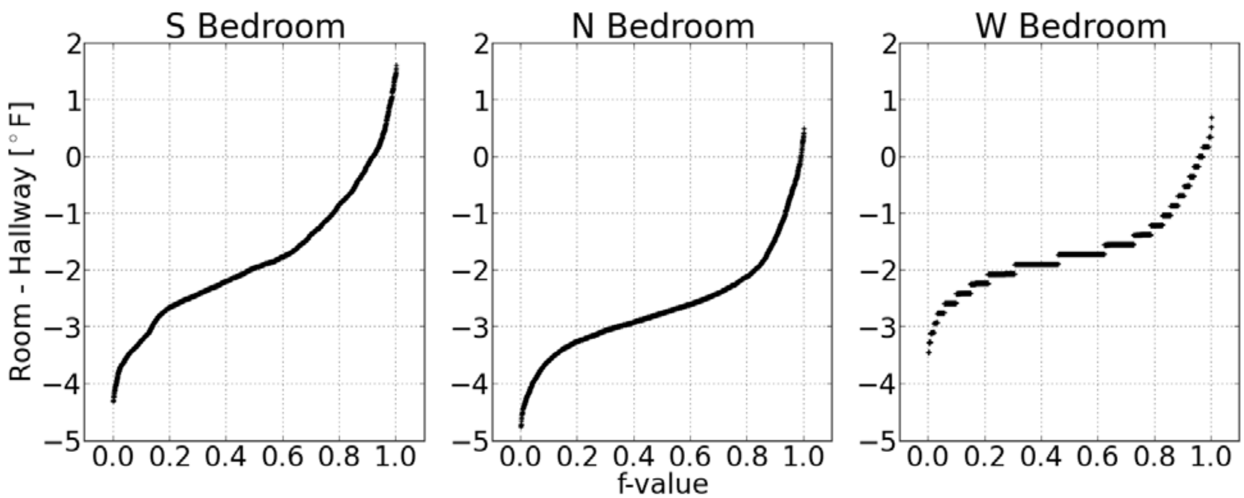

Figure 32. Devens frequency distribution of temperature differences

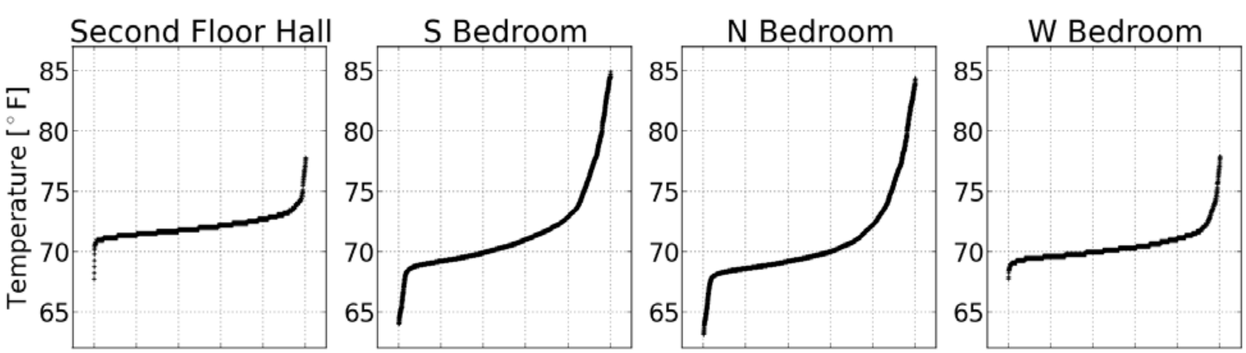

Figure 33. Devens frequency distribution of temperatures

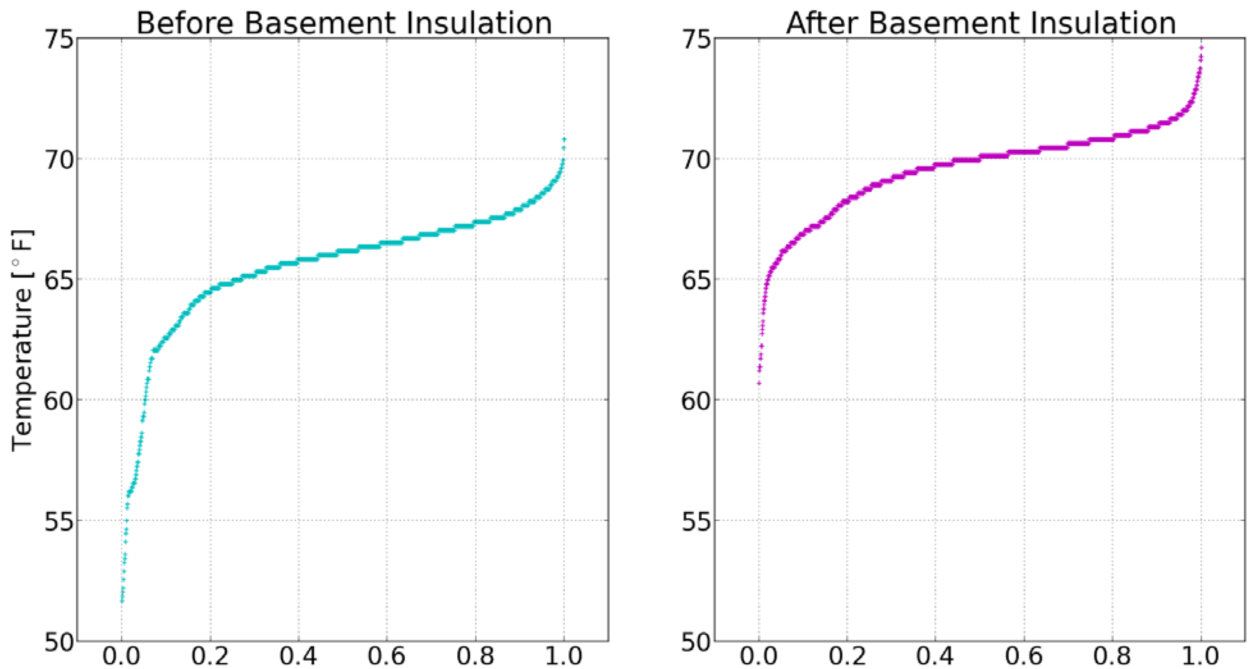

Figure 34. Devens distribution of first-floor temperatures

It seems likely that the depressed bedroom temperatures (relative to the hallway) are related to heat loss to the first floor. As described in Section 4.3.1, the first floor at Devens ran considerably cooler than the second, especially before the basement was insulated. Figure 35 plots the first-floor temperature, before and after insulation, for comparison with the plots above. However, since the two periods conflate different enclosure conditions with different outdoor conditions, only the central values of the distribution can be considered valid. The tails clearly occur at different extremes of weather. The first-floor set point was 70°F (Figure 29), whereas the second floor was heated to 72°F. The median temperature in the south and west bedrooms is quite close to 70°F. This may indicate that conduction through the floor had a greater influence on bedroom temperatures than did convection through the doors. This is important for understanding the effect of closing doors.

4.3.3 Mini-Split Energy Consumption

In Devens, the first floor mini-split unit used 691 kWh over the four months of monitoring, while the second floor used only 320 kWh. Figure 35 shows that the first-floor unit drew more power than the second-floor unit over a wide range of outdoor conditions. In Easthampton, the two units drew similar amounts of power at similar times (Figure 36). This is consistent with the additional load imposed on the first floor at Devens by the basement (Figure 37), which does not have its own mini-split head. A Manual J load calculation (ACCA 2006) predicts that the basement, with 3 in. of ccSPF on the walls, adds a heating load of 3500 Btu/h, about ¾ of the load for the first floor alone. Easthampton has a slab-on-grade foundation, with 6 in. of XPS under the slab, and substantially lower predicted heating load.

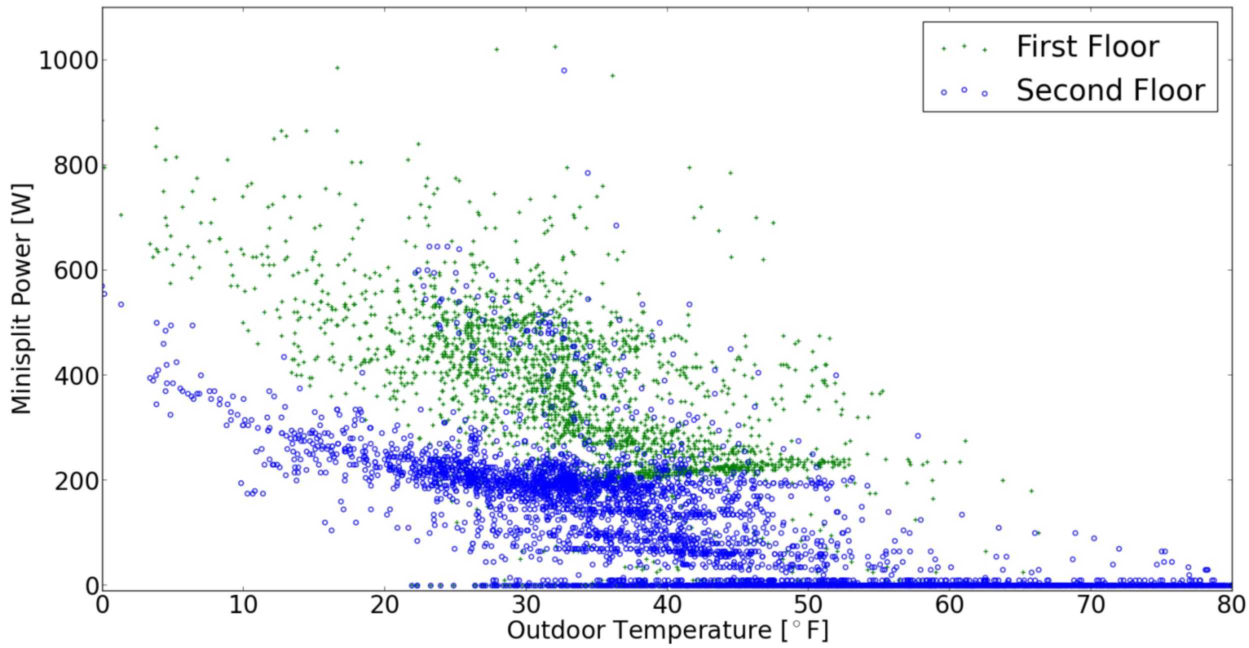

Figure 35. Devens mini-split power by floor

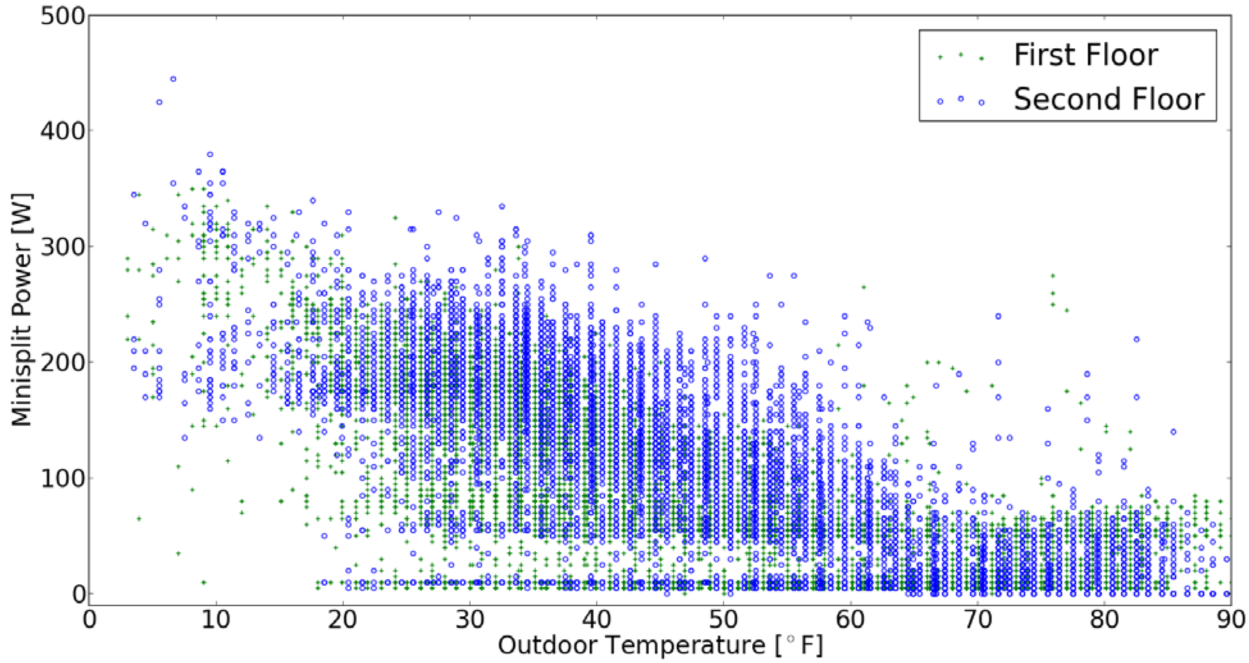

Figure 36. Easthampton mini-split power by floor

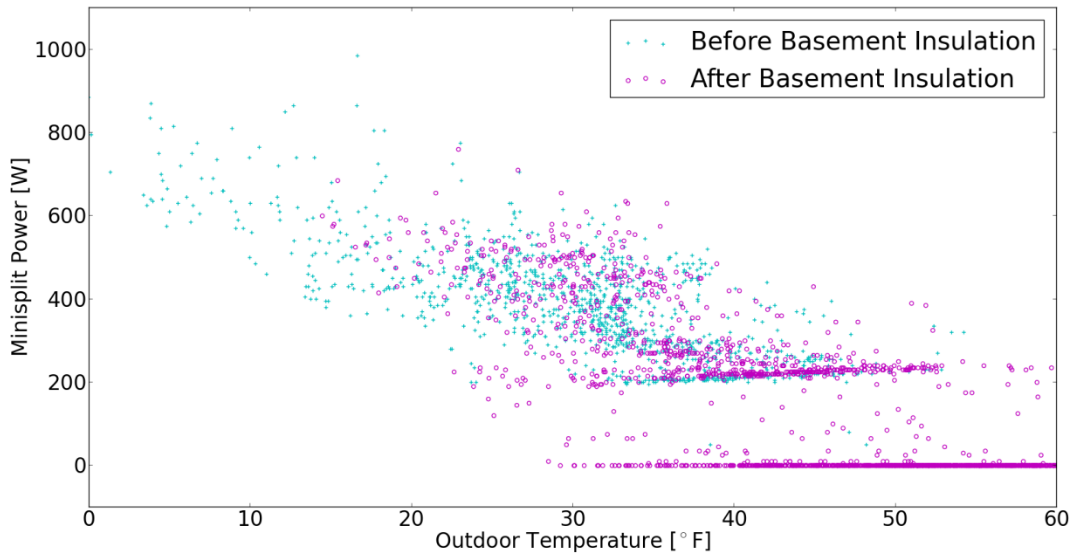

Figure 37. Devens first-floor power by basement insulation

Figure 38 compares power drawn by the first-floor mini-split before and after the basement was insulated. Both periods have useful data with outdoor temperatures between 25°F and 45°F, and under these conditions, the basement insulation did not much change energy consumption. It seems plausible that the increased indoor temperature offset the decreased conductance. Data from the upcoming winter will be necessary to understand how the completed house performs in the coldest weather.

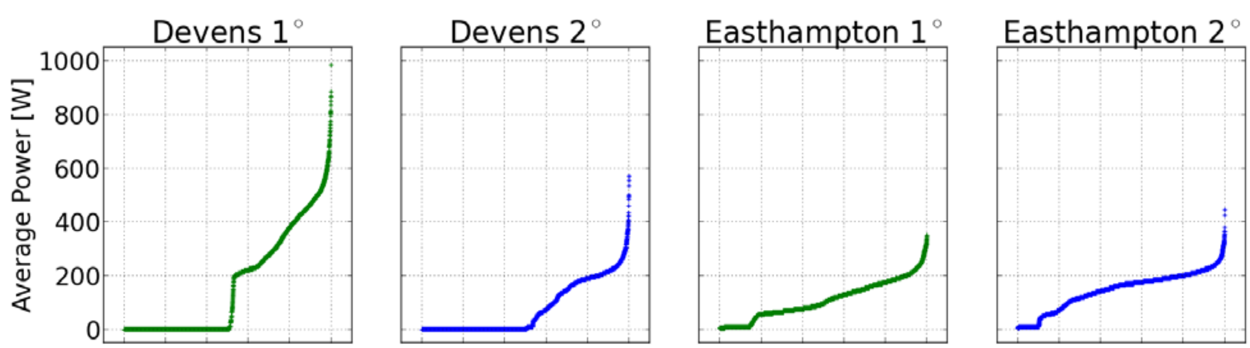

Figure 38. Distribution of mini-split power

Both mini-splits at Devens spend many hours drawing no power. The first-floor unit spends slightly more than half its time thus, despite high total energy consumption. The hours without power draw do not occur in contiguous periods but cyclically correspond to peaks in the first floor temperature (Figure 39). It seems clear from the Easthampton data—measuring the same product—that the heat pump is capable of ramping smoothly from 0 to 200 W. It is not known why the heat pump in Devens resumes operation at 200 W or higher, rather than ramping up more gradually.

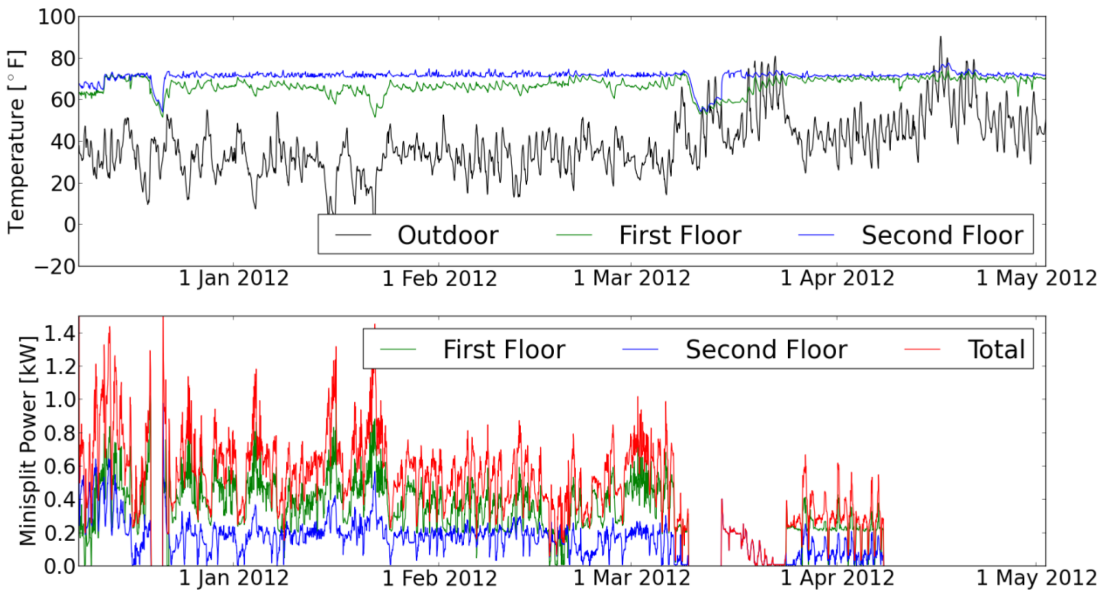

Figure 39. Devens mini-split power time series

Due to the low thermal losses of these buildings, solar gain and interior occupant gains contribute substantially to meeting the heating load. As these are unoccupied buildings, we only observe the effect of solar gain. This reduction in space heating energy can be observed as a change of balance point—the outdoor temperature above which no supplemental heating is required. The heating balance point has historically been assumed to be 65°F, but it is likely lower for low-load homes.

To smooth out startup effects and other noise in the data, the balance point for each house was found from the average power and average outdoor temperature over each day, rather than using the hourly data directly (Figure 40 and Figure 41). Data above 50°F were also excluded from the fit, as weather very close to the apparent balance point is often dominated by sun and other conditions not being considered in the regression.

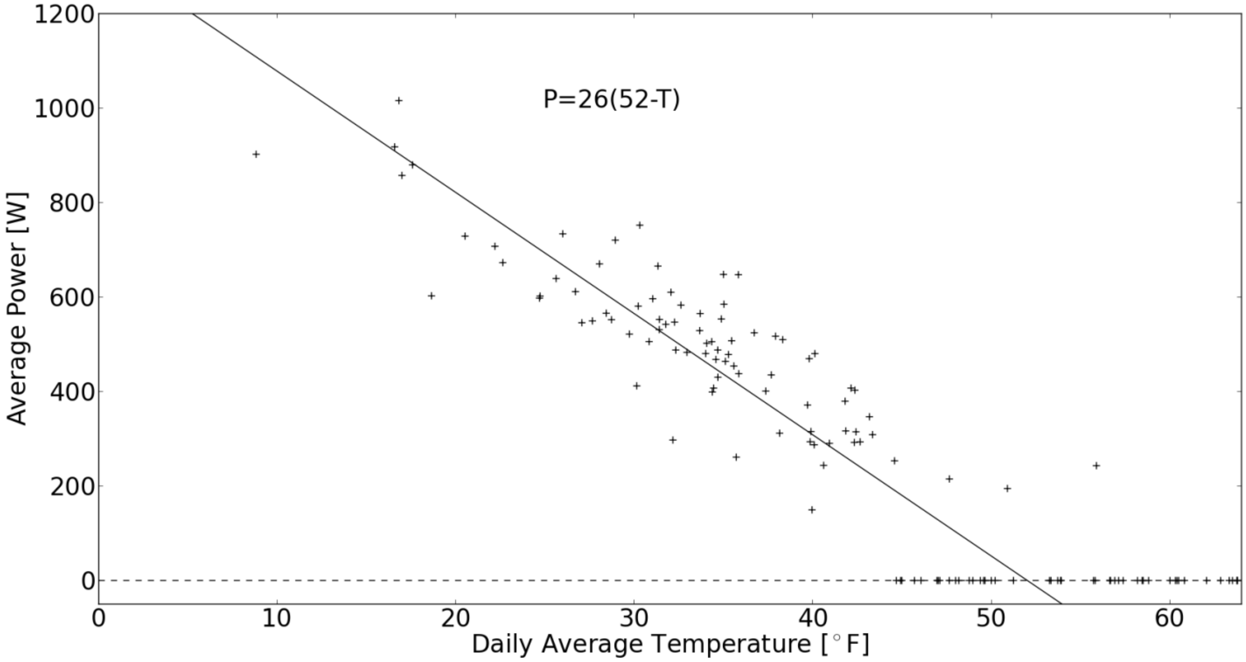

Figure 40. Devens mini-split balance point

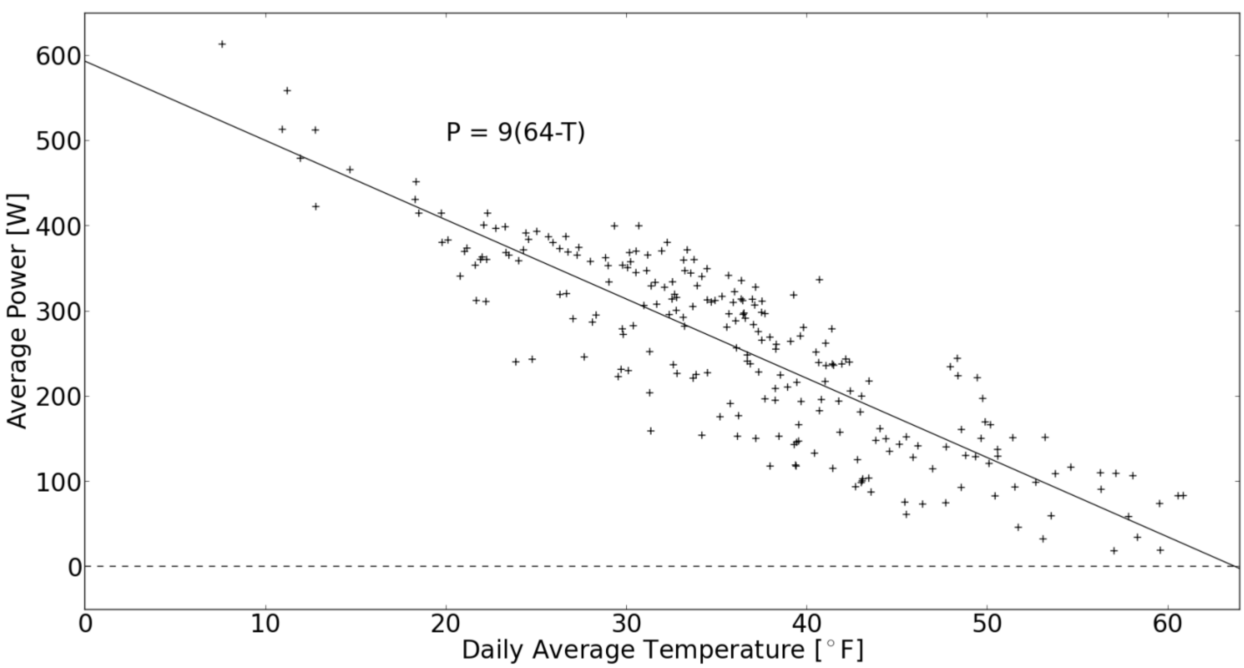

Figure 41. Easthampton mini-split balance point

For the set points being used (72°F second floor, 70°F first), the house Devens is found to have a balance point of 52°F, and to draw 26 W for each degree below that temperature. This line fits the daily average data with $R^2 = 0.82$. The Easthampton data are fit with a balance point of 64°F, using 9 W for each degree the temperature drops, and with $R^2 = 0.75$. However, the set point in Easthampton is rather low (68°F), so the balance point in typical use is likely higher.

These data are equivocal regarding the hypothesized balance point trend in low-load houses. 65°F is the typical balance point assumed in heating degree day (HDD) calculations. The Devens house appears to balance significantly lower than this, even without internal gains. But 65°F is within the 95% confidence interval of the Easthampton regression. There is no obvious reason to consider one of these houses more representative than the other.

4.4 Resident Survey

BSC sent a one-page survey to residents of the developments at Easthampton and Devens, as well as to residents of several older houses built by Transformations, Inc. and heated by mini-splits. The survey is attached to this report as Appendix A.

4.4.1 Survey Results

Eight homeowners responded to the survey. Four moved into Easthampton in 2012, and had not yet lived in their new homes through a winter. Three had spent one winter in their homes, and one had spent two winters. All but one reported that the new homes are more comfortable than their previous homes and the remaining homeowner rated the house as a 1 (Most Comfortable) on a five-point scale.

Two respondents report turning off the air conditioning during the summer at night and when they leave the house. Both of these keep the second-floor unit running at night, while turning off the first-floor mini-split. One homeowner did not answer this section of the survey; the others maintain fixed set points. One respondent reported having tried nighttime setbacks during cold weather and stopped due to the slowness of morning recovery during the coldest weather. These data suggest that winter setbacks are not very common in houses heated with heat pumps. The survey responses do not indicate that the incompatibility of heat pumps and winter nighttime setbacks is considered a liability. Summer setbacks, whether or not they save significant energy, do not present the same challenge to heat pump operation, because they occur at times of reduced or zero load.

Half of respondents report at least one room, almost always a bedroom, is somewhat uncomfortable in summer. Half of those comfort complaints were of the room being too cold, which may represent a lack of clarity in the survey. Of five homeowners who addressed winter comfort (including one who moved in March 2012), only one reported cold bedrooms. This is also the only respondent who reports keeping bedrooms always or mostly closed.

It is not clear from these data whether the high proportion of open doors represents a prior preference or a learned response to the limited thermal distribution. Several respondents use fans and open doors to improve distribution, suggesting an awareness that closed doors could reduce comfort. None indicate dissatisfaction with open doors, even by closing doors when in the room and opening them when not.

5 Moisture Monitoring of Twelve-Inch Double-Stud Walls

5.1 Background

Double-stud walls insulated with cellulose or low-density spray foam can have R-values of 40 or higher. Compared to approaches using exterior insulating sheathing, double-stud walls are typically less expensive, but have a higher risk of interior-sourced condensation moisture damage. Insulation outboard of structural sheathing increases the winter temperature of the sheathing, while additional insulation inboard of the sheathing decreases its temperature (Straube and Smegal 2009).

This is demonstrated in the thermal simulation results shown in Figure 42 and Figure 43, which show temperatures for a double-stud wall and a 4 in. exterior foam wall, assuming an interior temperature of 68°F and an exterior temperature of –4°F. The surface that is the most likely to experience condensation (interior side of exterior sheathing) is highlighted in each wall in gray, showing the relative risks of air leakage or vapor diffusion-based condensation.

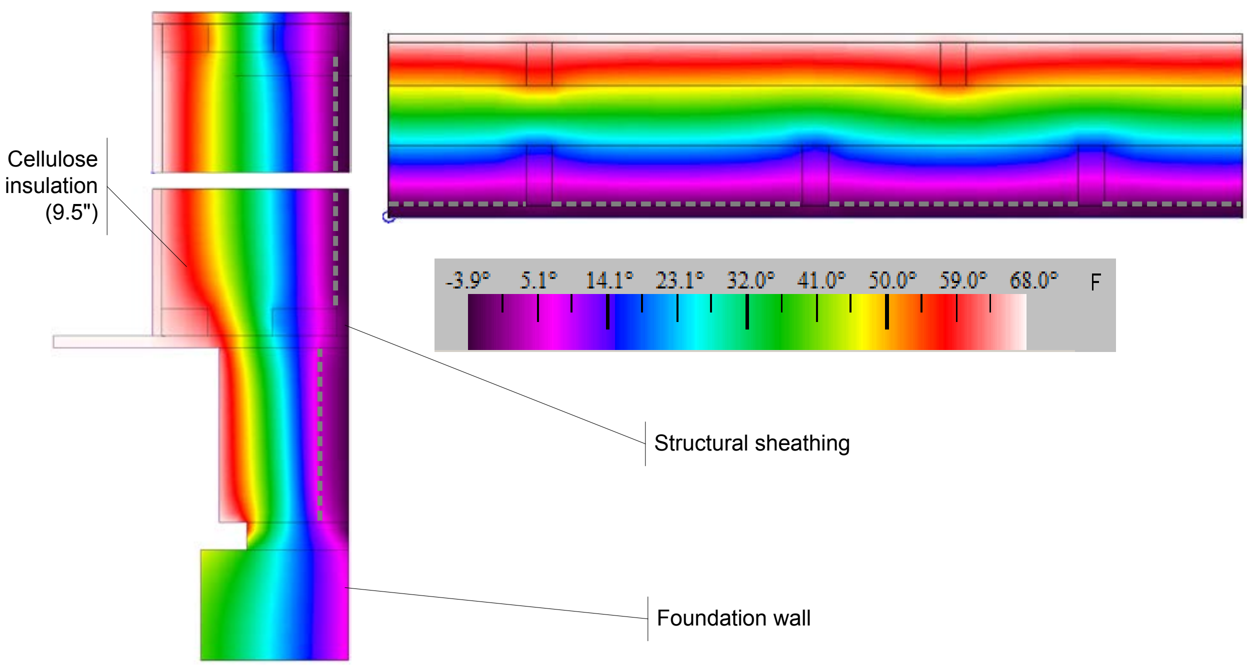

Figure 42. THERM results for double-stud walls (based on Straube and Smegal 2009); condensing plane highlighted in gray

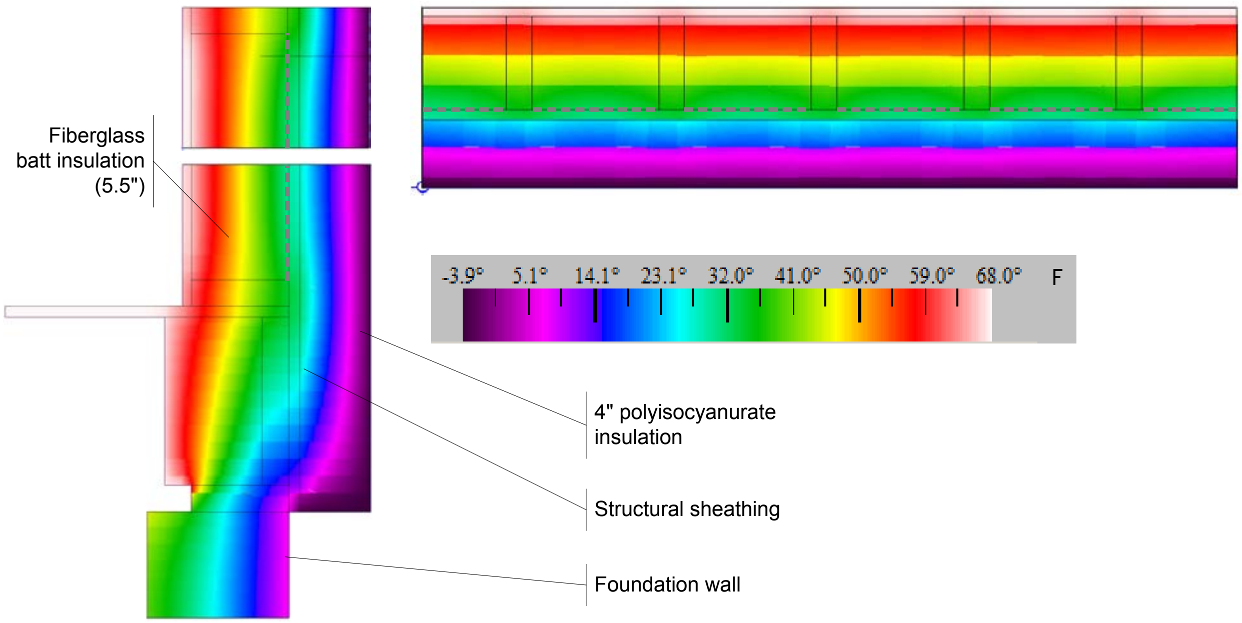

Figure 43. THERM results for 4-in. exterior foam wall (based on Straube and Smegal 2009); condensing plane highlighted in gray

If a double-stud wall is compared with a 2 × 6 wall with the same type of stud bay insulation and no exterior insulating sheathing, it is clear that the double-stud wall sheathing experiences colder wintertime temperatures, and less heat flow. Both of these factors increase the risks of moisture-related problems (Lstiburek 2008). Low-density spray foam, with similar R-value to cellulose, is believed to have lower moisture risk because its superior control of air leakage reduces the risk of wetting of the exterior sheathing due to interior-source moisture. However, the insulation material is still open to vapor diffusion: a 12-in. thickness of ocSPF 0.5 lb/ft^3 has a vapor permeability of 7.3 perms (both wet and dry cup; ASHRAE 2009), while 12 in. of cellulose is roughly 7–10 perms (dry and wet cup).

5.2 Experimental Design and Sensor Installation

The moisture monitoring experiment is being conducted at the Victorian house (Lot 3) at Devens. It is intended to assess the moisture risk of 12-in. thick double-stud walls insulated with cellulose and low-density spray foam.

Transformations, Inc. has been building double-stud walls insulated with 12 in. of ocSPF (0.5/lb^3 density). However, the company has been considering a change to netted and blown cellulose insulation for cost reasons. Cellulose is a common choice for double-stud walls due to its lower cost (in most markets). However, cellulose is an air-permeable insulation, unlike spray foams. For these reasons both materials were tested as a comparison.

5.2.1 Overview

Three wall assemblies were selected for this experiment; they were duplicated on opposite orientations (north and south), for a total of six test wall sections (see Table 7). The three test insulation materials are as follows:

- 12-in. 0.5 PCF spray foam in double-stud wall (as per the remainder of the house; typical installation is shown in Figure 44). The spray foam was installed in three passes with time allowed between the passes for cooling.
- 12-in. netted and dry blown-in cellulose in double-stud wall. The density was not directly measured, but it was reported to be 3.5 PCF. Typical densities achieved for proper dense pack installations behind netting are 3.5–4.0 PCF (Tauer 2012).
- 5½ in. of 0.5 PCF spray foam at exterior of double-stud wall, to approximate conventional 2 × 6 wall construction and insulation levels, acting as a control wall (a.k.a. “shorted” bay).

Table 7. Test Wall Listing

Wall ID	Orientation	Insulation	Nominal R-value	Notes
N1	North	0.5 PCF spray foam, 12 in.	46	Same as rest of house
N2	North	Netted/blown cellulose, 12 in.	42	
N3	North	0.5 PCF spray foam, 5½ in.	21	“Control”
S1	South	0.5 PCF spray foam, 12 in.	46	Same as rest of house
S2	South	Netted/blown cellulose, 12 in.	42	
S3	South	0.5 PCF spray foam, 5½ in.	21	“Control”

Figure 44. Typical installation of ½ lb/ft^3 spray foam in double-stud walls

The remainder of the wall is constructed as per the builder's conventional construction, with an oriented strand board (OSB)-based sheathing with an integrated drainage plane and taped seams (no separate house wrap), and vinyl siding. The interior finish is ½-in. gypsum board with latex primer and paint finish (Class III vapor retarder).

The control wall (5½ in. 0.5 PCF foam) is mean to represent common construction (2 × 6 stud frame walls); this assembly has no history or reputation of endemic moisture failures. Data from the control bay (with the same solar and rain exposure as the test walls) will assist interpretation of the results.

The test home is not oriented directly north-south (Figure 45), but the southernmost and northernmost walls were used for this research.

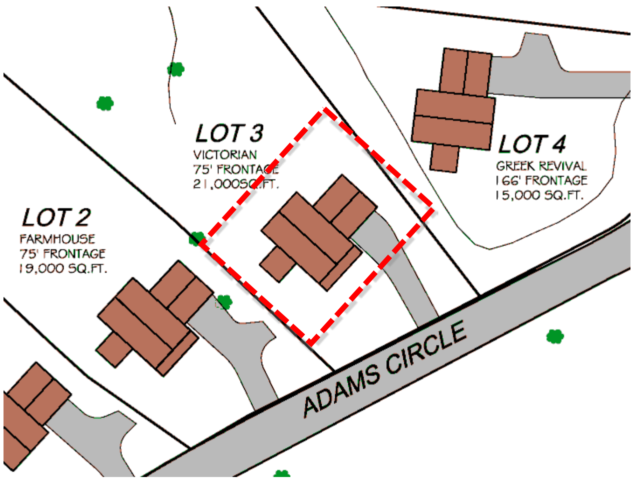

Figure 45. Overhead (L) and front (R) views of Lot 3 test house

The test walls were installed in second-floor bedrooms (Figure 46). The test bays are indicated by the dotted patterns, and the guard areas (noninstrumented portions) are filled with full-thickness spray foam to maintain separation between adjacent bays.

North-facing walls experience the least solar gain, while south-facing walls receive the most. The two orientations place upper and lower bounds on the moisture problems, as solar gain is the major source of energy to dry the sheathing in well-insulated walls.

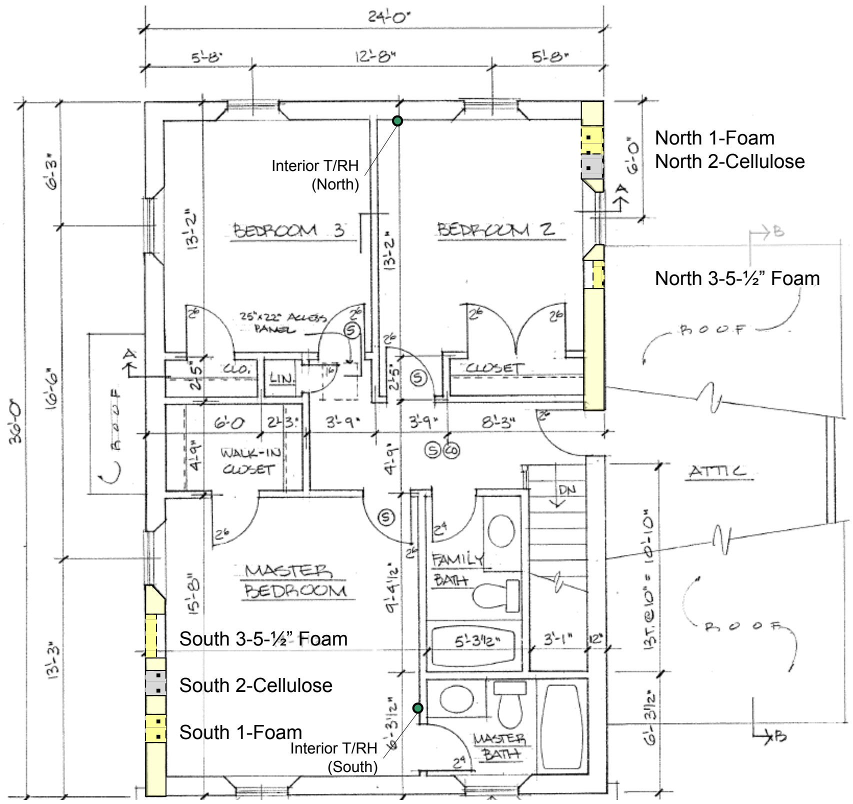

Figure 46. Test walls shown on second-floor plan, with guard bay insulation for separation

As shown in Figure 47 (right), the third bay ("control") on the north side is partially sheltered at the bottom by the sloping garage roof. No better location was available, due to the positioning of windows, bathrooms, and garage.

Figure 47. Test wall locations shown on exterior of house; south (L) and north (R) orientations

5.2.2 Wall Sensor Package

Four types of sensors are used to measure conditions within the walls:

- Temperature sensors (10k NTC thermistors (accuracy ± 0.2°C)
- Relative humidity (RH) sensors (thermoset polymer capacitive based sensors with onboard signal conditioning (accuracy ± 3%, 10%–90% RH)
- Wood moisture content (MC) (in-situ electrical-based resistance measurements between corrosion-resistant insulated pins).

The specifics of these sensors are covered in detail by Straube et al. (2002). Figure 48 shows typical sensor types and installations.

The left-hand image (Figure 48) shows a temperature and wood MC sensor installed at the exterior sheathing. The sensor with red shrink tubing is a temperature measurement (thermistor), and the blue wire leads run to wood MC pins.

The right-hand image (Figure 48) shows typical conditions mid-height in the study bay, with both temperature RH, sheathing MC, and stud moisture content sensors visible. The temperature/relative humidity (T/RH) sensor can be identified by the yellow heat shrink tubing; the sensor consists of a vapor-permeable polyolefin house wrap envelope around the T/RH sensor.

Figure 48. (L) Temperature and MC sensor at sheathing; (R) sensors at mid-height of stud bay

Figure 49 shows the “wafer” sensor, installed at the inboard side of the sheathing to measure conditions at the likely condensation plane. Screws were used as temporary clamps to hold the sensor in place until the adhesive set.

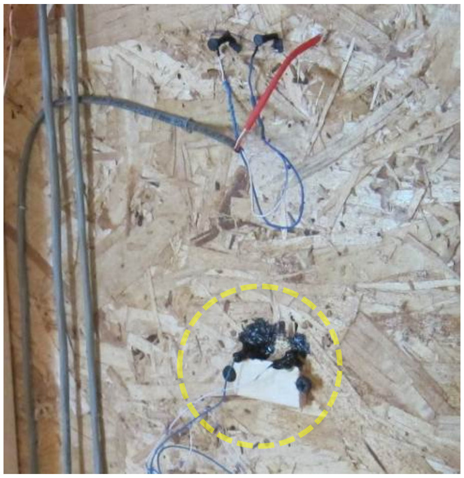
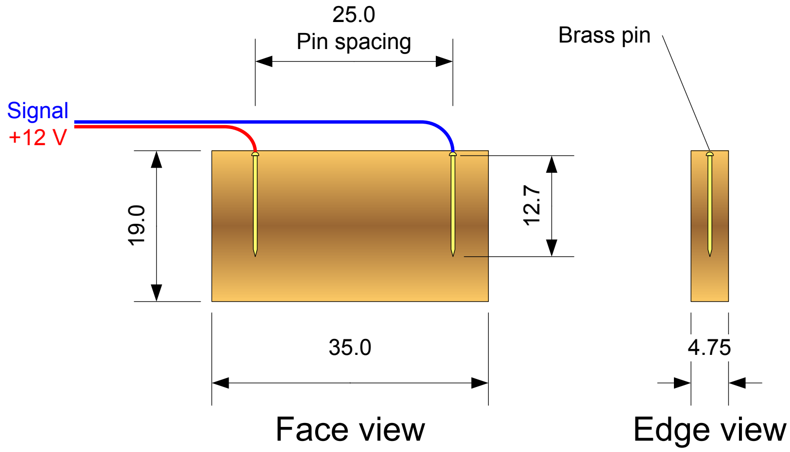

**Figure 49 (L) "Wafer" surrogate RH sensor at sheathing;
(R) schematic of sensor, with dimensions in mm**

The completed installation at the south walls is shown in Figure 50 prior to insulation. Stud bays were chosen to avoid anomalies such as electrical boxes, plumbing pipes, or corners of the building. Lateral air movement at the cellulose bay is controlled by full-thickness spray foam between test bays.

Sensor cables were stapled back to studs or sheathing to minimize thermal bridging and/or insulation displacement effects near the measurement location; cables were run away from the sensor perpendicular to the heat flow path, to minimize their effect (Straube et al. 2002).

Figure 50. South test walls after installation of sensors, showing double-stud layout

The test wall instrumentation plan for this research is shown in Figure 51.

- Sheathing moisture content is typically a key indicator for long-term durability and moisture risks; therefore, three sheathing MC/temperature sensors were installed at each wall (upper/middle/lower).
- The outermost stud MC was monitored at inboard and outboard edges.
- Temperature and RH were monitored at three depths in the stud bay (outboard/middle/inboard), which allows measurement of temperature and humidity gradients.
- The "wafer" sensor was installed at the inboard surface of the exterior sheathing, to measure surface humidity conditions at the likely condensing plane.
- A temperature sensor was installed at the interface between the insulation and the interior gypsum board.

The sensor complement is identical in the two 12-in. thick insulation (spray foam and cellulose) wall test bays. At the "shorted" or "control" bay (N3/S3), the sensor count is reduced. There is a "dead" air space between the interior gypsum board and the interior face of the stud bay spray foam. This is not an ideal comparison, but was required to keep the interior gypsum board in plane at this occupied house. Temperature and RH conditions within the void space are being recorded directly, for comparison with interior conditions. Only a single temperature sensor was placed between the inner face of the foam and the drywall, as negligible temperature or RH gradients are expected across this void space.

The base of wall N3 is shielded by the garage roof (Figure 47); the sensors at the "lower" sheathing location were shifted to the lowest exterior exposure in the stud bay.

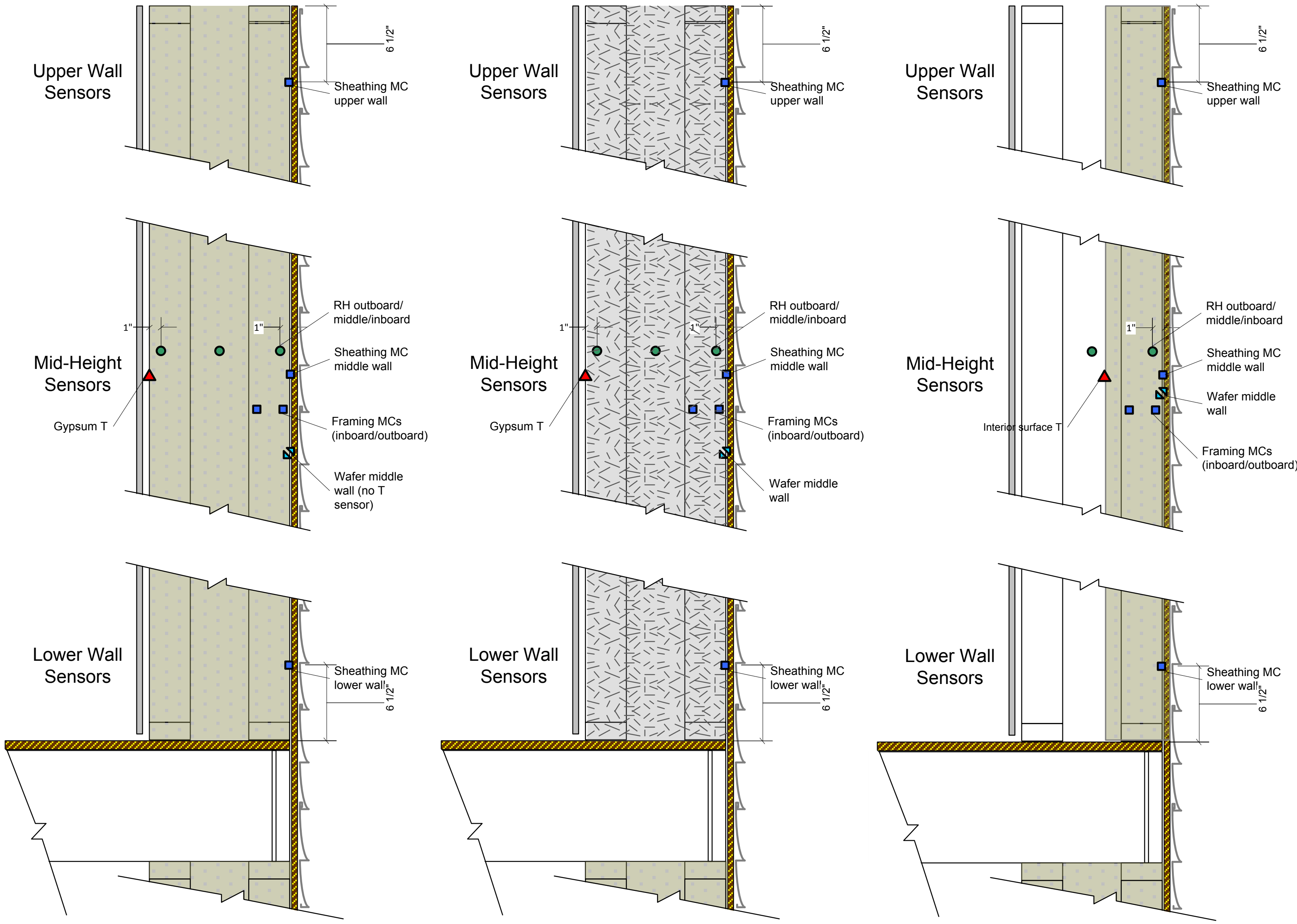

Figure 51. (L) Instrumentation diagram for 12-in. ocSPF; (C) 12-in. cellulose; (R) 5½-in. ocSPF

5.2.3 Additional Sensors and Data Collection Logistics

In addition to the sensors in the walls, T/RH sensors were located in the living spaces in the north and south rooms where test walls are being monitored. The enclosure is shown in Figure 52; the locations on the floor plan are shown in Figure 46.

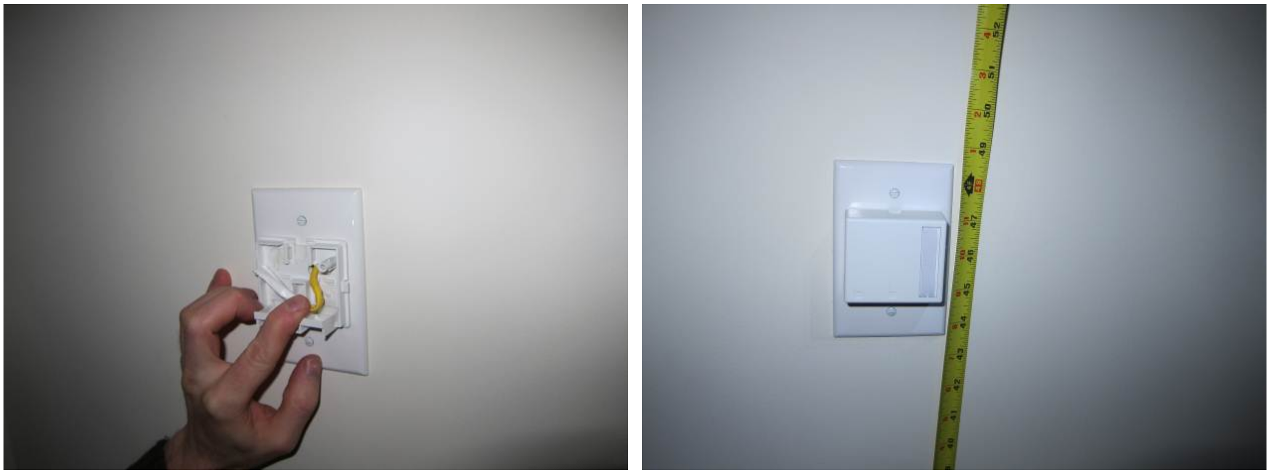

Figure 52. Sensor measure interior (bedroom) T/RH sensors

An exterior T/RH sensor (Figure 53, left) provides outdoor conditions synchronized to the wall measurements; it is located within a solar radiation shield. The data logger is located in the basement; data are collected at 5-min intervals, and hourly averages are recorded. No battery backup for the data logger is provided; however, the unit has nonvolatile memory, and will resume data collection after a power failure.

Figure 53. (L) Exterior T/RH sensor; (R) data collection from exterior connection port

An RS-232 serial cable was passed through the wall to a weathertight box mounted on the exterior. This allows on-site data collection without entering the house, as shown in Figure 53, right. Remote collection over a network connection is planned once the house is occupied and assuming that the occupants have a network connection for other reasons.

5.3 Results

5.3.1 Data Overview and Boundary Conditions

Eight months of data have been collected and analyzed to date (from December 2011 through July 2012). This captures data from the building's first winter (albeit unoccupied conditions), through spring and summer.

Interior and exterior temperature conditions are shown in Figure 54. Winter 2011–2012 conditions were exceptionally mild (4400 HDD Base 65°F versus 5600 HDD climate normal). Interior temperature held steady through the winter in both north and south bedrooms in the 69°–71°F range, except for a period in March when the mini-split units were inadvertently turned off. Basement temperatures ran in the 48°–56°F range through most of the winter before insulation was applied to the foundation walls in mid-February 2012. After application of insulation, temperatures were warmer, tracking closer to interior conditions, despite a lack of space conditioning in the basement.

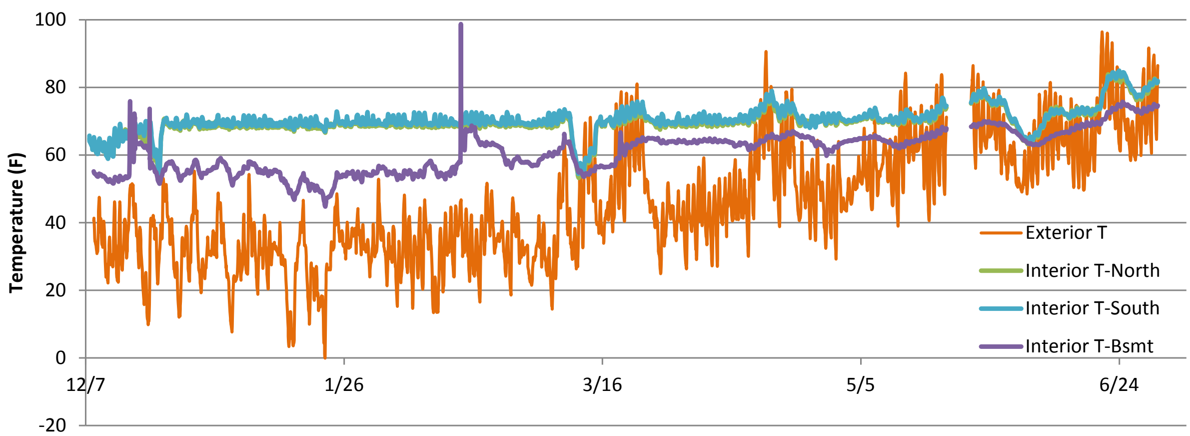

Figure 54. Exterior and interior (test rooms and basement) temperatures

Interior RH conditions are shown in Figure 55; interior wintertime RH levels fell to the 10%–20% range for much of the winter, which are exceptionally dry conditions. There was no occupancy through the winter, and therefore no interior moisture generation (occupants, showering, cooking), explaining the low RH levels. However, drying of construction moisture was occurring during the winter. Basement RH levels were higher, as would be expected due to lower temperatures.

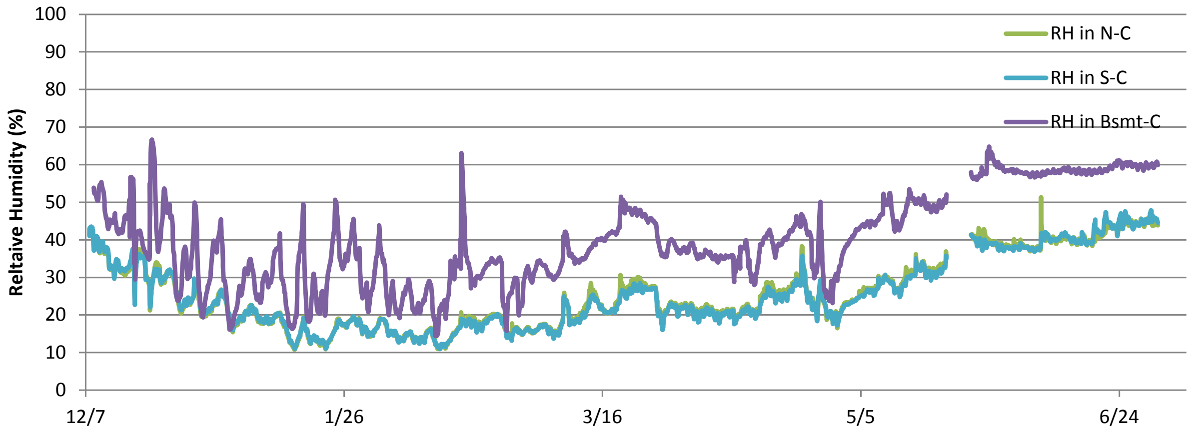

Figure 55. Interior RHs (test rooms and basement)

Interior temperature and RH conditions were used to generate dew point temperatures (absolute air MC), which were plotted with outdoor temperatures (Figure), Interior moisture conditions are very close to outdoor conditions, as would be expected without interior moisture generation. After basement insulation (February 2012), basement dew points were higher than above-grade spaces, which might be attributed to drying of the basement slab.

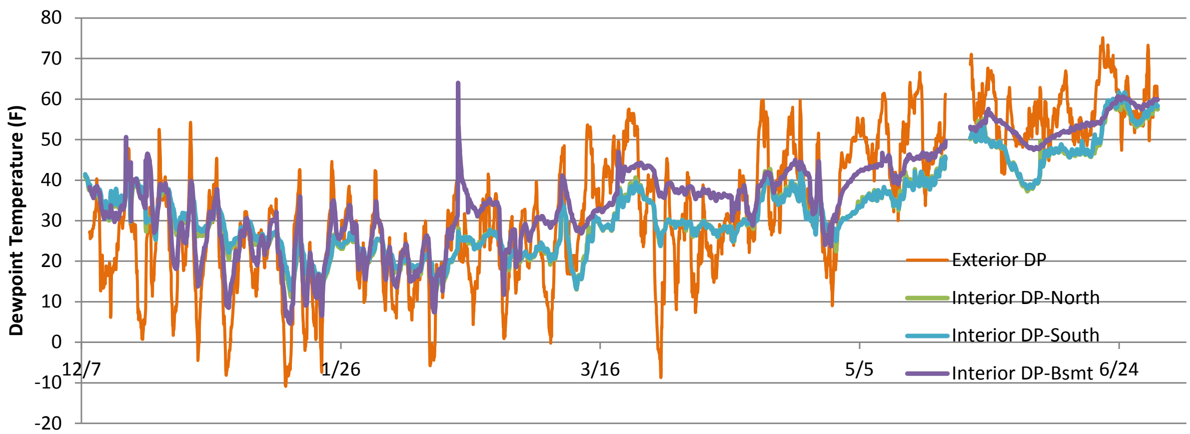

Figure 56. Exterior and interior (test rooms and basement) dew point temperatures

5.3.2 Monitored Wall Results

Sheathing MCs for the north-facing walls are shown in Figure 57; they show the expected seasonal rise and fall, with peak MCs in wintertime. The north 12-in. ocSPF wall (N1) showed a peak wintertime sheathing MC near 12%–15%; the 5½-in. ocSPF wall (N3) was similar to N1, but with slightly higher peak MCs (15%–20%). However, the 12-in. cellulose wall (N2) showed considerably higher MCs, in the 25%–28% range.

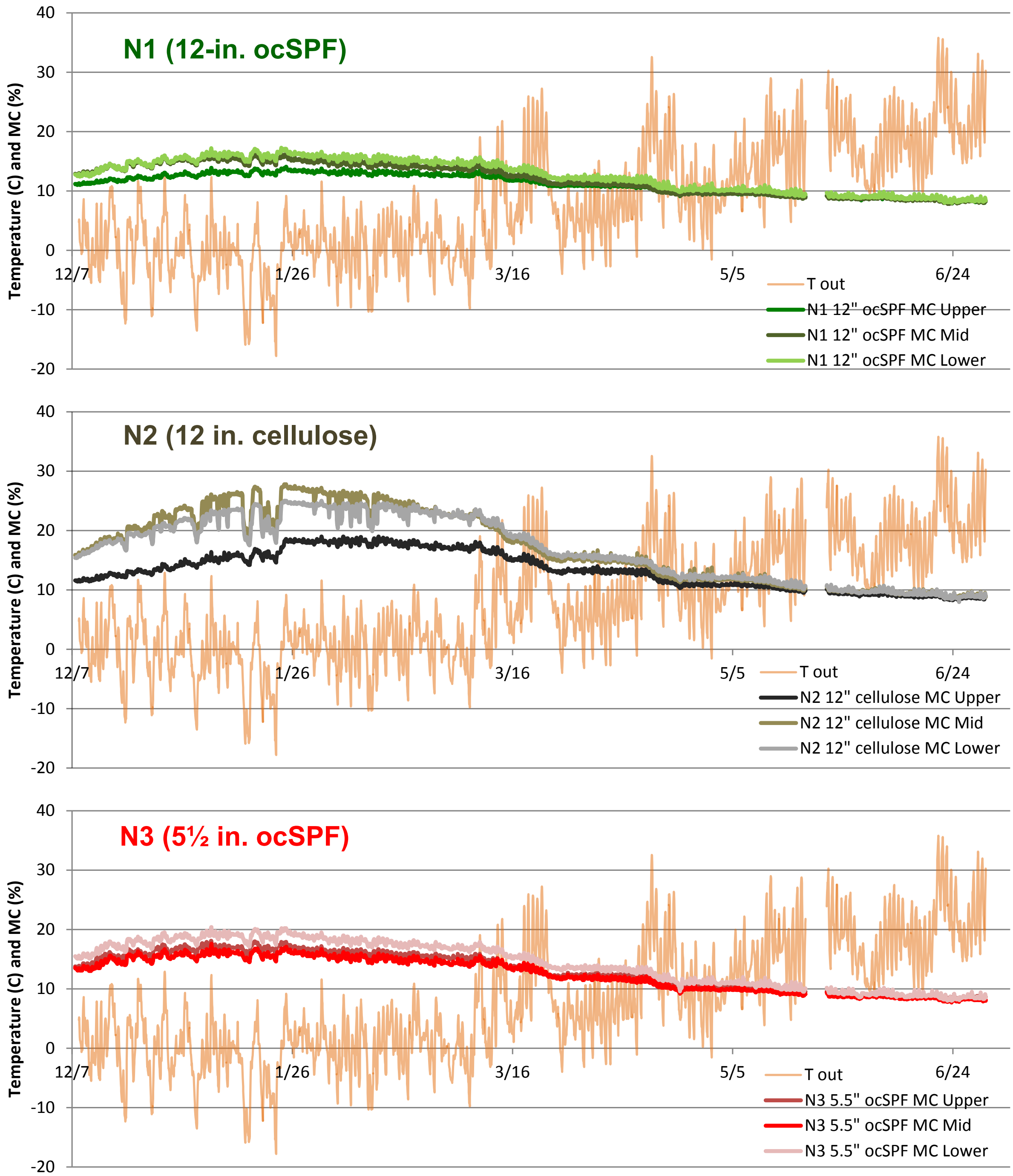

Figure 57. North side sheathing MCs, with exterior temperature for reference

The anomalies seen in the cellulose (N2) wintertime behavior (sudden jumps in MC) coincide with freezing temperatures; it is likely that freezing of bound water in the sheathing results in different electrical resistance response, and thus measured MC.

In the summer, all wall sheathings dry to roughly the same MC levels (10% or lower range).

The south-facing walls are all considerably dryer than the north-facing walls, but with a similar pattern, where the 12-in. cellulose wall (S2) has slightly higher wintertime peak MCs (Figure 58), All walls dry to the 8% range in the summer; the intermittent data seen during summertime indicate periods dryer than the measurement range of the data logger (wood electrical resistance is too high for logger setup).

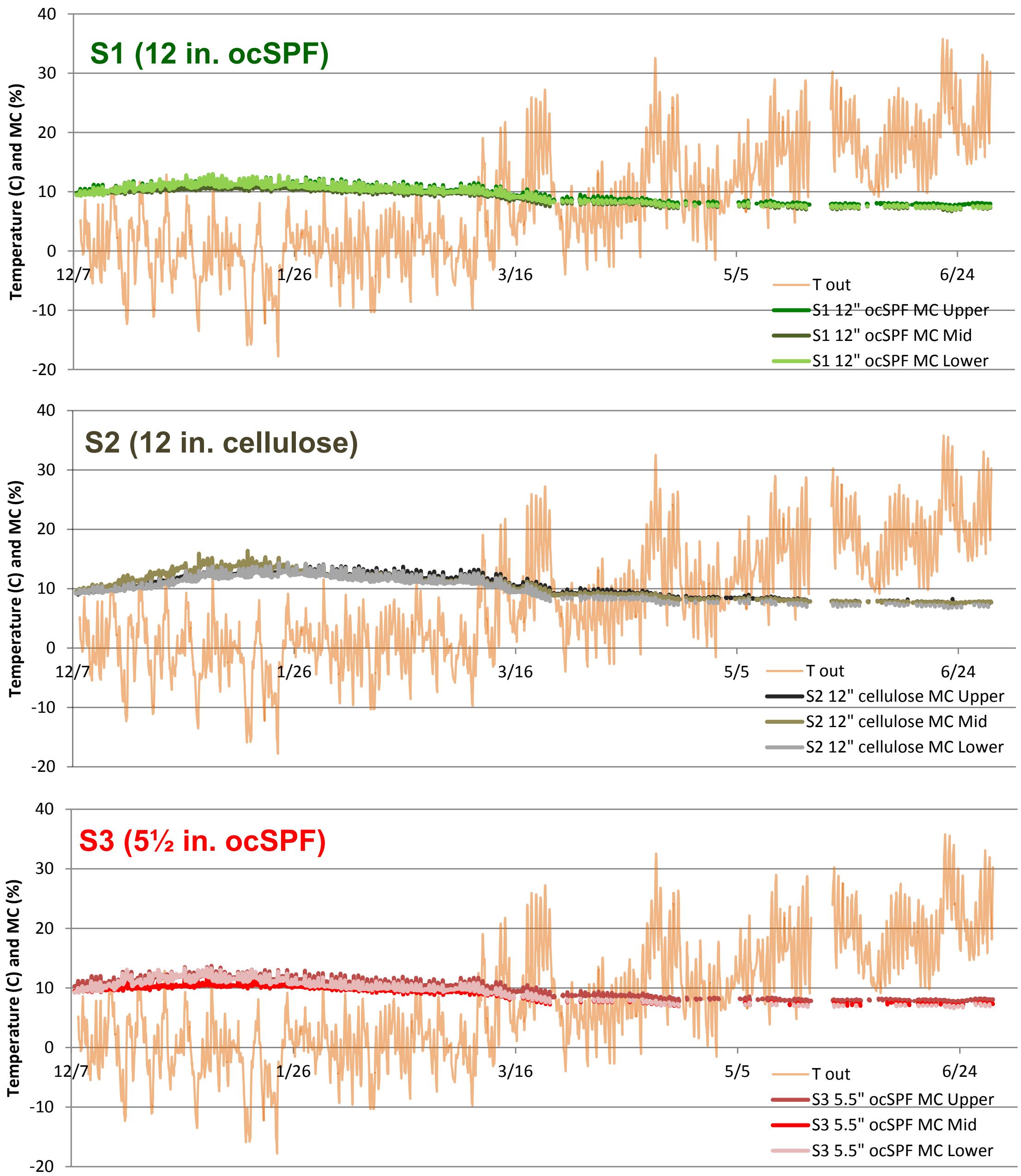

Figure 58. South side sheathing MCs, with exterior temperature for reference

Other sensors were examined to confirm the sheathing MC behavior. The “wafer” sensor results for the three north-facing walls are plotted in Figure 59, which reflect conditions at the exterior sheathing-to-insulation interface.

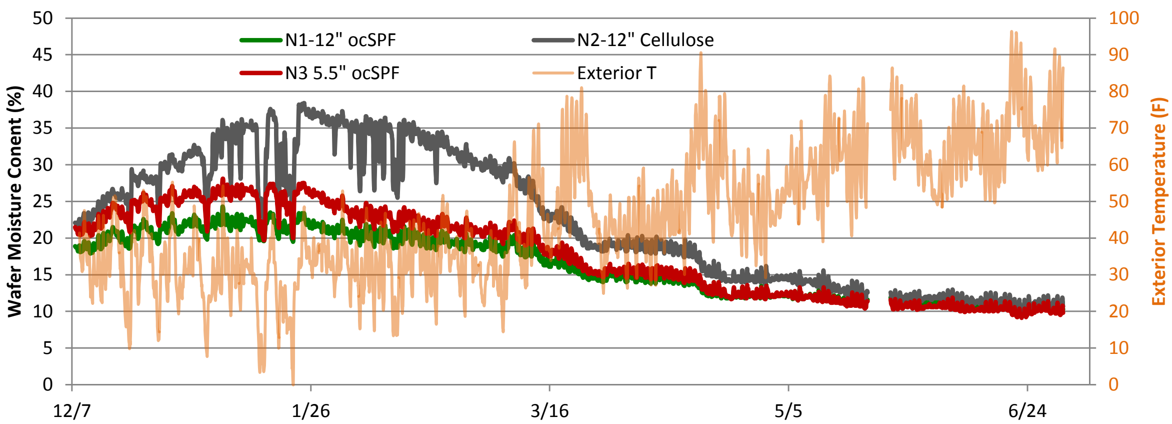

Figure 59. South side "wafer" sensor moisture contents, with exterior temperature for reference

The response of these wood-based sensors should be understood when interpreting these results. Based on previous work (Ueno and Straube 2008), the "wafer" sensors come to equilibrium with 100% RH conditions (closed box containing water) at 28%–30% MC. However, immersing the sensors in liquid water increases their MC to the 40%–45% range.

The "wafer" response is consistent with the sheathing MC measurements: 12 in. of 0.5 PCF foam remains the dryest through the winter, followed by 5½ in. of 0.5 PCF foam. The cellulose wall shows much higher wintertime peak moisture levels, consistent with condensation occurring at the sheathing. In contrast, the 0.5 PCF foam walls remain below the 100% RH level. During the summer, all "wafer" sensors dry to the 10%–2% moisture content range.

The south-facing wall "wafer" results are shown in Figure 60; again, patterns are analogous to the previous sheathing MC measurements.

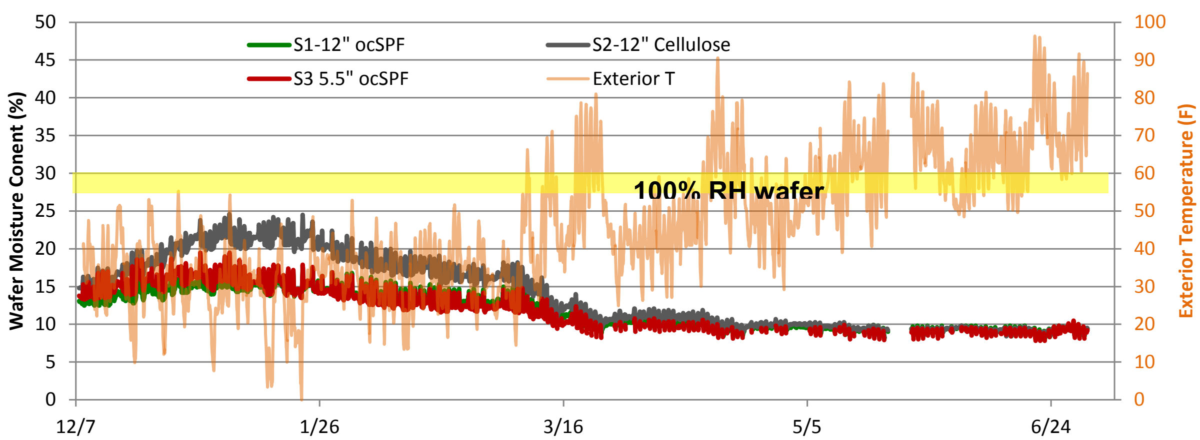

Figure 60. South side "wafer" sensor MCs, with exterior temperature for reference

The cellulose wall shows higher moisture levels, but all walls remain below the 100% RH-equivalent level. During the summer, the wafers dry to below 10% MC.

The RH measurements can be used to further confirm the previous results; the RH measurements for the north-facing walls (outboard side) are plotted in Figure 61. The temperatures at the RH sensors follow the expected wintertime pattern: N1 and N2 are close to identical (tracking outdoor conditions), and N3 is slightly warmer (due to reduced insulation inboard of the sensor). During the summer, all RH sensors at the sheathing fall to the 50%–65% range, as the temperature gradient and moisture drive are inward, away from the sheathing.

The RH results are consistent with previous measurements: the cellulose wall has higher humidity levels at the sheathing than the 0.5 PCF foam walls. The RH sensor is installed roughly ½ in. away from the face of the exterior sheathing.

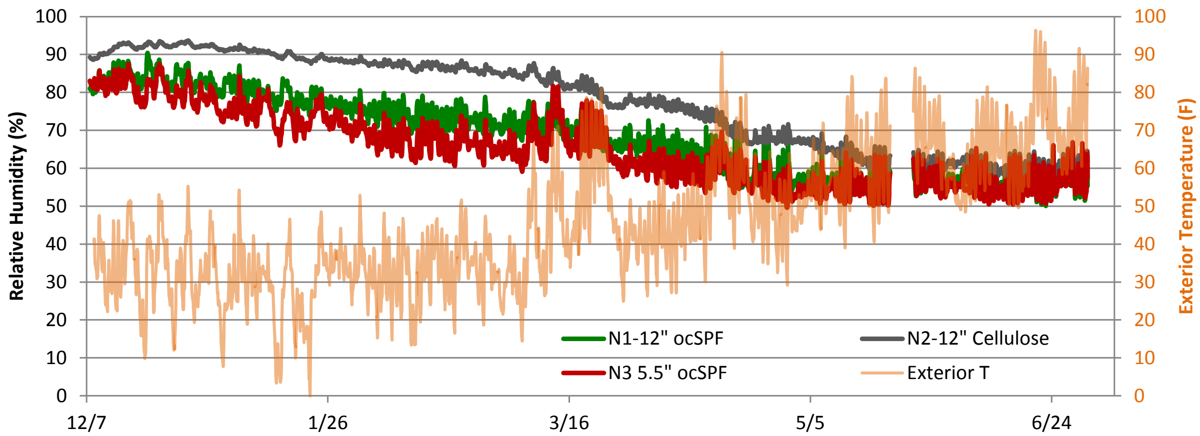

Figure 61. North-facing wall exterior side RH, with exterior temperature for reference

The inboard RH sensors for the north-facing walls are plotted in Figure 62, with exterior temperature and interior RH for reference. It appears that the RH levels essentially track interior conditions. The void space inboard of N3/S3 showed similar behavior.

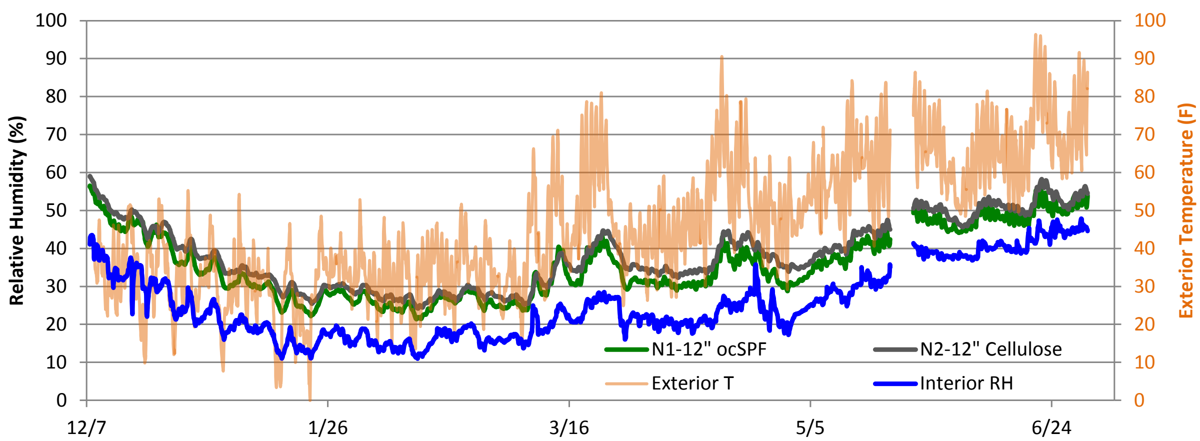

Figure 62. North-facing wall interior side RH, with interior RH and exterior temperature for reference

5.3.3 Analysis and Interpretation

One caveat on interpreting the data is that the boundary conditions were unrepresentative of typical conditions. First, winter 2011–2012 was much milder than normal (4400 HDD Base 65°F versus 5600 HDD climate normal). Second, the house was unoccupied, and therefore had no internal occupant moisture generation; wintertime interior RH conditions were consistently in the 15%–20% range (very dry), at normal indoor temperatures (70°F). As a result, these results are not the "worst case" in terms of interior-sourced wintertime condensation risks.

Even with these less-challenging conditions, the MCs at the sheathing of the north-facing cellulose wall peaked at levels high enough to cause concern. Wintertime peak measurements were in the 25%–28% range, while the other (0.5 PCF foam) walls remained below 20%. Traditional guidance is to keep wood MC below 20%; decay fungi are inhibited below this level (Carll and Highley 1999), with optimum growth occurring in the 25%–30% MC range. Decay fungi become active at MC levels above 28% (Straube and Burnett 2005).

In addition, the "wafer" sensors show that sheathing condensation might be occurring at peak wintertime conditions in the cellulose wall, unlike the 0.5 PCF walls. Although high RH conditions are associated with mold and decay, liquid water (i.e., condensation) greatly accelerates degradation of common building materials (Doll 2002).

However, the MCs should interpreted with temperatures in mind. Biological activity is inhibited at low temperatures, so high MCs in mid-winter pose less risk than in warmer seasons. Sustained high MCs at moderate temperatures pose the greatest durability risks. In the collected data, all walls dried to MCs well within the safe range during the summer.

Another consideration is that cellulose is treated with borate salts as a preservative and fire retardant. Borates are highly effective at inhibiting mold growth; they appear to leach into adjacent materials (e.g., gypsum board and wood sheathing), providing some protection to them.

One puzzling result was that the 12 in. of 0.5 PCF foam showed consistently drier wintertime conditions than the 5½ in. of 0.5 PCF foam. Common wisdom is that double-stud walls have colder sheathing, and thus experience greater moisture risks than conventional (e.g., 2 × 6) walls. However, these results might be explained by the vapor permeability of the assembly. Although 0.5 PCF ocSPF is generally thought of as vapor permeable, at the thickness applied at the double-stud wall here, there is significant vapor resistance. Table 8 shows the vapor permeability of the insulation layer alone, as well as in series with a 10 perm vapor retarder (Class III vapor retarder).

Table 8. Vapor Permeability of Insulation and Assemblies

Wall ID	Insulation Material	Vapor Permeability (Insulation Only)	Vapor Permeability (Add 10 Perm Class III Vapor Retarder)
N1/S1	12 in. 0.5 PCF foam	1.8–2.5 perms	1.5–2.0 perms
N2/S2	12 in. cellulose	7.0–10 perms	4.0–5.0 perms
N3/S3	5½ in. 0.5 PCF foam	4.0–5.5 perms	2.9–3.5 perms

It appears that at this thicknesses applied here, the ocSPF used here provides reasonable vapor control from interior-sourced moisture. Note that the spray foam values are not identical to the ASHRAE value stated previously; they are taken from manufacturer's data.

The vapor permeance of the painted and primed gypsum was not measured at this site; however, measurements at previous sites showed results in the 7–11 perm (dry cup) range, consistent with the value used for a Class III vapor retarder (10 perm). Schumacher and Reeves (2007) reported permeance measurements of 8 perms for drywall with two coats of latex paint, and 30 perms for drywall samples finished with a knock-down coating (a.k.a. California Ceiling).

It must be noted that the spray foam is an air-impermeable material, while cellulose is air permeable (does not meet air barrier material requirement of 0.02 $l/(s\text{-}m^2)$ at 75 Pa). However, cellulose (at higher densities) is an effective airflow retarder. Whether interstitial airflow has any role in the moisture behavior in this wall is unknown, but it may be a factor.

For reference, the use of a Class III vapor retarder is allowed by code in conventional construction, assuming a vented cladding (ICC 2009). In Zone 5, allowable assemblies include vented cladding (such as vinyl siding) over OSB, plywood, fiberboard, or gypsum sheathing. However, a double-stud wall has different behavior than conventional (2 × 4 or 2 × 6) construction.

Hygrothermal modeling was not performed at this time, with eight months' of data. The planned process is to only perform hygrothermal modeling (for comparison with monitored results) after the collection of at least one year of data, and preferably more (to account for the initial year's unoccupied conditions).

6 Financing Options for Photovoltaic Systems

6.1 Transformations, Inc. Financing Options

Transformations, Inc. offers three feasible options to the homeowners for obtaining PV systems. The developer has put substantial research and effort into developing affordable and viable alternatives. Local incentives—as well as state and federal tax credits—contribute to making the residential PV systems financially attractive (Scott 2011). These options aid the buyers in obtaining properly sized PV arrays for their homes at reasonable cost.

One option the developer offers is to lease the system. This option is best suited for homebuyers who may not have enough capital or be able to qualify for a higher loan. Transformations, Inc. works with three different providers that offer competitive terms for the lease. The lease term is approximately 18 years and subsequently the homeowner is able to buy the system out. This option allows the homeowner to purchase the power the PV system is producing at a discounted price of 10% with no need to maintain the system.

Another option is to purchase the system, which allows homeowners to keep all of the energy that is generated by the system. This alternative is suitable for homebuyers who are able to borrow a greater amount because the PV system cost is either included in the price of the home or financed with a separate loan. Including the cost of the PV system in with the mortgage that currently offers annual percentage rates in the 3%–4% range for a 30-year fixed year mortgage, is often the best option for the buyer. However, some of the larger solar systems (18.33 kW) have had a harder time appraising out for the full value of the system and home. Therefore, Transformations, Inc. has used a backup alternative of having the homebuyer obtain a second mortgage for the PV array. Also, the developer works with a local lender who offers a home equity line of credit with 2.99% annual percentage rate for three years with no points, no closing costs, no annual fees, and up to 100% financing.

In the Devens and Townsend developments, the PV system is part of the house package. In Easthampton, the homeowners have an option of adding PV arrays to their homes. Typically, homebuyers of the market rate homes choose to purchase the system and the homebuyers of the affordable homes decide to either lease it or not install it at all. Thus far, the two Custom Homes (Lots 30 and 43) have chosen to purchase the system. The Model Home (Lot 13) includes the lease option and the Easthampton (Lot 40) has yet to be sold and does not currently feature a PV array. The homeowners of the Small Saltbox (Lot 17) and the Hadley (Lot 24) are considering the lease option and the homeowners of the Cottage (Lot 23) decided to opt out.

6.2 Massachusetts Department of Energy Resources Solar Carve-Out Program

The Renewable Portfolio Standard (RPS) launched by the Massachusetts Department of Energy Resources (DOER) offers the SRECs to eligible projects (EPA 2009). RPS requires that a portion of the state's total electricity come from renewable resources—for example, residential PV systems. There are 33 states, plus the District of Columbia, that have established RPS requirements and the conditions of each program differ significantly.

In Massachusetts, the DOER Solar Carve-Out program's goal is to install 400 MW of solar electricity (Massachusetts Clean Energy Center 2012). An SREC is created for every megawatt-hour of solar electricity created and each SREC can be sold to the utility companies to meet the demand set by the program. The installed PV system has to be registered with the state program, and once it starts producing the energy the homeowner is able to track the production and hire an aggregator who will sell the SRECs back to the utility. The aggregation fee is typically around 5% of the SREC contract price.

The value of an SREC is typically determined by the market demand; in Massachusetts the DOER has calculated the Alternative Compliance Payment (ACP) rate of the SRECs for the next 10 years. The rates determined by the DOER represent penalty rates that utilities are obligated to pay if not able to meet the requirements of the Solar Carve-Out program. However, due to a higher solar energy market supply the value of the SRECs has decreased. The SRECs can be obtained at the Solar Credit Clearinghouse Auction for $300 (minus the 5% auction fee and the 5% aggregation fee).

Table 9 lists the values of the SRECs as determined by the DOER as well as the potential incentives for a 10-kilowatt (kW_{peak}) system installed in 2012. Currently in Massachusetts, new systems can obtain SRECs for 40 quarters (10 years). Over time, they will be reduced by as much as 4 quarters in any given year. The ACP rate represents the maximum incentive that SREC owners can obtain and the auction rate may be (but is not guaranteed to be) the minimum incentive.

Table 9. Value of Solar Renewable Energy Certificates in Massachusetts

Compliance Year	ACP Rate*/MWh (Maximum Incentives)		Auction Rate/MWh (Minimum Incentives)	
	Per SREC	Per Year	Per SREC	Per Year
2012	$550.00	$5,747.50	$300.00	$2,978.25
2013	$550.00	$5,747.50	$300.00	$2,978.25
2014	$523.00	$5,465.35	$300.00	$2,978.25
2015	$496.00	$5,183.20	$300.00	$2,978.25
2016	$472.00	$4,932.40	$300.00	$2,978.25
2017	$448.00	$4,681.60	$300.00	$2,978.25
2018	$426.00	$4,451.70	$300.00	$2,978.25
2019	$404.00	$4,221.80	$300.00	$2,978.25
2020	$384.00	$4,012.80	$300.00	$2,978.25
2021	$365.00	$3,814.25	$300.00	$2,978.25
Total Rebates		**$48,258.10**		**$29,782.50**

* The ACP rates for SRECs are determined by the Massachusetts DOER for a period of 10 years. An aggregation fee of 5% is included in the calculation of both yearly values. An additional auction fee of 5% is included in the calculation of the yearly auction rate values. The SREC income is likely to land between the two sets of incentives but the minimum is not guaranteed by the DOER.

Eleven SRECs (11.2 MWh) are assumed to be generated per year based on a system located in Easthampton, Massachusetts (Figure 63). The calculation was prepared using the PVWatts™ Grid Data Calculator (Version 2), which has been developed by National Renewable Energy Laboratory (NREL) (NREL 2012). The calculator determines energy production and cost savings for PV systems in any location in the world.

Station Identification	
Cell ID:	0271366
State:	Massachusetts
Latitude:	42.3 ° N
Longitude:	72.5 ° W
PV System Specifications	
DC Rating:	10.0 kW
DC to AC Derate Factor:	0.770
AC Rating:	7.70 kW
Array Type:	Fixed Tilt
Array Tilt:	39.8 °
Array Azimuth:	180.0 °
Energy Specifications	
Cost of Electricity:	13.6 ¢/kWh

Results			
Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value ($)
1	2.87	713	96.95
2	3.68	823	111.90
3	4.66	1108	150.65
4	4.76	1056	143.58
5	5.06	1114	151.47
6	5.16	1060	144.13
7	5.12	1074	146.03
8	5.13	1079	146.71
9	4.73	991	134.75
10	4.08	935	127.13
11	2.84	652	88.65
12	2.56	622	84.57
Year	4.22	11225	1526.26

Figure 63. PVWatts calculation for a house with a 10-kW system located in Easthampton, Massachusetts

Transformations, Inc. typically retains SRECs and uses their value to drive down the prices of its net-zero energy homes to slightly above those of conventional construction. This enables faster adaption of net-zero energy homes in Massachusetts.

6.3 Other Incentives

In addition to the SRECs, incentives are available from the Massachusetts Clean Energy Center for projects that use services from investor-owned utilities. The incentives are offered for the installation of a system up to 10 kW_{peak}, with a rebate capped at 5 kW_{peak}. In addition, there is also a Massachusetts state tax credit of $1,000 and a federal tax credit of 30% of the system cost available to the homebuyer.

The State of Massachusetts offers generous incentives for the PV systems, but the RPS programs are available in other states. However, since the program requirements in other states may be different than in the state of Massachusetts, homeowners, builders, and developers should inquire about the program requirements in their states to learn the details.

Also, other local or state incentives may be available to the homeowners for purchasing PV systems, and performing thorough research about the existing options is important in order to maximize the savings. Homeowners interested in the incentives should check with the state and local agencies as well as their utilities to find out about available energy efficiency programs in their areas.

The following is a list of website page links where information can be found about incentive programs in the individual states as well as the state of Massachusetts:

- Database of State Incentives for Renewables & Efficiency
  www.dsireusa.org
- Massachusetts Department of Energy Resources Solar Carve-Out Program
  www.mass.gov/eea/energy-utilities-clean-tech/renewable-energy/solar/rps-solar-carve-out/about-the-rps-solar-carve-out-program.html
- Massachusetts Clean Energy Center
  www.masscec.com
- Mass Save
  www.masssave.com

7 Basements Versus Above-Grade Construction Cost Comparison

In the Devens and Townsend developments, basements are included in the original designs of the homes. The basic package for the houses in the Easthampton development includes slab-on-grade foundations. Most buyers, however, are interested in having basements; the buyers of the market-rate homes in the Easthampton development have asked to add basements to the designs of their new homes. Buyers typically perceive basements as an added value to the homes, and see the potential of finishing the space and using it as additional living space.

Including a basement in the design of a home presents many challenges in regards to water management and insulation. Ensuring that the site water management or thermal performance of the space is properly addressed is important to the overall performance of the house.

Various research projects have focused on examining the best practices for insulation and water management when building a basement. Multiple articles and research projects have developed robust details and approaches for addressing those issues (Lstiburek 2006; Smegal and Straube 2010; Ueno and Lstiburek 2010; Aldrich et al. 2012). Case studies have been published demonstrating the implemented approaches on a number of projects. These documents do not, however, include information comparing the cost of adding a basement versus constructing a slab-on-grade foundation, and expanding the above grade living space.

In the article published in the *Journal of Light Construction* in 2010, the author discussed best practices for constructing frost-protected shallow slab-on-grade foundations (Gibson 2010). The author estimated that compared to a full 850-ft^2 basement, building a frost-protected shallow slab-on-grade foundation can save approximately $20,000. This is due to eliminating the foundation subcontractor, the concrete needed for a full foundation wall, the first-floor deck, as well as the excavation costs. This estimate, however, does not provide current cost values for a slab-on-grade foundation.

7.1 Basement and Slab-on-Grade Construction Comparison

Transformations, Inc. has developed standard packages for both including a basement in the home design and building a house with a slab-on-grade. In the Easthampton development the future homeowners of the market-rate houses are able to customize their homes based on their desires and needs. The affordable homes are stemwall slab-on-grade construction.

For the full basements (Figure 64), the basement slab assembly consists of (from bottom to top): a layer of crushed stone with filter fabric, one layer of 2-in. XPS rigid insulation, a layer of 6-mil polyethylene, and the concrete slab. For moisture control, dampproofing is installed on the outside of the foundation wall, extending from the top of the footing to grade. A capillary break at the junction between the top of the footing and the foundation wall controls capillary rise from the footing to the interior. A 3½-in. layer of ccSPF insulation is installed at the foundation wall and over the rim joist. The developer gives the homebuyers the option of finishing the space with studs and drywall; the unfinished option includes the required ignition barrier in the form of an intumescent paint.

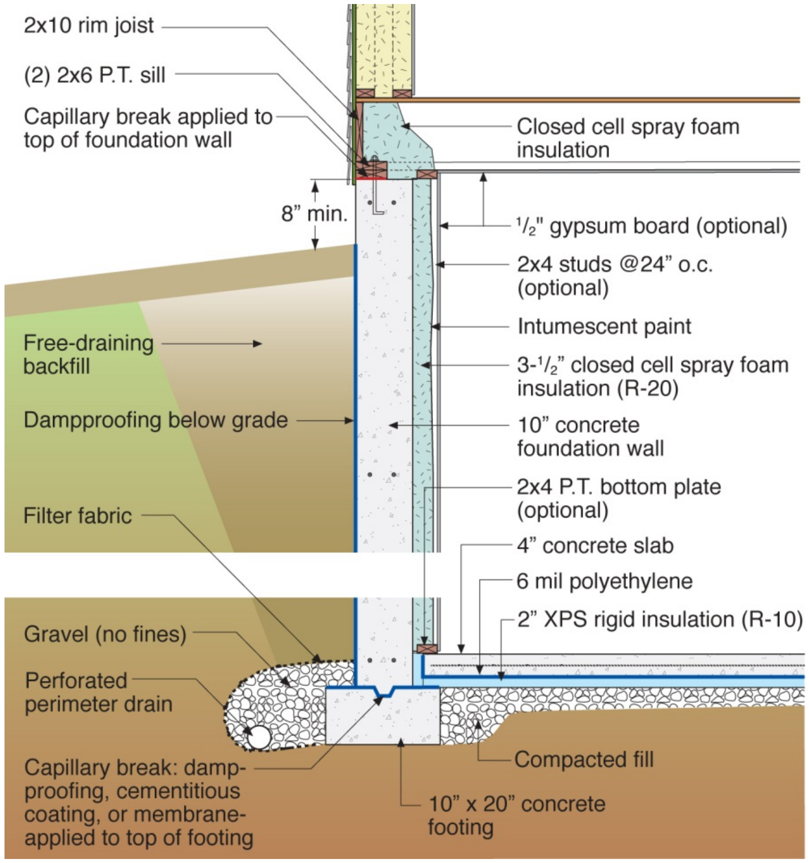

Figure 64. Foundation wall with 3½ in. of ccSPF insulation

The slab-on-grade assembly (Figure 65) consists of (from bottom to top): a layer of crushed stone with filter fabric, three layers of 2-in. XPS rigid insulation, a layer of 6 mil polyethylene, and the concrete slab. Two layers of 2-in. XPS rigid insulation are installed at the slab edge; the edge insulation is hidden under the inner (nonstructural) framing of the double-stud wall. The stemwall footings are below local frost depth.

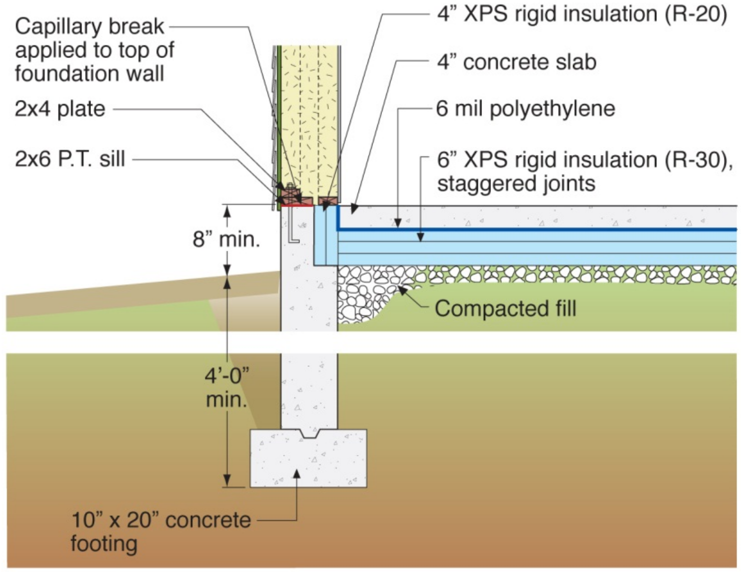

Figure 65. Slab-on-grade construction

7.2 Cost Analysis

The developer has provided per square foot cost data for constructing a basement as well as per square foot cost data for a slab-on-grade foundation (Table 10). The information is based on the "Farmhouse" model with a footprint of 24 ft × 36 ft (864 ft^2) located in the Easthampton development. That particular model was used for the construction of the Model Home (Lot 13), which has the slab-on-grade, and the Custom Home (Lot 30), which has the full basement. The cost difference between building a full basement versus a stemwall slab-on-grade is approximately $10,000 ($12/ft^2). Of course, this cost includes high performance water control measures, and durable insulation measures that create a warm, dry, comfortable—and therefore more usable—space.

Table 10. Basement Construction Cost

	Basement Cost	Slab-On-Grade Cost
Site Work	$18,850 (including structural fill, geo fabric)	$14,350 (including structural fill, geo fabric)
Foundation Labor	$3,750	$2,600
Foundation Concrete	$5,950	$3,450
Slab Insulation	$1,200 (2-in. XPS)	$2,800 (3 layers of 2-in. XPS)
First Floor Deck Materials	$800 (estimated)	–
Basement Wall Insulation	$3,150 (3½-in. ccSPF)	–
Total	**$33,700**	**$23,200**

To compensate for the lack of a basement, Transformations, Inc. typically offers the homebuyers the use of an unconditioned room above the garage. The garage size varies based on whether it is a one-car garage with a footprint of 12 ft × 22 ft (264 ft^2) or a two-car garage with a footprint of 22 ft × 24 ft (528 ft^2). The cost of turning the space into a usable storage room is marginal as it only requires the addition of floor sheathing to this vented attic space. The approximate cost of the floor sheathing for a one-car garage is $350 and $700 for a two-car garage. This estimate includes cost of materials and labor.

Another option of adding usable space to the house is to finish the unconditioned room above the garage. This alternative will provide the homebuyers with a finished living space but the cost is considerably higher. Given that the options for the finishes can vary significantly, the approximate cost to finish a room above a one-car garage (264 ft^2) is $10,000 and for a space above a two-car garage (528 ft^2) the cost is $20,000.

Another alternative that is available to the homebuyer is to increase the footprint of the home. This option, however, will raise the overall price of the house significantly. To determine the cost of adding extra square footage to a house, the cost values for a Farmhouse model were used. The market price of the Model Home in the Easthampton development is $287,000. In order to construct a 12 ft × 14 ft (168 ft^2) one-story addition to the Farmhouse model it would cost approximately $21,000 (this estimate does not include cost of foundation). Of course, this increased footprint assumes that the lot setbacks will accommodate a house of this size.

To summarize the cost analysis for the "Farmhouse" model as described above, the cost per square foot related to constructing a full basement versus above-grade space is as follows:

- Full basement: $39
- Slab-on-grade foundation: $27
- Unconditioned space above garage: $1.30 for one-car garage and $1.70 for two-car garage
- Finished space above garage: $38 for one-car garage and $76 for two-car garage
- 12 ft × 14 ft (168 ft^2) one-story addition: $125.

7.3 Basement Versus Above-Grade Advantages and Disadvantages

Basements can be problematic in regards to water management and insulation, and they can be viewed as dark and negative spaces in the houses. However, when constructed properly they can provide excellent storage area, space for mechanical equipment, and secondary living space. One of the interesting points of Transformations Inc.'s construction is, however, that their design minimizes the space required for mechanical equipment in the basement. Space conditioning is provided by ductless heat pumps (no basement space needed), and domestic hot water is provided by a wall-hung tankless unit (space only required for servicing). The PV inverters are also located in the basement.

Figure 66. (L) Tankless water heater; (R) PV inverters in unfinished basement

Transformations, Inc. also presents an opportunity of finishing the basement and providing additional living space, which will increase the value of a home. Two factors to consider in the basement versus slab decision are regional homebuyer expectations and site conditions.

As the experience to date in Easthampton has demonstrated, homebuyers in the New England region typically expect basements in their homes; slab-on-grade foundations are viewed as a lesser option. The lack of a basement for storing personal items and to house the mechanical equipment can be an issue for some. However, many homebuyers view basements only as storage spaces and would never consider them for providing additional living space. Homebuyers also consider the impact of basement space on resale value.

Another factor to consider is the site that the house will be built on. If the site is fairly flat it makes sense to build a slab-on-grade foundation, but if the terrain is more complicated, the cost of constructing a slab-on-grade may be similar to a full basement, as the excavation costs will be significant.

Slab-on-grade foundation can be viewed as less problematic (in terms of water control issues), and many homebuyers would prefer a smaller storage area located above grade. Spaces located above grade are typically considered as more healthy, clean, and attractive when compared to a basement. However, the cost of finished and conditioned space above grade is significantly higher than the basement incremental cost. On the other hand, unconditioned but enclosed storage space (attic) is substantially lower cost than a basement on a per square foot basis.

8 Conclusion and Further Work

8.1 Overview

The advanced efficiency package implemented by the developer in the Devens, Easthampton, and Townsend developments exceeds the 30% energy savings goal set by the Building America program for new homes in the cold climate for 2013. Based on the results collected to date, the two major components of the package—the double-stud walls filled with ocSPF insulation and the ductless mini-split heat pump equipment—have performed well. However, BSC is continuing the moisture monitoring research in the Devens development; data has been collected through June 2013, and further analysis will be contained in future BSC reports. Mini-Split Heat Pump Performance and Thermal Distribution

- What range of temperatures is experienced in bedrooms of homes heated by point sources?

  Under favorable conditions, mini-split heat pumps can provide thermal comfort and uniformity equal to conventional forced-air systems (± 2°F). The required conditions include a super-insulated building enclosure, excellent airtightness, moderate solar gains, and uniform set points within the building. Although one heat pump per floor is a common configuration, conductance between floors drives a large part of the thermal distribution. The two floors cannot be operated independently, nor successfully maintain different set points. This report does not address the effect of closing doors, which is expected to be important.

- How do buyers perceive the performance of the ductless mini-split heat pumps? Are the room-to-room temperature differences in homes with ductless heat pumps apparent to the residents?

  Although the winter of 2011–2012 was generally mild, the heat pumps performed well on several days near the design temperature, and did not reach maximum output. Occupants report high levels of comfort, consistent with the measured temperature uniformity. Most occupants seem to accept the concept of keeping bedroom doors open most of the time, facilitating thermal distribution and thus enhancing comfort.

8.2 Moisture Monitoring of Twelve-Inch Double-Stud Walls

- Does the use of ocSPF, rather than cellulose, in the wall cavities of double-stud walls change the MC of the wall assembly? Does this change the risk assessment for this construction approach?

  Eight months of monitored results were available for the comparison between double-stud walls with 12 in. of ocSPF, 12 in. of netted and dry blown-in cellulose, or 5½ in. of ocSPF. The first winter showed sheathing MCs high enough to cause concern in the double-stud cellulose wall, but acceptable conditions in the remaining walls. However, all walls dried to safe ranges in the summer. In addition, it is possible that the cellulose wall can withstand high MC levels without damage due to borate preservatives and moisture storage.

The team has been collecting data to present date (June 2013); further analysis will be covered in future BSC reports. The first winter measured data without occupancy (and thus interior moisture generation); the second winter demonstrated the effect of higher interior humidity levels. If high MCs are seen in the winter of 2012–2013, it will be interesting to see if the sheathing dries back to the same levels in the following spring and summer.

If the experiment can continue through an additional winter (2013–2014), and the homeowner agrees, it may be interesting to apply vapor retarder paint to the interior gypsum board at the test walls. This would determine whether vapor permeability or some other mechanism (such as air leakage) dominates the sheathing MC behavior.

- Do results of hygrothermal analysis correlate with field-measured MCs, in terms of risks of wintertime moisture accumulation in wood-based sheathings?

  Hygrothermal modeling was not performed at this time, with eight months' of data. The planned process is to only perform hygrothermal modeling (for comparison with monitored results) after the collection of at least one year of data, and preferably more (to account for the initial year's unoccupied conditions).

8.3 Financing Options for Photovoltaic Systems

- How can a PV array sufficient for net-zero performance be financed with no or minimal increase in annualized energy related cost to the homeowner, through SRECs and novel finance agreements? How can this model be applied to regions outside of Massachusetts?

  Transformations, Inc. was able to create three very viable options for financing a solar array that can suit a number of buyers—the lease option and two purchase options. The developer recognized that in some instances potential buyers were having difficulties financing the systems and responded to the needs of the buyers by offering an alternative financing option.

  The incentives offered by various programs in the state of Massachusetts as well as state and federal tax credits aid homebuyers in acquiring PV systems for their homes at an affordable price. However, the incentive programs in other states may differ significantly. Homebuyers should learn the details about the available incentive programs in their areas that will allow them to obtain a PV system and reach net-zero energy at a reasonable cost.

8.4 Basements Versus Above-Grade Construction Cost Comparison

- Basements are a common feature of cold climate construction, but they present special challenges for insulation and water management. How does the per square foot cost of basements compare to adding above-grade space?

  There are a number of factors to consider when choosing between adding a full basement and building a slab-on-grade foundation. The incremental cost of a high performance (well insulated and water managed) basement is high compared to a well-insulated slab; the builder's incremental cost was roughly $12/ft^2. Unconditioned attic storage space can be added at a low cost ($1.30–$1.70/ft^2); however, adding space conditioning and finishes would increase the cost of additional above-grade square footage considerably

(\$38–\$76/ft^2). Enlarging the footprint of the house is another possible option but it is significantly more expensive when compared to the other alternatives (\$125/ft^2).

The experience to date in Easthampton has demonstrated that homebuyers in the New England region typically expect basements. Excluding a basement from a home design can have significant impact on the value of the house in a region where basements are expected. However, the characteristics of a particular site where the house is going to be located are important factors, as the excavation costs can be substantial.

When presented with an opportunity for including a basement in a home design, budget and the desirable or needed square footage play a big role in the decision making. The available options for substituting the basement space with the additional above-grade area as well as advantages and disadvantages for building basements and slab-on-grade foundations, are intended to help builders and homebuyers assess the true cost as well as value of constructing either option.

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Appendix A: Mini-Split Heat Pump Performance Surveys

bsc TRANSFORMATIONS™ Zero Energy Homes — U.S. DEPARTMENT OF ENERGY — Energy Efficiency & Renewable Energy — Building AMERICA U.S. Department of Energy

Performance of the Mini-Split Air Source Heat Pumps

Name [redacted] **Address** 14 Cavite street

Please provide answers and additional comments for the questions 1 through 11 below:

1. When did you move into your house? Month April Year 2012
2. How comfortable are you in your house? Please select 1 through 5.

Winter Time: Most Comfortable				Least Comfortable	Summer Time: Most Comfortable				Least Comfortable
☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

3. How does your comfort compare to the last place you lived? ☑ More Comfortable ☐ About the Same ☐ Less Comfortable
4. What temperature is your thermostat set to? First Floor (Heating/Cooling) ____/ 70 Second Floor (Heating/Cooling) ____/ 70
5. Do you adjust the thermostat setpoint at night? Y X N ____
   If yes, what temperature do you set it to? First Floor (Heating/Cooling) ____/ OFF Second Floor (Heating/Cooling) ____/ 70
6. Do you adjust the thermostat setpoint when not home? Y X N ____
   If yes, what temperature do you set it to? First Floor (Heating/Cooling) ____/ OFF Second Floor (Heating/Cooling) ____/ OFF
7. Do you use any other heating or cooling devices, such as space heaters, window AC units, portable fans, etc? Y ____ N X
   If yes, what device and in which room? ____
8. Are parts of your house warmer or colder than you want? If yes, please select 1 through 5.

	Winter Time: Too Cold		Just Right		Too Warm	Summer Time: Too Cold		Just Right		Too Warm
Living Room	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
Dining Room	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
Kitchen	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
Bathroom 1	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
Bathroom 2	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
Bedroom 1	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
Bedroom 2	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
Bedroom 3	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5

9. Do you open or close windows to improve comfort?

Summer Time	☐ Always Open	☐ Mostly Open	☑ Mostly Closed	☐ Always Closed
Winter Time	☐ Always Open	☐ Mostly Open	☐ Mostly Closed	☐ Always Closed

10. How do you operate bedroom doors?

When in Bedroom	☐ Always Open	☑ Mostly Open	☐ Mostly Closed	☐ Always Closed
When not in Bedroom	☐ Always Open	☐ Mostly Open	☐ Mostly Closed	☐ Always Closed

11. Which of the following most affect your door operation choices?

☐ Keeping room warmer/cooler ☐ Room too stuffy/odors building up ☑ Privacy

Performance of the Mini-Split Air Source Heat Pumps

Name [redacted] **Address** 93 Adams Circle, Devens, MA 01434

Please provide answers and additional comments for the questions 1 through 11 below:

1. When did you move into your house? Month November Year 2011
2. How comfortable are you in your house? Please select 1 through 5.

Winter Time					Summer Time				
Most Comfortable				Least Comfortable	Most Comfortable				Least Comfortable
☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

3. How does your comfort compare to the last place you lived? ☐ More Comfortable ☐ About the Same ☐ Less Comfortable
4. What temperature is your thermostat set to? First Floor (Heating/Cooling) 63 / 78 Second Floor (Heating/Cooling) 63 / 78
5. Do you adjust the thermostat setpoint at night? Y ______ N X

   If yes, what temperature do you set it to? First Floor (Heating/Cooling) ____/____ Second Floor (Heating/Cooling) ____/____
6. Do you adjust the thermostat setpoint when not home? Y ______ N X

   If yes, what temperature do you set it to? First Floor (Heating/Cooling) ____/____ Second Floor (Heating/Cooling) ____/____
7. Do you use any other heating or cooling devices, such as space heaters, window AC units, portable fans, etc? Y X N ______

   If yes, what device and in which room? Space heater(winter) and fan(summer) in study room.
8. Are parts of your house warmer or colder than you want? If yes, please select 1 through 5.

	Winter Time					Summer Time				
	Too Cold		Just Right		Too Warm	Too Cold		Just Right		Too Warm
Living Room	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Dining Room	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Kitchen	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Bathroom 1	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Bathroom 2	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Bedroom 1	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Bedroom 2	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Bedroom 3	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

9. Do you open or close windows to improve comfort?

Summer Time	☐ Always Open	☐ Mostly Open	☐ Mostly Closed	☐ Always Closed
Winter Time	☐ Always Open	☐ Mostly Open	☐ Mostly Closed	☐ Always Closed

10. How do you operate bedroom doors?

When in Bedroom	☐ Always Open	☐ Mostly Open	☐ Mostly Closed	☐ Always Closed
When not in Bedroom	☐ Always Open	☐ Mostly Open	☐ Mostly Closed	☐ Always Closed

11. Which of the following most affect your door operation choices?

☐ Keeping room warmer/cooler ☐ Room too stuffy/odors building up ☐ Privacy

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

TRANSFORMATIONS™ Zero Energy Homes

Building America U.S. Department of Energy

Performance of the Mini-Split Air Source Heat Pumps

Name [redacted] **Address** 97 Adams Circle, Devens MA 01434

Please provide answers and additional comments for the questions 1 through 11 below:

1. When did you move into your house? Month June Year 2012
2. How comfortable are you in your house? Please select 1 through 5.

Winter Time					Summer Time				
Most Comfortable				Least Comfortable	Most Comfortable				Least Comfortable
☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

3. How does your comfort compare to the last place you lived? ☐ More Comfortable ☐ About the Same ☐ Less Comfortable
4. What temperature is your thermostat set to? First Floor (Heating/Cooling) _____/75 Second Floor (Heating/Cooling) _____/75
5. Do you adjust the thermostat setpoint at night? Y _______ N N

   If yes, what temperature do you set it to? First Floor (Heating/Cooling) _____/_____ Second Floor (Heating/Cooling) _____/_____
6. Do you adjust the thermostat setpoint when not home? Y _______ N N

   If yes, what temperature do you set it to? First Floor (Heating/Cooling) _____/_____ Second Floor (Heating/Cooling) _____/_____
7. Do you use any other heating or cooling devices, such as space heaters, window AC units, portable fans, etc? Y _______ N N

   If yes, what device and in which room? ____________________
8. Are parts of your house warmer or colder than you want? If yes, please select 1 through 5.

	Winter Time					Summer Time				
	Too Cold		Just Right		Too Warm	Too Cold		Just Right		Too Warm
Living Room	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Dining Room	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Kitchen	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Bathroom 1	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Bathroom 2	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Bedroom 1	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Bedroom 2	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Bedroom 3	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

9. Do you open or close windows to improve comfort?

Summer Time	☐ Always Open	☐ Mostly Open	☐ Mostly Closed	☐ Always Closed
Winter Time	☐ Always Open	☐ Mostly Open	☐ Mostly Closed	☐ Always Closed

10. How do you operate bedroom doors?

When in Bedroom	☐ Always Open	☐ Mostly Open	☐ Mostly Closed	☐ Always Closed
When not in Bedroom	☐ Always Open	☐ Mostly Open	☐ Mostly Closed	☐ Always Closed

11. Which of the following most affect your door operation choices?

☐ Keeping room warmer/cooler ☐ Room too stuffy/odors building up ☐ Privacy

[redacted]

TRANSFORMATIONS Zero Energy Homes

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

Building America U.S. Department of Energy

Performance of the Mini-Split Air Source Heat Pumps

Name [redacted] Address 13 River Valley Way, Easthampton, MA 01027

Please provide answers and additional comments for the questions 1 through 11 below:

1. When did you move into your house? Month March Year 2012
2. How comfortable are you in your house? Please select 1 through 5.

Winter Time					Summer Time				
Most Comfortable				Least Comfortable	Most Comfortable				Least Comfortable
[ ] 1	[✓] 2	[ ] 3	[ ] 4	[ ] 5	[ ] 1	[✓] 2	[ ] 3	[ ] 4	[ ] 5

3. How does your comfort compare to the last place you lived? [✓] More Comfortable [ ] About the Same [ ] Less Comfortable
4. What temperature is your thermostat set to? First Floor (Heating/Cooling) 70 / 62 Second Floor (Heating/Cooling) 70 / 62
5. Do you adjust the thermostat setpoint at night? Y ____ N X
   If yes, what temperature do you set it to? First Floor (Heating/Cooling) ___/___ Second Floor (Heating/Cooling) ___/___
6. Do you adjust the thermostat setpoint when not home? Y ____ N X
   If yes, what temperature do you set it to? First Floor (Heating/Cooling) ___/___ Second Floor (Heating/Cooling) ___/___
7. Do you use any other heating or cooling devices, such as space heaters, window AC units, portable fans, etc? Y X N ____
   If yes, what device and in which room? Portable fans to move the air to where we need it.
8. Are parts of your house warmer or colder than you want? If yes, please select 1 through 5.

	Winter Time					Summer Time				
	Too Cold		Just Right		Too Warm	Too Cold		Just Right		Too Warm
Living Room	[ ] 1	[ ] 2	[ ] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[✓] 3	[ ] 4	[ ] 5
Dining Room	[ ] 1	[ ] 2	[✓] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[✓] 3	[ ] 4	[ ] 5
Kitchen	[ ] 1	[ ] 2	[✓] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[✓] 3	[ ] 4	[ ] 5
Bathroom 1	[ ] 1	[ ] 2	[✓] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[✓] 3	[ ] 4	[ ] 5
Bathroom 2	[ ] 1	[ ] 2	[✓] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[✓] 3	[ ] 4	[ ] 5
Bedroom 1	[ ] 1	[ ] 2	[✓] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[ ] 3	[✓] 4	[ ] 5
Bedroom 2	[ ] 1	[✓] 2	[ ] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[ ] 3	[✓] 4	[ ] 5
Bedroom 3	[ ] 1	[✓] 2	[ ] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[ ] 3	[✓] 4	[ ] 5

9. Do you open or close windows to improve comfort?

Summer Time	[ ] Always Open	[ ] Mostly Open	[ ] Mostly Closed	[✓] Always Closed
Winter Time	[ ] Always Open	[ ] Mostly Open	[ ] Mostly Closed	[✓] Always Closed

10. How do you operate bedroom doors?

When in Bedroom	[ ] Always Open	[ ] Mostly Open	[ ] Mostly Closed	[✓] Always Closed
When not in Bedroom	[ ] Always Open	[ ] Mostly Open	[ ] Mostly Closed	[✓] Always Closed

11. Which of the following most affect your door operation choices?

[✓] Keeping room warmer/cooler [ ] Room too stuffy/odors building up [✓] Privacy

Performance of the Mini-Split Air Source Heat Pumps

[redacted] [redacted] **Address** 30 Treehouse Circle, Easthampton, MA 01027

Please provide answers and additional comments for the questions 1 through 11 below:

1. When did you move into your house? Month March (we will only answer summer questions) Year 2012
2. How comfortable are you in your house? Please select 1 through 5.

Winter Time					Summer Time				
Most Comfortable				Least Comfortable	Most Comfortable				Least Comfortable
☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☐ 3	[4] 4	☐ 5

3. How does your comfort compare to the last place you lived? [4] More Comfortable ☐ About the Same ☐ Less Comfortable
4. What temperature is your thermostat set to? First Floor (Heating/Cooling) 72 /_____ Second Floor (Heating/Cooling) 72 /_____
5. Do you adjust the thermostat setpoint at night? Y _______ N x

   If yes, what temperature do you set it to? First Floor (Heating/Cooling) _____/_____ Second Floor (Heating/Cooling) _____/_____
6. Do you adjust the thermostat setpoint when not home? Y _______ N x

   If yes, what temperature do you set it to? First Floor (Heating/Cooling) _____/_____ Second Floor (Heating/Cooling) _____/_____
7. Do you use any other heating or cooling devices, such as space heaters, window AC units, portable fans, etc? Y y N _______

   If yes, what device and in which room? portable fans in upstairs bedrooms
8. Are parts of your house warmer or colder than you want? If yes, please select 1 through 5.

	Winter Time					Summer Time				
	Too Cold		Just Right		Too Warm	Too Cold		Just Right		Too Warm
Living Room	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	[4] 3	☐ 4	☐ 5
Dining Room	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	[4] 3	☐ 4	☐ 5
Kitchen	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	[4] 3	☐ 4	☐ 5
Bathroom 1	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	[4] 3	☐ 4	☐ 5
Bathroom 2	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	[4] 3	☐ 4	☐ 5
Bedroom 1	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	[4] 3	☐ 4	☐ 5
Bedroom 2	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	[4] 3	☐ 4	☐ 5
Bedroom 3	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	[4] 3	☐ 4	☐ 5

9. Do you open or close windows to improve comfort?

Summer Time	☐ Always Open	[4] Mostly Open	[4] Mostly Closed	[4] Always Closed
Winter Time	☐ Always Open	☐ Mostly Open	☐ Mostly Closed	☐ Always Closed

10. How do you operate bedroom doors?

When in Bedroom	[4] Always Open	[4] Mostly Open	☐ Mostly Closed	☐ Always Closed
When not in Bedroom	☐ Always Open	☐ Mostly Open	☐ Mostly Closed	☐ Always Closed

11. Which of the following most affect your door operation choices?

[4] Keeping room warmer/cooler [4] Room too stuffy/odors building up ☐ Privacy

Note : The downstairs heat pump does not work nearly as well as the upstairs unit or our newly installed unit in bonus room.

bsc — TRANSFORMATIONS Zero Energy Homes — U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy — Building America U.S. Department of Energy

[redacted]

[redacted] Address 23 Coppersmith Way Townsend, MA

Please provide answers and additional comments for the questions 1 through 11 below:

1. When did you move into your house? Month July Year 2010
2. How comfortable are you in your house? Please select 1 through 5.

Winter Time					Summer Time				
Most Comfortable				Least Comfortable	Most Comfortable				Least Comfortable
☐ 1	☐ 2	☑ 3	☐ 4	☐ 5	☑ 1	☐ 2	☐ 3	☐ 4	☐ 5

3. How does your comfort compare to the last place you lived? ☑ More Comfortable ☐ About the Same ☐ Less Comfortable
4. What temperature is your thermostat set to? First Floor (Heating/Cooling) 65 / 75 Second Floor (Heating/Cooling) 60 / 75
5. Do you adjust the thermostat setpoint at night? Y ✓ N ____
   If yes, what temperature do you set it to? First Floor (Heating/Cooling) 60 / off Second Floor (Heating/Cooling) same 60 / 75 or off
6. Do you adjust the thermostat setpoint when not home? Y ✓ N ____
   If yes, what temperature do you set it to? First Floor (Heating/Cooling) 60 / off Second Floor (Heating/Cooling) 60 / off
7. Do you use any other heating or cooling devices, such as space heaters, window AC units, portable fans, etc? Y ✓ N ____
   If yes, what device and in which room? fan during hot in bedrooms only
8. Are parts of your house warmer or colder than you want? If yes, please select 1 through 5.

	Winter Time					Summer Time				
	Too Cold		Just Right		Too Warm	Too Cold		Just Right		Too Warm
Living Room	☐ 1	☑ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
Dining Room	☐ 1	☑ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
Kitchen	☐ 1	☑ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
down Bathroom 1	☐ 1	☑ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
up Bathroom 2	☐ 1	☑ 2	☐ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
Bedroom 1	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
Bedroom 2	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5
Bedroom 3	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5	☐ 1	☐ 2	☑ 3	☐ 4	☐ 5

9. Do you open or close windows to improve comfort?

Summer Time	☐ Always Open	☑ Mostly Open	☐ Mostly Closed	☐ Always Closed
Winter Time	☐ Always Open	☐ Mostly Open	☐ Mostly Closed	☑ Always Closed

10. How do you operate bedroom doors?

When in Bedroom	☐ Always Open	☑ Mostly Open	☐ Mostly Closed	☐ Always Closed
When not in Bedroom	☑ Always Open	☑ Mostly Open	☐ Mostly Closed	☐ Always Closed

11. Which of the following most affect your door operation choices?

☐ Keeping room warmer/cooler ☐ Room too stuffy/odors building up ☑ Privacy [redacted]rmance of the Mini-Sp[redacted]

[redacted] Address 5 Penny LN, Townsend, MA 01469

Please provide answers and additional comments for the questions 1 through 11 below:

1. When did you move into your house? Month Sept Year 2011
2. How comfortable are you in your house? Please select 1 through 5.

Winter Time					Summer Time				
Most Comfortable				Least Comfortable	Most Comfortable				Least Comfortable
[ ] 1	[ ] 2	[ ] 3	[x] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5

3. How does your comfort compare to the last place you lived? [x] More Comfortable [ ] About the Same [ ] Less Comfortable
4. What temperature is your thermostat set to? First Floor (Heating/Cooling) 68 / 68 Second Floor (Heating/Cooling) Ø / 68
5. Do you adjust the thermostat setpoint at night? Y X N ___
   If yes, what temperature do you set it to? First Floor (Heating/Cooling) 70 / 70 Second Floor (Heating/Cooling) Ø / 70
6. Do you adjust the thermostat setpoint when not home? Y X N ___
   If yes, what temperature do you set it to? First Floor (Heating/Cooling) 65 / 70 Second Floor (Heating/Cooling) Ø / 70
7. Do you use any other heating or cooling devices, such as space heaters, window AC units, portable fans, etc? Y X N ___
   If yes, what device and in which room? Small Bedroom Floor FAN
8. Are parts of your house warmer or colder than you want? If yes, please select 1 through 5.

	Winter Time					Summer Time				
	Too Cold		Just Right		Too Warm	Too Cold		Just Right		Too Warm
Living Room	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5
Dining Room	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5
Kitchen	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5
Bathroom 1	[ ] 1	[ ] 2	[ ] 3	[x] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5
Bathroom 2	[ ] 1	[ ] 2	[ ] 3	[x] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5
Bedroom 1	[ ] 1	[ ] 2	[ ] 3	[x] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5
Bedroom 2	[ ] 1	[ ] 2	[ ] 3	[x] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5
Bedroom 3	[ ] 1	[ ] 2	[ ] 3	[x] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5

9. Do you open or close windows to improve comfort?

Summer Time	[ ] Always Open	[x] Mostly Open	[ ] Mostly Closed	[ ] Always Closed
Winter Time	[ ] Always Open	[ ] Mostly Open	[ ] Mostly Closed	[x] Always Closed

10. How do you operate bedroom doors?

When in Bedroom	[ ] Always Open	[ ] Mostly Open	[ ] Mostly Closed	[x] Always Closed
When not in Bedroom	[x] Always Open	[ ] Mostly Open	[ ] Mostly Closed	[ ] Always Closed

11. Which of the following most affect your door operation choices?

[ ] Keeping room warmer/cooler [ ] Room too stuffy/odors building up [x] Privacy

bsc TRANSFORMATIONS Zero Energy Homes U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy Building America U.S. Department of Energy

Performance of the Mini-Split Air Source Heat Pumps

Name [redacted] Address 6 Penny Lane, Townsend MA 01469

Please provide answers and additional comments for the questions 1 through 11 below:

1. When did you move into your house? Month 8-1-2011 Year 2011

2. How comfortable are you in your house? Please select 1 through 5.

Winter Time					Summer Time				
Most Comfortable				Least Comfortable	Most Comfortable				Least Comfortable
[x] 1	[ ] 2	[ ] 3	[ ] 4	[ ] 5	[x] 1	[ ] 2	[ ] 3	[ ] 4	[ ] 5

3. How does your comfort compare to the last place you lived? [ ] More Comfortable [x] About the Same [ ] Less Comfortable

4. What temperature is your thermostat set to? First Floor (Heating/Cooling) 68 / 70 Second Floor (Heating/Cooling) N/A / N/A

5. Do you adjust the thermostat setpoint at night? Y ______ N ✓

   If yes, what temperature do you set it to? First Floor (Heating/Cooling) ____/____ Second Floor (Heating/Cooling) ____/____

6. Do you adjust the thermostat setpoint when not home? Y ______ N ✓

   If yes, what temperature do you set it to? First Floor (Heating/Cooling) ____/____ Second Floor (Heating/Cooling) ____/____

7. Do you use any other heating or cooling devices, such as space heaters, window AC units, portable fans, etc? Y ______ N ✓

   If yes, what device and in which room? ______

8. Are parts of your house warmer or colder than you want? If yes, please select 1 through 5.

	Winter Time					Summer Time				
	Too Cold		Just Right		Too Warm	Too Cold		Just Right		Too Warm
Living Room	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5
Dining Room	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5
Kitchen	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5
Bathroom 1	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5	[ ] 1	[x] 2	[ ] 3	[ ] 4	[ ] 5
Bathroom 2	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5
Bedroom 1	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5	[ ] 1	[x] 2	[ ] 3	[ ] 4	[ ] 5
Bedroom 2	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5
Bedroom 3	[ ] 1	[ ] 2	[ ] 3	[ ] 4	[ ] 5	[ ] 1	[ ] 2	[x] 3	[ ] 4	[ ] 5

9. Do you open or close windows to improve comfort?

Summer Time	[ ] Always Open	[ ] Mostly Open	[x] Mostly Closed	[ ] Always Closed
Winter Time	[ ] Always Open	[ ] Mostly Open	[x] Mostly Closed	[ ] Always Closed

10. How do you operate bedroom doors?

When in Bedroom	[ ] Always Open	[x] Mostly Open	[ ] Mostly Closed	[ ] Always Closed
When not in Bedroom	[ ] Always Open	[x] Mostly Open	[ ] Mostly Closed	[ ] Always Closed

11. Which of the following most affect your door operation choices?

[ ] Keeping room warmer/cooler [ ] Room too stuffy/odors building up [x] Privacy

Appendix B: Model Home (Lot 13) Home Energy Rating Certificate

Home Energy Rating Certificate

River Valley Way

Easthampton, MA 01027

5 Stars Plus
Verified Condition

Uniform Energy Rating System | **Energy Efficient**

1 Star	1 Star Plus	2 Stars	2 Stars Plus	3 Stars	3 Stars Plus	4 Stars	4 Stars Plus	5 Stars	5 Stars Plus
500-401	400-301	300-251	250-201	200-151	150-101	100-91	90-86	85-71	70 or Less

HERS Index: **4**

General Information

Conditioned Area:	1795 sq. ft.	HouseType:	Single-family detached
Conditioned Volume:	14323 cubic ft.	Foundation:	Slab
Bedrooms:	3		

Mechanical Systems Features

75 Air-source heat pump: Electric, Htg: 10.5 HSPF. Clg: 23.0 SEER.
Air-source heat pump: Electric, Htg: 10.5 HSPF. Clg: 23.0 SEER.
Water Heating: Instant water heater, Natural gas, 0.92 EF, 0.0 Gal.
Duct Leakage to Outside: 0.00 CFM.
Ventilation System: Supply Only: 120 cfm, 21.1 watts.
Programmable Thermostat: Heating: Yes Cooling: Yes

Building Shell Features

Ceiling Flat:	R-89, R-24	Exposed Floor:	R-42
Vaulted Ceiling:	R-58	Window Type:	U:0.20, SHGC:0.26
Above Grade Walls:	U-0.021	**Infiltration:**	
Foundation Walls:	NA	Rate:	Htg: 1.52 Clg: 1.52 ACH50
Slab:	R-20.0 Edge, R-30.0 Under	Method:	Blower door test

Lights and Appliance Features

Percent Interior Lighting:	100.00	Range/Oven Fuel:	Electric
Percent Garage Lighting:	0.00	Clothes Dryer Fuel:	Electric
Refrigerator (kWh/yr):	416.00	Clothes Dryer EF:	2.67
Dishwasher Energy Factor:	0.77	Ceiling Fan (cfm/Watt):	0.00

The Home Energy Rating Standard Disclosure for this home is available from the rating provider.

REM/Rate - Residential Energy Analysis and Rating Software v13.0

This information does not constitute any warranty of energy cost or savings.

Registry ID:
Rating Number:
Certified Energy Rater:
Rating Date: 3/14/11
Rating Ordered For:

Estimated Annual Energy Cost

Verified Condition

Use	MMBtu	Cost	Percent
Heating	9.6	$504	576%
Cooling	1.4	$72	82%
Hot Water	14.2	$201	230%
Lights/Appliances	18.9	$996	1137%
Photovoltaics	-32.0	$-1686	-1925%
Service Charges		$0	0%
Total		**$88**	**100%**

This home meets or exceeds the minimum criteria for all of the following:

EPA ENERGY STAR Version 2 Home
2009 International Energy Conservation Code

TITLE
Company
Address
City, State, Zip
Phone #
Fax #

buildingamerica.gov

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

DOE/GO-102013-3902 ▪ September 2013