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Long-Term Monitoring of Mini-Split Ductless Heat Pumps in the Northeast

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The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

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

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

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Definitions

ACCA	Air Conditioning Contractors of America
ACH 50	Air Changes per Hour at 50 Pascals
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BR	Bedroom
BSC	Building Science Corporation
Btu	British Thermal Unit
CARB	Consortium for Advanced Residential Buildings
CFM	Cubic Feet per Minute
CFM 50	Cubic Feet per Minute At 50 Pascals
COP	Coefficient of Performance
DHP	Ductless Heat Pump
DOE	U.S. Department of Energy
ft^2	Square Foot/Square Feet
HDD	Heating Degree Day
HDD 65°F	Heating Degree Day, Base 65°F
HSPF	Heating Season Performance Factor
kBtu/h	Thousand Btu per Hour
kVA	Thousand Volt Amperes
kWh	Kilowatt-Hour
MSHP	Mini-Split Heat Pump
RH	Relative Humidity
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
T/RH	Temperature/Relative Humidity
V	Volt
W	Watt
XPS	Extruded Polystyrene

Executive Summary

This report covers the long-term performance of mini-split heat pumps (MSHPs) in Massachusetts (zone 5A); it is the culmination of up to 3 years' worth of monitoring in a set of eight houses. This research examined electricity use of MSHPs, distributions of interior temperatures and humidity when using simplified (two-point) heating systems in high-performance housing, and the impact of door open/closed status on temperature distributions. The use of simplified space conditioning distribution (MSHPs) provides significant first-cost savings, which are used to offset the increased investment in the building enclosure.

A literature search was conducted on two topics: MSHP performance and single-point/simplified heating distribution.

Overall, this project demonstrated that simplified space conditioning distribution using MSHPs can provide excellent performance, as shown in many houses. However, there are some cases and situations that designers should be aware of as potential failures. Occupant operation can have significant impacts on performance. Key results from the monitoring include the following:

- **General MSHP operation patterns.** Some patterns were seen among many of the monitored houses; it was useful to confirm expected behavior for the equipment. When a constant interior set point is used, the MSHP modulates up and down with outdoor temperature, running almost continuously throughout the winter to meet load. The first-floor unit provides the majority of the heating (compared to the second-floor unit) because of thermal buoyancy. Conversely, in summertime the second-floor unit often provides the majority of the cooling. As would be expected in a zone 5A climate, heating consumption far outweighs cooling consumption.
- **Equipment capacity and sizing.** There were no cases where there were issues with equipment sizing or lack of capacity, which indicated that these cold-temperature heat pumps are a viable strategy as a single heat source in cold climates. This indication was confirmed by the monitoring—the MSHPs seldom hit maximum power draw, which suggested that there was substantial excess capacity even during worst-case winter conditions (much colder than local design temperatures). This is consistent with the installed capacity of the equipment. The oversizing (compared to calculated loads) ranged from 150% to 200% in most cases. Oversizing MSHPs can actually be beneficial because (1) they modulate their capacity, and (2) their highest efficiency is obtained when the unit is running at the lower end of its capacity range.
- **Normalized use versus simulations.** MSHP heating use was tabulated for the various houses, normalized by heating degree days (HDDs), and compared with simulation predictions for heating use. There is considerable scatter in the results. Correlations varied from 57% above to 26% below the simulation prediction. Possible explanations were provided for various individual houses being above or below simulation predictions. Given the limited correlation between actual and simulated use, it is difficult to draw any conclusions on the accuracy of the energy model.
- **Normalized use (kWh/ft^2·HDD at 65°F [HDD 65]).** The heating electricity use was also normalized by HDDs and square footage. Average consumption was 0.00030

kWh/ft^2·HDD 65, which is reasonably close to simulation predictions (0.00028 kWh/ft^2·HDD 65). This information also provides a comparison metric for other houses heated with MSHPs.

- **Interior temperature distributions (4°F difference).** The Air Conditioning Contractors of America recommends a maximum 4°F difference within a home or zone (highest minus lowest temperature); the temperature data were evaluated using this criterion. Results spanned a wide range. Looking specifically at wintertime operation, results ranged from 96% of hours within the 4°F band to only 19% of hours; however, some weaknesses of this metric were pointed out. In addition, summertime data were analyzed; they indicate that summer conditions are less challenging than winter conditions for simplified distribution—at least given the solar gains (glazing ratios and solar heat gain coefficients) in these houses.
- **Door operation effects on bedroom temperatures.** Previous work showed that bedrooms during closed-door hours had greater differences between hallway and bedroom temperatures compared to open-door hours. The current data were analyzed; however, limited conclusions could be drawn. Many houses had very few closed-door hours, which might reflect actual operation or instrumentation issues. In another house, MSHPs were operated in an on-off manner (instead of using a constant set point), which resulted in few usable data for evaluating door operation.
- **Thermal buoyancy effects (use of single MSHP on first floor).** Due to their small loads, two small houses were equipped with a single MSHP on the first floor. However, during the first summer, the second floor did not cool down to set point (10°F or warmer than the first floor) even with the use of transfer fans. These issues are clearly due to thermal buoyancy; conditioned air rises from the first-floor unit in the winter but stays on the first floor during the cooling operation. An additional MSHP was retrofitted to the second floor, correcting this issue.
- **Open-plan first-floor temperature distributions.** In general, open-plan first floors had few issues. The few exceptions were caused by geometry and thermal buoyancy (an open stairwell intercepting heating air before it could reach across the space) and localized air leakage (dryer vent), which resulted in a single cold room.
- **Bonus room comfort issues at Easthampton:** One house experienced comfort issues that are instructive. The owners complained of a bedroom suite and a bonus room that were consistently cold in wintertime. A constant set point was used, but leaving doors open was not compatible with their lifestyle and schedule. Monitoring confirmed that extended winter periods with closed doors resulted in temperatures in the high 50s in the bedroom suite and high 40s in the bonus room. This house is larger than other monitored houses (2300 ft^2 versus 1100–1700 ft^2 for others). In addition, it has unfavorable geometries in the problem areas. The bonus room had severe conditions of exterior temperatures on five of its six sides. Calculations indicated that this was not an equipment undersizing issue but a heat-distribution issue. The problem was resolved by installing a 3:1 (indoor units: outdoor unit) MSHP with indoor heads in all three bedrooms.
- **Temperature setbacks (on/off operation):** Previous work has shown that deep temperature setbacks of simplified heating systems can exacerbate temperature

unevenness issues. One homeowner complained of temperature unevenness; when the data were examined it was clear that they operated their MSHP in an "on-off" manner rather than using a fixed set point. This approach resulted in wide swings in interior temperature (between 60°F and 70°F+). The electricity use showed many hours with the MSHP running at maximum capacity followed by periods with the unit shut off. When operated in this manner, the MSHP is heating at its least efficient (maximum output) state. Electricity consumption was a high consumption outlier; when compared with simulations it was the worst-performing house—the heating use was 57% higher than simulation.

1 Introduction

This report covers research on the long-term performance of mini-split heat pumps (MSHPs) in a Northeast climate (U.S. Department of Energy [DOE] zone 5A); it is the culmination of up to 3 years' worth of monitoring in a set of eight houses. This research examined electricity use of MSHPs, distributions of interior temperatures when using simplified (two-point) heating systems in high-performance housing, and the impact of door open/closed status on temperature distributions. In addition, the builder's real-world experience with these systems (including homeowner comfort issues) is discussed.

1.1 Problem Background

Conventional furnaces and split-system air conditioners are grossly oversized for many current high-performance houses. It is common for such houses to have design loads of 12–18 kBtu/h; in comparison, 40 kBtu/h (nominal) is the smallest common furnace size. Conventional split system cooling systems start at 18 kBtu/h (1.5 tons), and high-efficiency systems are often unavailable below 24 kBtu/h (2 tons). Holladay (2011) discusses the problem of selecting space conditioning equipment for low-load houses and discusses various solutions.

Reduced mechanical system cost is often given as one of the benefits of increased building insulation and airtightness. Unfortunately, the first-cost 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.

Inverter-driven ductless heat pumps (DHPs) or MSHPs offer a promising answer to these issues. They have been widely installed in Asia and Europe for more than 40 years and have rapidly gained traction in North America. They are commonly available in sizes from 9 kBtu/h to 18 kBtu/h (0.75–1.5 tons), with some larger sizes as well. The equipment is more expensive on a per-ton basis compared to fully ducted conventional systems. However, they offer significant installed cost savings relative to conventional system when distribution costs are accounted for. Many MSHPs have a rated coefficient of performance (COP) typically at the top tier of commercially available equipment; they also offer variable-speed compressors, which render them even more efficient at off-peak conditions and reduce the downsides of oversizing equipment. More recently, manufacturers have offered MSHPs that maintain their nominal heating output at 5°F or below, making them viable as a sole source of heating in cold climates without a backup heating system.

The remaining—and substantial—challenge for wider deployment of MSHPs is the uncertainty surrounding thermal comfort in houses without distribution of hot and cold air to every room. Installing MSHP heads in each bedroom will increase costs sufficiently to negate their price advantage over conventional ducted systems.

1.2 Builder and Research Project Background

Transformations, Inc. is a residential development and building company with a proven track record of delivering high-performance superinsulated housing at a cost-effective price point in a variety of Massachusetts markets (DOE zone 5A). Its production houses commonly include renewable energy systems and have often achieved net zero and net positive performance. Building Science Corporation (BSC) has been working with Transformations since 2009 under the Building America program on a variety of single-family and duplex projects (see Ueno et al. 2013a). Transformations, Inc. was named a DOE Challenge Home 2013 Winner (Housing Innovation Awards) in both the custom home and production home categories.

Part of Transformations Inc.'s strategy of producing high-performance homes without a significant cost increase is to offset the cost of upgrading the building enclosure/shell by reducing the size and cost of the mechanical systems. The builder uses MSHPs in its production work, typically with a simplified distribution system of one indoor head/unit per floor. This has proven to be a very successful strategy in many of its past developments; however, many practitioners feel that additional research is warranted on the distribution of heating and cooling from point or simplified sources, and its effect on occupant comfort.

Therefore, monitoring equipment was installed at two Transformations, Inc. communities. Four houses at the Devens Green Zero Energy Community (Harvard, Massachusetts) and four at The Homes at Easthampton Meadow Zero Energy Attainable Community (Easthampton, Massachusetts) were selected for instrumentation. Further information on these communities and houses can be found in Appendix B and Appendix C. The instrumentation package included temperature and relative humidity (T/RH) measurements in several interior locations, electricity use of the MSHPs, door open/closed status, and exterior T/RH. The door status was recorded because it appears to have a strong effect on the temperature distributions of single point or simplified space conditioning systems. Details on instrumentation can be found in Appendix A.

1.3 Relevance to Building America's Goals

Given the Building America goals of reducing home energy use by 30%–50% (compared to 2009 energy codes for new homes and pre-retrofit energy use for existing homes), Transformations Inc.'s houses are a demonstration that this type of performance is achievable cost effectively on a production basis. Providing research, validation, and guidance on the use of MSHPs and simplified mechanical systems is useful to support this builder in continuing construction.

This research on MSHPs and temperature distributions addresses a Building America Critical Path Milestone, as described in the document "Building America Critical Path Innovations Leading to 50% Savings" (NREL 2013). This research falls under the category of Space Conditioning under Distribution System Solutions with Negligible Heat Losses that states: "Document distribution of T/RH distribution among rooms, utilizing MSHPs or equivalent as primary system, assuming economics prevent installation of a unit in every room."

1.4 Tradeoffs and Other Benefits

The most obvious benefit to research on simplified heating systems such as MSHPs is the cost implications of reduced scope/size mechanical systems. As discussed previously, this strategy works in tandem with the improvements in enclosure performance. This is discussed in more detail in Section 3.

An additional advantage of MSHPs is that temperature zoning can be achieved based on the number of heads available. Temperature variations between the first and second floors due to thermal stratification are a common problem.

Another cost reduction comes from the elimination of natural gas service to the house. As energy demand for space heating drops in high-performance homes, the cost of installing and maintaining gas distribution becomes harder to justify. When monthly gas service charges and increased mortgage cost are counted as part of the heating cost, heat pumps and additional photovoltaic power 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.

Finally, the elimination of burning fossil fuel within the house essentially removes safety risks from combustion byproducts compromising indoor air quality. Additional savings are achieved by eliminating the chimney or combustion venting, as well as any need to supply combustion air.

1.5 Research Topics and Research Questions

Key research questions include the following:

- What range of temperatures is experienced in bedrooms of homes heated by point sources? As subsets of this work, what are the effects of door open/closed status, floor-to-floor thermal stratification, and house geometry on these temperatures and occupant comfort?
- What is the typical heating balance point for a selection of these superinsulated houses? In this case, the term *balance point* means the outdoor temperatures above which no heating is required.
- What are the electrical power consumption characteristics of MSHPs used in a cold climate, including monthly aggregate consumption, and consumption as a function of temperature?

2 Background and Literature Search

The background and literature search section is divided into two interrelated subjects. First, an overview is presented on DHPs or MSHPs, from the current literature. Second, the topic of single-point or simplified heating distribution is discussed; there is some overlap between these two subjects, but this division provides some structure.

2.1 Ductless Heat Pumps/Mini-Split Heat Pump Background

2.1.1 Winkler: Laboratory Testing of Mini-Split Heat Pumps

Winkler (2011) described laboratory testing of two MSHP units (Fujitsu 12RLS and Mitsubishi FE12NA; both 12 kBtu/h nominal capacity). The team developed detailed performance maps, expanding on available performance data from the manufacturers. Heating and cooling testing was done under steady-state and cycling conditions.

On an installed per-ton basis, MSHPs are more expensive than conventional systems. However, they have very high rated efficiencies (25 seasonal energy efficiency ratio [SEER] or higher, compared to 18 SEER and higher for conventional systems). One reason for this testing was to validate those ratings under a wider range of conditions than the standardized tests.

Test variables included outdoor temperature, interior unit fan speed, and exterior unit compressor speed. The team found that experimental data matched manufacturers' reported values. Maximum capacity measurements indicated that the units had even greater heating capacity than stated in manufacturers' data, in particular, at cold ambient temperatures.

Under low and intermediate loads (part load conditions), both MSHPs had higher efficiencies than the conventional comparison high SEER forced-air heat pump systems. However, at peak load, the conventional systems had slightly higher efficiencies (by 10%–25%).

The author noted that MSHPs have a wide range of compressor speeds; therefore, they often do not cycle on and off, instead modulating their capacity to meet load while running constantly. This stands in contrast to conventional systems: even with two stages of heating/cooling, they will typically be sized to cycle on and off. The low, continuous operation of MSHPs is the most advantageous and efficient operating mode.

2.1.2 Baylon: Northwest Ductless Heat Pump Pilot Project

Baylon et al. (2012) reported on the results of the Northwest Ductless Heat Pump Pilot Project, under the auspices of the Northwest Energy Efficiency Alliance. This project involved the field monitoring of 95 homes retrofitted with MSHPs throughout the Pacific Northwest. The MSHPs were installed to supplement (and partially displace) existing electric resistance heat; electricity savings were measured and analyzed. This program was also driven by the relatively low installed costs of MSHP in retrofits (~$3500–$5000 per head): they are much simpler to install in existing homes than a fully ducted gas furnace or heat pump system.

Measured coefficients of performance (COPs) for all installations averaged to 3; the results are shown with DOE climate zone and a representative city's 99.6% heating design temperature in Table 1. During warmer parts of the heating season, COPs well in excess of 4 were measured. There is some relationship between measured COP and temperature conditions. However, the lower COP of the Inland Empire (Washington/Idaho) group was ascribed less to climate than to a preponderance of lower efficiency MSHP equipment.

Table 1. Measured MSHP Seasonal COPs With Climate Information

(Baylon et al. 2012)

Cluster	MSHP COP (Mean)	MSHP COP (St. Dev.)	DOE Climate Zone	99.6% Design Temperature
Willamette (OR)	3.40	0.32	4C	21.8°F
Puget Sound (WA)	3.05	0.56	4C	24.5°F
Inland Empire (WA/ID)	2.41	0.59	5B	2.9°F
Boise/Twin Falls (ID/WA)	2.96	0.30	5B	2.7°F
Eastern Idaho (ID)	2.84	0.30	6B	–4.9°F
Average Total	3.00	0.55	–	

The study demonstrated significant savings across the climate zones, relative to electric resistance heating. Cooling use was also monitored; MSHP efficiency was markedly better than the existing window air conditioner units, but overall cooling savings were small, compared to heating savings. This fact is easily explained by the small cooling load in this region, and the moderate increase in cooling efficiency (compared to the large increase in heating efficiency: COP ~1 for resistance heat versus ~3 for MSHPs). Surveys indicated that occupants were almost uniformly satisfied with the installed MSHPs.

In this study, the existing resistance heat was left in place (and operated at the homeowner's discretion in bedrooms); the MSHP offset heating loads in the main living space of the house.

Another useful outcome of this work was that a large number of MSHPs were installed under field conditions. This resulted in a sampling of both high- and low-quality installations. The researchers collected and presented installation best practice recommendations for MSHPs, to obtain the best performance, reliability, and aesthetic results (Manclark and Thomas 2011).

2.1.3 Rosenbaum: Green Building Advisor Column

Rosenbaum (2014a) provided an overview of what he had learned using MSHPs in a variety of high-performance projects. Advantages of these systems include elimination of combustion in the building (and venting), ability to supply both heating and cooling, and low installed cost. Lessons learned included:

- Efficiency levels (coefficient of performance) are roughly in line with manufacturers' specifications, based on comparing submetered electricity use to energy model predictions. However, these observations are not detailed efficiency measurements.
- Low-temperature performance has been excellent in a variety of products and projects. Several MSHPs had sufficient capacity to meet set point below design temperatures, even without an intentional oversizing factor. Products designed for low-temperature performance (Mitsubishi "H2i" or "Hyper Heat" series) are rated to –13°F, and were still operating at –20°F. He reported that other practitioners have seen similar behavior out of units not actually rated for extremely low temperatures.

- In a similar vein, Rosenbaum noted good output temperatures (120°F in December–January in zone 5A) in units designed for low-temperature operation, reducing the risks of cold blow complaints.
- Temperature setbacks are not an effective strategy with MSHPs: when temperatures are set up, the unit runs at maximum capacity (and lowest efficiency) to return to set point temperature. This was primarily studied in terms of heating setback, but cooling setup may have similar behavior. In addition, these units are typically sized tightly relative to the load, and will therefore have longer recovery times.
- Variable-speed cooling operation reduces the negative of oversizing (a common issue if the unit is sized for the heating load); anecdotal evidence suggests good dehumidification performance.
- Rosenbaum has consistently measured carbon emission savings (and energy cost savings) when replacing existing fossil-fuel heating equipment (commonly boilers) with MSHPs, given the current fuel mix of the grid in the Northeast.

2.1.4 Rosenbaum: kWh/ft^2·Heating Degree Day 65°F Metric

Rosenbaum (2014b) presented similar material at the Northeast Sustainable Energy Association BuildingEnergy 2013 conference, covering the basics of MSHP systems and his project experience with this equipment. He presented monthly submetered electrical heating/cooling data, calculating the rough efficiency of several installations, with the normalized metric of kWh/ft^2·HDD 65 (Table 2).

He also noted that although a single head might match the design loads of a superinsulated two-story house, a first-floor unit will be unable to cool the second floor, due to thermal buoyancy/ stratification. However, this type of installation can provide heating for both floors.

Table 2. Normalized Electricity Consumption of Inverter-Driven Heat Pumps

(Rosenbaum 2014b)

Description/Location	Square Feet	System Type	kWh/ft^2·HDD 65
Single-Family Deep Energy Retrofit, Chilmark, MA	1,258 (over basement)	Ducted single-zone system	0.000281
PassivHaus, Brattleboro, VT	2,392	Non-ducted single-zone system	0.000138
Dormitory/Faculty Apartments, Deerfield, MA	11,000	Multi-zone variable refrigerant flow system	0.000187

2.1.5 Meyer: Efficiency Maine Pilot Program

Meyer (2014) presented a case study on the installation of roughly 3000 DHPs in Maine (zone 6A), under the auspices of a utility program. One set of 1000 installations used MSHPs as supplemental heat in existing houses; the units were purchased privately, and then a rebate of $600/unit was provided. The average installed cost was $3200/unit (prior to rebate), with very positive reactions (91% of surveyed homeowners would definitely recommend installation).

Another set of installations was roughly 2000 MSHPs installed in low-income housing, intended to replace or displace electric resistance baseboard heat (which was left in place as backup).

Average installed price was $2100; the lower price was attributed to the volume purchases made for apartment complexes. The low-income retrofit program energy savings were analyzed; there was an average of 25%–50% savings, with an average simple payback of 7 years. These calculated savings were even conservative, given that post-retrofit surveys found that 25% of occupants did not run the MSHP at all, instead relying on resistance heat. He also provided the equipment and installation specifications used in the program, to ensure higher quality installations.

2.1.6 Harley: Zone 6A Mini-Split Heat Pump Monitored Performance

Harley (2014) presented 1 year's monitoring of a house in zone 6A (Stamford, Vermont) that used two MSHPs for heating and cooling. The installed equipment was a single-point DHP on the first floor, and a second system serving the second and third floors. The latter system included two indoor heads: a wall-mounted ductless unit serving the third floor, and a small ducted system serving the second floor.

He monitored interior and exterior temperatures, and electricity consumption of the two systems; he also performed co-heating as a comparison (temporarily using electric resistance), to calculate operating efficiency (COP). When plotting calculated COP against outdoor temperature, results were similar to manufacturer's data, with COP varying from 3–4 at mild temperatures (~45°F), and 2–2.5 at cold temperatures (0°–10°F). His calculated heating-only seasonal COP was in the 2.6 to 2.8 range. The crankcase heater was at first thought to be a significant draw (30 W continuous), but further study showed it is only active below 34°F ambient, and was a total consumption of 120 kWh/year.

The first-floor unit provided the majority of the house's heating (due to thermal buoyancy). He found that mounting the unit at window sill height (instead of high on the wall) provided a good balance between heating and cooling performance (thermal stratification issues).

He also ran a test on using a constant set point, compared to use of nighttime setbacks; net seasonal efficiency was better/higher with a constant set point. This is consistent with the fact that when a MSHP is recovering from an overnight setback, it will be operating for long periods at high speed (worst efficiency), and it will be operating at the coldest (typically early morning) ambient temperatures.

2.1.7 Key Takeaways

Key takeaway conclusions on the performance and use of MSHPs include the following:

- Laboratory testing of MSHPs indicates that units have capacity and efficiency levels consistent with the manufacturers' data. Field experience corroborates this information. In fact, in some cases, total heating capacity at low ambient temperatures was greater than stated in the literature. Efficiency at part load (low and intermediate speeds) was better than conventional split systems, but efficiency at maximum speed was worse than conventional systems.
- Field testing of MSHPs installed in climate zones 4C, 5B, and 6B indicate that wintertime COPs of 3 or higher are achieved in service, with COPs of 4 during warmer weather.

- Temperature setbacks are not an effective strategy with MSHPs: when temperatures are set up, the unit runs at maximum capacity (and lowest efficiency) to return to set point temperature.
- Field testing of MSHPs installed in climate zones 6A indicate wintertime COPs of 2–2.5 at coldest temperatures, and 3–4 at milder (~45°F) temperatures.
- Installed costs of MSHPs were stated to be ~$3500–$5000 per head (retrofit installation), $3200 per unit (retrofit), and $2100 (volume retrofit of apartment complex).

2.2 Simplified/Point-Source Heating Background

The concept of simplified or point-source heating distribution is to take advantage of the investment in the building enclosure (insulation and airtightness) with a lower cost heating system that is not fully distributed throughout the house. The fundamental physics involve the relative heat flows into and out of the room. The winter operating temperature of rooms exposed to exterior conditions will be a balance between heat flowing into the room (via open doorways, conduction through interior wall and floor partitions, and interior gains), and heat flowing out of the room (through exterior enclosure components). The key is whether exterior-side insulation levels are high enough (and heat loss low enough) to maintain comfort conditions during design conditions.

Projects that use simplified or point-source heating typically have exceptional insulation and airtightness levels; the terms *high-performance enclosures* and *superinsulated buildings* are common descriptions. Although there is not uniform agreement about building enclosure characteristics, most projects discussed below meet the insulation levels described as "high-R enclosures" by Straube (2011). For DOE climate zone 5A (per most of the projects described here), recommended minimums would include R-30 walls, R-65 vented attics, R-15 basement walls, triple-glazed windows (U <0.24), and airtightness in the 1 ACH50 range. An excerpt showing recommended insulation levels for all climate zones is provided below in Table 3.

Table 3. Recommended "True" Minimum R-Value (±)[a] Including Thermal Bridging

(Straube 2011)

Climate Zone	Wall	Vented Attic	Compact Roof	Bsmt Wall	Exposed Floor	Slab Edge[b]	Windows (U/SHGC[c])	Sub-Slab[d]
1	10	40	35	5	10	None	Yes	None
2	15	50	40	10	20	5	0.35/<0.25	None
3	20	50	45	10	20	7.5	0.30/<0.30	5
4	25	60	45	15	30	7.5	0.30/<0.35	7.5
5	30	65	50	15	30	10	0.24/<0.50	7.5
6	35	75	60	20	40	10	0.18/-	10
7	40	90	65	25	45	15	0.15/-	15
8	50	100	75	35	50	20	0.15/-	20

[a] Recommended values based on experience
[b] Slab edge insulation includes all of stem wall or monolithic slab edge
[c] Solar heat gain coefficient
[d] Full area coverage of slabs

2.2.1 Barakat: Heat Flow Through Open Doorways

One aspect of the heat balance is heat flow through open doorways. Barakat (1985) reviewed the subject of inter-zone convective heat transfer in buildings, in the context of passive solar heating. Previous work found that 4100 Btu/h (1200 W) could be transferred by natural convection through a door opening with a large (7.2°F) temperature differential. However, natural convection heat transfer rates from the literature were much lower (900–1100 Btu/h or 250–320 W), when using a more reasonable temperature difference (2.7°F). In addition, he noted the flow pattern through door openings is a convective loop that is restricted by the wall over the door head; additional flow might be possible by providing a less restrictive path.

2.2.2 Prahl: Western Massachusetts and Illinois Monitoring Results

Prahl et al. (2007) presented monitoring results from several cold climate projects with superinsulated enclosures, heated with point-source/simplified systems. Three Western Massachusetts houses were monitored (1200–1500 ft^2, two bedrooms): two with point-source gas-fired through-the-wall heaters, and one with a conventional ducted gas furnace as a comparison point. An Illinois PassivHaus was monitored (1450 ft^2, three bedrooms); it used electric resistance baseboard heaters in each room, each independently thermostatically controlled. The authors noted that in terms of comfort metrics, Air Conditioning Contractors of America (ACCA) guidance recommends room-to-thermostat temperatures within 2°F (maximum 4°F difference room to room).

In the Massachusetts houses, the effect of temperature setbacks was pronounced. One house used a constant set point: it had room temperatures within the ±2°F limit; in particular, uniform floor-to-floor temperatures were maintained. The other house had nighttime setbacks, with large swings in set point (60°–75°F typical), resulting in much larger floor-to-floor differences (2°–12°F); however, the bedrooms (all on the second floor) were close in temperature. Most surprisingly, though, the house with a fully ducted gas furnace had large floor-to-floor differences (4°–8°F typical). Second-floor bedrooms in the ducted furnace house were relatively close in temperature. For reference, in all cases, the homeowners reported that they rarely closed bedroom doors.

In the Illinois house, room-to-room temperatures varied by up to 10°F; however, given the room-by-room (zonal) heating, this is attributed to occupant preferences (thermostat set point). Very little floor-to-floor stratification was measured.

The authors concluded that point-source distribution maintains comfort conditions in smaller houses, if set points are kept relatively constant and bedroom doors remain open. They also suggested that distribution or transfer of air may improve thermal uniformity and provide ventilation air distribution. Based on this work, temperature distributions for larger homes with simplified distribution were still an open question. In addition, the authors noted that uneven temperature distributions and duct distribution problems are an issue in houses with fully distributed ductwork.

2.2.3 Consortium for Advanced Residential Buildings and Aldrich: Wisdom Way Monitoring

The Consortium for Advanced Residential Buildings (CARB 2010a) and Aldrich (2012) reported on low-energy houses at Wisdom Way Solar Village in Greenfield, Massachusetts. Ten duplexes (20 homes) were built with high-performance enclosure and mechanical specifications. Unit sizes ranged from 1100–1700 ft^2, with two to four bedrooms, and one or two stories over unconditioned basements (R-40 insulation in the floor above the basement). Each home was heated with a single, sealed-combustion, natural gas room heater (located in the central area of the open-plan first floor), with outputs of 10 or 16 kBtu/h (low/high fire). In addition, a distribution fan was installed to improve ventilation effectiveness and create more uniform interior temperatures, pulling air from the first-floor ceiling and distributing it to the bedrooms (20–25 CFM each bedroom).

Savings relative to a conventional heating system (boiler and fin-tube baseboard) was estimated at $4000/unit; the estimated cost of enclosure upgrades was $7000/unit.

Short-term thermal comfort testing in conjunction with the National Renewable Energy Laboratory in early 2009 yielded promising results: at outdoor temperatures of 10°–15°F, bedrooms would remain within 3°–4°F of the main space if small internal gains (425 Btu/h or 125 W) are present. For reference, human heat output at sedentary conditions is roughly 250 Btu/h (75 W) sensible and 100–200 Btu/h (30–60 W) latent load (ASHRAE 2009). This testing also indicated that upstairs bedrooms would run significantly colder than the first floor with doors closed, but that opening doors or adding small amounts of heating (60 W) caused bedroom temperatures to converge close to downstairs temperatures.

This was followed by longer term monitoring (winter 2009–2010) of interior temperature distributions in four homes. This monitoring showed that upstairs bedroom temperatures were colder than downstairs, but when surveyed, the occupants did not report major comfort issues. Electric space heaters were available in upstairs bedrooms, but were rarely used. The success/failure metric was percentage of wintertime with less than a 4°F temperature differential between rooms (maximum-minimum, per ACCA Manual RS [ACCA 1997]); most houses had temperatures that stayed within that range. The most successful house had differentials under 4°F for 97% of the winter; the least successful 68%.

More consistent temperatures were seen in houses with a constant set point (as opposed to temperature setbacks). The team also informed homeowners that setbacks would save little energy, make comfort worse, and cause problems due to long recovery times.

CARB (2010a) gave an example of calculating the relative heat gains/losses from a room using a UA analysis (U-value × area, to provide a static heat loss rate of Btu/hour·°F). This calculation quantifies conduction through interior partitions/floors, internal gains, and distribution fan gains. Based on the short-term monitoring, they created an Excel spreadsheet combining UA analysis with empirical estimates of door open/closed heat transfer rates. The Excel tool was used for "what if" scenarios in various operating states and outdoor temperatures.

2.2.4 Consortium for Advanced Residential Buildings: Colrain, Massachusetts Mini-Split Heat Pump Evaluation

CARB (2010b) also monitored energy use and temperatures in two houses at the Katywil development in Colrain, Massachusetts (zone 5A). Both houses were single story over walkout basement, 2200 ft^2 (basement plus first floor), with high-performance enclosures.

One house was heated with MSHPs, and the other with radiant flooring powered by solar thermal and an electric boiler backup. The MSHP house had one head on the first floor (2 tons), and one in the walkout basement (1 ton). The house also has electric resistance heating in bedrooms and a wood stove.

The monitored energy use was compared to energy modeling done with REM/Rate; the measured consumption was half of modeled predictions. This difference might be due to wood heating, occupant operation of the building to maximize solar gains, low set points, and possibly better heat pump efficiency than reflected in the model.

Interior temperature distributions in the two houses were examined; the original intent was to use the radiant floor house (with room-by-room zoning) as a control, compared to the MSHP house. However, passive solar gains and wood stove use made this comparison less useful; interior temperatures in the radiant floor house varied more than in the MSHP house. The MSHP house had room-to-room temperature differences under 4°F for 60% of the time; the radiant floor house only 23% of the time. The larger temperature differences in the radiant floor house were attributed to wood stove operation in the living room.

The homeowner of the MSHP house had complaints on the mini split system, including aesthetics, excess noise, and high standby power draw (27 W constant).

2.2.5 Stecher: Building America Expert Meeting

IBACOS led a Building America Expert Meeting on simplified space conditioning in high-performance housing in 2011 and invited other researchers and practitioners to present on their experiences (Stecher 2011). They examined thermal transfer within the house, hypothesizing that convective air movement through open doors (300–600 Btu/h) and transfer grilles, plus conduction through partitions (0.3–0.6 Btu/h·ft^2) could be sufficient to maintain comfort conditions (per Feist et al. 2005). Speakers at the meeting covered the following:

- Carter Scott of Transformations spoke on his experience using both ducted and ductless MSHPs in his high-performance houses. His work with an early generation of MSHPs showed that cold weather output (in zone 5A) was inadequate; additional heating capacity was added after problems arose during the first winter. But other than this case, no comfort complaints had been reported with these simplified systems. Transitioning to later generations of MSHPs solved the cold weather output issues.
- Kohta Ueno of BSC reported on early monitoring of a Transformations house in Townsend, Massachusetts, which included bedroom temperatures and door open/closed indicators, covered in Ueno et al. (2013a). The occupants used deep temperature setbacks, which resulted in large temperature differentials between the hallway (MSHP location) and bedrooms. There was a large temperature spike in the hallway (from the MSHP), but the master bedroom temperature "lagged" behind at a cooler temperature.
- Monitoring also showed that periods with bedroom doors closed definitely showed larger temperature differentials from the hallway (see Figure 1). In general, the majority of the data showed bedroom temperatures within 5°–7°F of the hallway. Some measurements indicated that snow blockage of an outdoor condenser unit may have occurred during the winter of 2011 (drop in indoor temperature following a large snowfall).

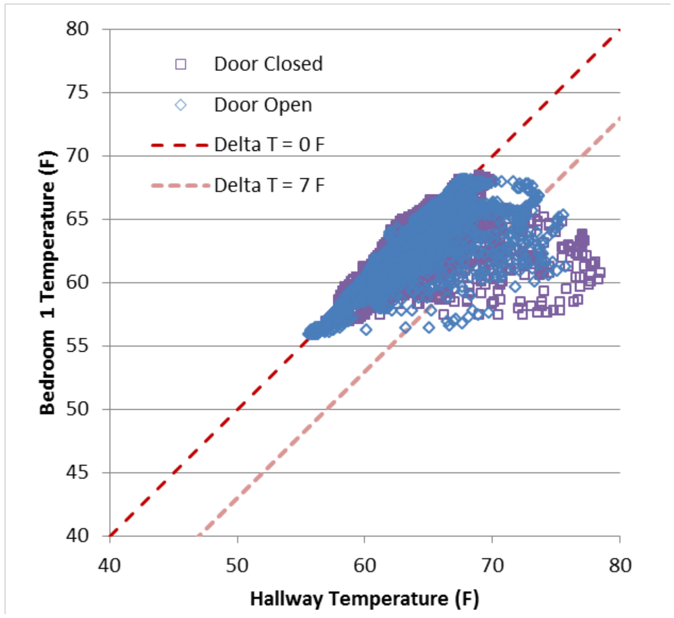


Figure 1. Townsend data of hall temperature versus bedroom 1 temperature, door open/closed

- Duncan Prahl of IBACOS covered a year's worth of monitoring data from a small (1200-ft^2) high-performance house in central Illinois; the mechanical system was a MSHP on the first floor, with electric resistance baseboard heaters in individual rooms. During cooling operation, all rooms were within 2°F of the thermostat; however, some control conflicts arose between the resistance heating and the MSHP. The unit was located high in a stairwell, resulting in less than ideal distribution of heating to the first floor. He also presented results from Eliakim's Way (discussed under Stecher et al. 2012), and early results from the Pittsburgh laboratory house (discussed under Stecher 2013).
- Robb Aldrich of Steven Winter Associates/CARB presented work covered in CARB (2010a) and Aldrich (2012).
- David Baylon of Ecotope presented on the results from the Northwest Ductless Heat Pump Pilot Project (discussed previously by Baylon et al. 2012).

The meeting concluded with a discussion of the IBACOS test plan to research simplified space conditioning; research questions covered temperature and humidity variations, system response to extreme loads, and temperature response to erratic occupant thermostat set points.

2.2.6 Rosenbaum: Eliakim's Way (Massachusetts) Energy Monitoring

Rosenbaum (2011) monitored energy consumption of eight high-performance, affordable, single-family homes at Eliakim's Way, in West Tisbury, Massachusetts (zone 5A); these homes were designed to achieve net zero performance. They are superinsulated two- and three-bedroom houses (1300–1500 ft^2), with two stories over basements. Space heating and cooling were provided with a single MSHP wall cassette located in the first-floor living area, and supplemental heat in bedrooms (operated at the occupants' discretion) was provided with electric resistance radiant panels. This is a strategy used by the builder to compromise between single-point and distributed heating. The MSHP and electric radiant panels were submetered, among other loads.

For the most part, heat pump usage for heating was similar among the houses; however, the use of electrical radiant panel heating varied by a factor of 14 to 1; the use of resistance heating was the homeowner's choice of balancing comfort and energy costs. Radiant panel electricity consumption varied from roughly 10% of the MSHP's use to 150% of the MSHP's use. Three bedroom houses also used significantly more radiant panel energy. Temperatures in the bedrooms at this development were discussed by Stecher et al. (2012).

2.2.7 Stecher: Eliakim's Way (Massachusetts) Temperature Monitoring

Stecher et al. (2012) presented detailed analysis of temperature monitoring at four houses at Eliakim's Way during the winter of 2010–2011; door status was not monitored. The team assessed comfort using the ±2°F limit recommended by ACCA. Across the four houses, temperatures were within the ±2°F limit for 15%–30% of hours; if the range is expanded to a ±4°F limit, it increases to 30%–65% of hours.

The data clearly demonstrated that varying the set point (using a daily temperature setback/setup strategy) results in greater bedroom temperature variations from the main space set point. In addition, energy analysis found that setback strategies did not result in net energy savings.

The solar-tempered design (predominantly south glazing in living space) resulted in temperature rises of more than 7°F on sunny days. The team conjectured that houses with greater electric resistance use had higher numbers of hours with closed bedroom doors, as suggested by the collected data. The team also suggested the use of transfer fans (maximum flow 350 CFM) as a better alternative to electric resistance radiant panel heating in bedrooms. The team also noted that despite temperature differences, the builder had not received any comfort complaints from the occupants.

2.2.8 Stecher: Pittsburgh Laboratory House

Stecher (2013) presented the IBACOS work on building and monitoring a high-performance unoccupied new construction laboratory house in Pittsburgh, Pennsylvania, which had four selectable space conditioning systems. The systems were:

- A traditional, fully ducted (all rooms) distribution system (two thermostatic zones, first/second)
- A single point of heating/cooling delivery on the first floor with low volume distribution fan (~20 cfm per bedroom or 300 cfm total) and two thermostatic zones
- Single-point heating/cooling on the first floor with thermostatically controlled over-door transfer fans (hallway to bedroom, 75 CFM, commercially available units)
- Two points of heating/cooling delivery: one on the first floor, and the other in the second-floor hallway; no active system to connect bedrooms to the upstairs hallway.

The house was cycled through the four systems in 12-day periods over 1 year of monitoring (both heating and cooling seasons).

The results were assessed using applicable ASHRAE and ACCA criteria; the authors provide extensive background on these criteria. The percentage of time when bedrooms met ASHRAE Standard 55-2010 comfort requirements in various modes is shown in Table 2 under ASHRAE conditions; doors were closed in all cases except "no active distribution." The failure locations are called out in the cell or the notes below.

Table 4. Percentage Time Rooms Meet Comfort Requirements at Peak Conditions

(Stecher 2013)

System Type	Cooling		Heating	
	% Hours Pass	Failures	% Hours Pass	Failures
Traditional Fully Ducted (Doors Closed)	n/a	n/a	95%–100%	BR4
Low Volume Distribution (Doors Closed)	97%–100%	2nd landing, BR3 (west)	99%–100%	2nd landing, BR4
One Point With Over-Door Transfer Fans (Doors Closed)	89%–100%	2nd landing, living room	8%–100% (100% in BRs)	2nd landing, living room
Two Point With No Active Distribution (Doors Open)	n/a	n/a	1%–100% (100% in BRs)	Living, dining room

Similar results are shown in Table 5 for swing season conditions (not heating and cooling design temperatures).

Table 5. Percentage Time Rooms Meet Comfort Requirements at Swing Conditions

(Stecher 2013)

System Type	Cooling		Heating	
	% Hours Pass	Failures	% Hours Pass	Failures
Traditional Fully Ducted (Doors Closed)	93%–100%	BR3 (west), master bath	87%–100%	MBR, BR2, BR3, BR4, M. bath
Low Volume Distribution (Doors Closed)	98%–100%	2nd landing, BR3, BR4	83%–100%	BR4
One Point With Over-Door Transfer Fans (Doors Closed)	91%–100% (97%–100% in BRs)	2nd landing, BR3, BR4	9%–100% (100% in BRs)	2nd landing, living room
Two Point With No Active Distribution (Doors Open)	100%	n/a	64%–100% (100% in BRs)	Dining, living, breakfast room

Overall, these results indicate that although fully ducted systems have high performance, they do not guarantee 100% of hours within ASHRAE conditions. This is not entirely surprising, given the diversity of room loads as solar gain changes throughout the day, versus the single point of control in a zone. Although both simplified systems show more failing hours than the ducted systems, bedrooms often had 100% passing conditions. Some of the failures were "cyclic failures" (fluctuations of greater than 2°F occurring every 15 minutes), often at the second-floor landing: this is consistent with the second-floor heat source being at the landing, resulting in a periodic "burst" of heat in a limited space. Other failures in the simplified system often occurred in first-floor rooms; for reference, the house square footage was 2772 ft^2 (roughly evenly split between the first and second floors).

Data were also analyzed in terms of ACCA Manual RS criteria (ACCA 1997), including temperature difference from room-to-thermostat, and room to room. Only heating results were collected, at both peak and off-peak conditions.

Monitoring results also showed the effect of system sizing on temperature variations: when the house was recovering from a setback, the location with the single-point outlet spiked rapidly, outside of comfort conditions. The authors noted that a system sized closer to loads would reduce the magnitude of the temperature variation.

The thermostatically controlled transfer fans (75 CFM) were used in one case; however, there were multiple occasions when operation could not meet target temperatures. In addition, the fans were judged to be relatively noisy.

2.2.9 Northeast Sustainable Energy Association Workshop: Simplified Space Conditioning in Low Load Houses

IBACOS led a half-day workshop at the Northeast Sustainable Energy Association 2013 BuildingEnergy conference on simplified space conditioning strategies in low load houses; presenters from multiple Building America teams presented their most current work. BSC's presentations from the conference are available online (see Ueno 2013c, 2013d; Bergey 2013).

- Duncan Prahl of IBACOS began the discussion noting that single-point or simplified heating will always be considered "pushing the envelope" or taking some risk: those who wish to be completely risk averse should consider installing a typical, fully ducted space conditioning system.
- BSC continued with an overview of the space conditioning low-load houses, roughly defining them as houses with design loads that are one half to one third of an equivalent code-compliant house. At common house sizes, these are design loads in the 15–25 kBtu/h range. The resulting problem is that common heating, ventilating, and air conditioning equipment is grossly oversized for these houses, resulting in short cycling and oversized ductwork/services relative to the load.
- Daniel Bergey of BSC presented the results from Transformations monitoring covered in Ueno et al. (2013a), which was the preliminary portion of the work covered in this report.
- Kohta Ueno of BSC presented on comfort issues occurring at one Transformations house, covered in detail in this report (see Section 6.6, "Bonus Room Comfort Issues at Easthampton").

- Duncan Prahl and Dave Stecher of IBACOS presented on a variety of low-load projects in cold climates that examined the problem of simplified distribution. They included the Eliakim's Way work (Stecher et al. 2012) and results from the laboratory house (Stecher 2013).
- Robb Aldrich of Steven Winter Associates covered work at Wisdom Way (see CARB 2010a and Aldrich 2012).

The consensus from the presenters was that simplified distribution can provide comfort in low-load houses in many cases; ideally, the bedroom doors would be kept open for most hours, to let them come into equilibrium with the main space. However, closed doors will cause larger temperature differentials. In addition, the group agreed that temperature setbacks increase temperature differences to the bedrooms, and should be avoided, given their limited benefit in low-load houses.

2.2.10 Rosenbaum: Green Building Advisor Column

Rosenbaum (2014a), in addition to discussing MSHP performance, covered temperature distributions achieved in superinsulated houses in cold climates (0°F or higher design temperatures) with simplified space conditioning and a compact floor plan. He found that with a single MSHP and bedroom doors open, he could achieve bedroom temperatures within 2°F of the main space (location of the indoor wall cassette). Door status was often the driver behind the use of resistance heating in the bedrooms (see Rosenbaum 2011). However, a commenter in the ensuing online discussion found that in his experience, 2°F variations are optimistic, and that he has more commonly seen 2°–8°F variations in his work with similar houses.

2.2.11 Key Takeaways

Key takeaway conclusions from the combined work of multiple researchers on simplified space distribution include the following:

- Single-point or simplified heating and cooling systems can work well in superinsulated, very airtight, compact houses. It has been demonstrated in multiple cases to provide good results with few customer complaints. Variations in room-to-room temperature are a function of how the house is operated (noted below).
- The use of simplified space conditioning systems can result in substantial first cost savings, which can be used to offset the increased investment in the building enclosure/shell.
- Use of simplified space conditioning system can reduce or eliminate issues of moving ductwork within the conditioned space, which is often a logistical issue for builders.
- The operation of doors can have a substantial effect on interior temperatures: upstairs bedrooms often remain close to interior conditions when their doors are left open, but temperature differences increase when they are closed.
- Thermostat setbacks, of space conditioning to different temperature set points, results in much greater variations in room-to-room temperature. It is not recommended, due to limited savings in superinsulated houses, and long recovery times due to right-sized mechanical equipment.

- Transfer fans can reduce room-to-room temperature variations; "harvesting" the warmest air from the ceiling near the space conditioning system is the best strategy. However, there is a limited amount of heat transfer available at typical interior temperature ranges.
- Bedrooms or other closed rooms can be equipped with electric resistance heat in order to address colder temperatures. The use of these heating systems varies strongly on a occupant-by-occupant basis. In addition, installation of these heaters should address potential control conflicts between the bedroom heat and the main heating system.
- A first-floor single-point system often can heat a compact two-story house; however, this geometry is problematic during the cooling season, as thermal buoyancy will keep the cold air on the first floor.
- A fully ducted distribution system does not guarantee even temperatures. In addition, a conventional furnace or heat pump is often grossly oversized in low-load houses, resulting in larger swings in temperature, and equipment short cycling.
- There are many ways to describe success or failure of temperature evenness in these simplified distribution system houses. It is often difficult to distill the results into a simple, easily understood form, given day-to-day variations that might occur.

3 Builder Mini-Split Heat Pump Experience

Transformations, Inc. has extensive experience building its high-performance housing at a variety of Massachusetts locations, in both a production and a custom home setting. The majority of its construction uses MSHPs for space conditioning. Its field experience with these systems is recounted here, before presenting the detailed data analysis. In addition, this section covers equipment specifications, providing background for understanding the collected data.

3.1 Enclosure and Mechanical Characteristics

The high-performance houses built by Transformations, Inc. have been covered in previous work, including Bergey and Ueno (2011), Ireton (2013), and Ueno et al. (2013a). The basic enclosure and mechanical specifications for its production work is shown in Table 6. There are some variations from these characteristics; for instance, the roof is sometimes a compact/unvented assembly, when rooms are located within the sloped volume of the roof. The ventilation system is upgraded to an energy recovery ventilator or other options, in some cases. Finally, the heating and cooling system has been modified at the Easthampton development from this basic specification, as discussed under in Section 3.4, “Experience with Multihead Systems.”

Table 6. Transformations, Inc. Typical Enclosure and Mechanical Specifications

Item	Description
Full Basement	2 in. extruded polystyrene (XPS) rigid insulation (R-10) under slab 3 ½ in. of closed-cell spray foam insulation (R-20) at basement walls
Slab on Grade	6 in. XPS rigid insulation (R-30) under the slab and 4 in. of XPS rigid insulation (R-20) at the edge of the slab
Above-Grade Walls	Double-stud wall with 12 in. of open-cell spray polyurethane foam (0.5/ft^3) insulation (R-46 nominal)
Attic	Ventilated attic; 18 in. of cellulose insulation (R-63)
Windows	Vinyl frame double-hung triple glazed U = 0.22 SHGC = 0.17 typical
Airtightness	1.0 to 1.5 ACH50 range, typical
Heating/Cooling	Two Mitsubishi FE12NA (MUZ-FE12NA + MSZ-FE12NA) DHPs; one per floor, typical
Domestic Hot Water	Navien tankless instantaneous water heater, NR-180, in basement or conditioned space
Ventilation	Panasonic 30 CFM exhaust-only fan, continuous operation with boost option, two fans (baseline system; varies in some houses)

The building enclosure characteristics for a typical basement and slab-on-grade house are illustrated in Figure 2.

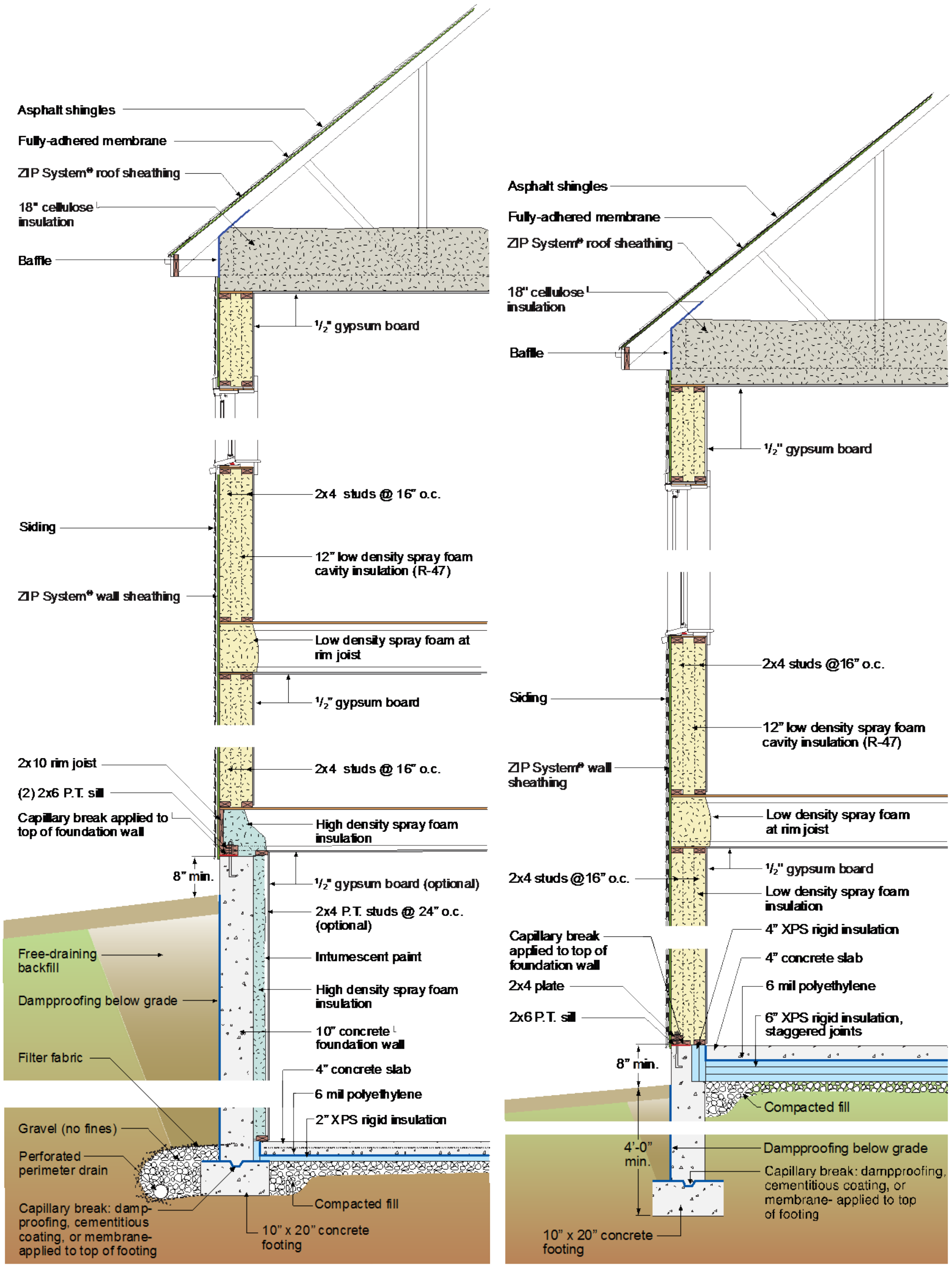


Figure 2. Transformations enclosure overview for basement (L) and slab on grade (R)

3.2 Mitsubishi Mini-Split Heat Pump Equipment Efficiency Ratings

The mainstay of Transformations Inc.'s work is the Mitsubishi 12,000 Btu/h (nominal) 1:1 MSHP (FE12NA series); the specifications are shown in Table 7. In addition, at Easthampton, production has been shifted over to a Mitsubishi MXZ series MSHP (three indoor units, one outdoor unit), for the upstairs bedrooms.

Table 7. Manufacturer Efficiency Data for Mitsubishi MSHP and Multisplit Systems

Metric	Units	Mitsubishi FE12NA	Mitsubishi MXZ*
Outdoor Unit	–	MUZ-FE12NA	MXZ-3B24NA
Indoor Unit	–	MSZ-FE12NA	MSZ-GE06NA-B (x2) MSZ-GE09NA-B (x1)
SEER	Btu/h·W	23	17.5
HSPF	Btu/h·W	10.6	9.3
Rated Cooling Capacity	Btu/h	12,000	22,000
Cooling Capacity Range	Btu/h	2,800–12,000	12,600–25,500
Rated Heating Capacity	Btu/h	13,600	25,000
Heating Capacity Range	Btu/h	3,000–21,000	11,400–30,600
Heating COP @ 47°F	–	4.2	3.9
Heating COP @ 17°F	–	3.1	3.0

* With all heads in non-ducted configuration, per Easthampton installation

The manufacturer publishes equipment heating capacity as a function of temperature for both maximum output and at rated conditions, as shown in Figure 2 for the FE12NA unit.

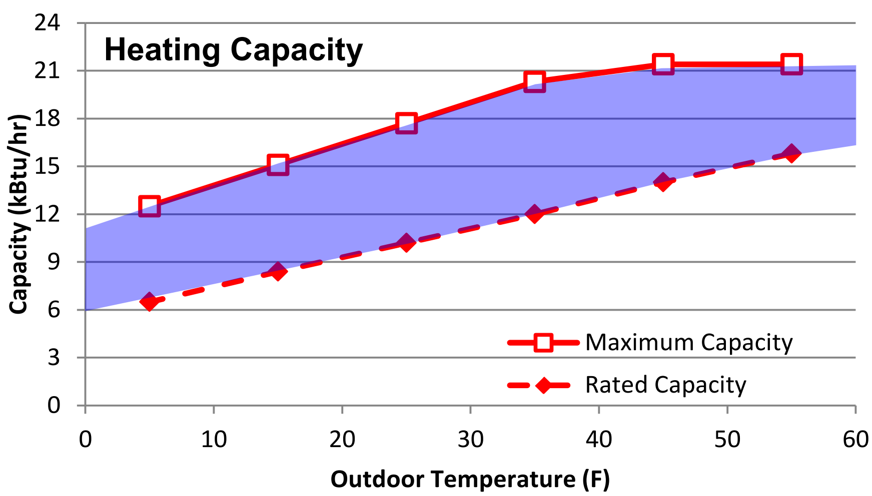


Figure 3. Mitsubishi FE12NA heating capacity at rated and maximum conditions

The plot shows that even at extreme temperatures (5°F), the equipment at maximum capacity still reaches its nominal 12,000 Btu/h output. This is due to the low-temperature capability of this series of equipment (trade name of "H2i" or "Hyper Heat"). The shaded blue area shows that in reality, the equipment operates in the range between the rated and maximum conditions, or even at less than rated capacity at low-load conditions.

The COP of the equipment can be calculated for both rated and maximum capacity, based on the heating output and electricity draw (Figure 2). As expected, efficiency falls with decreasing outdoor temperature (typical heat pump behavior), and operating the unit at maximum capacity reduces efficiency (as discussed by Winkler 2011).

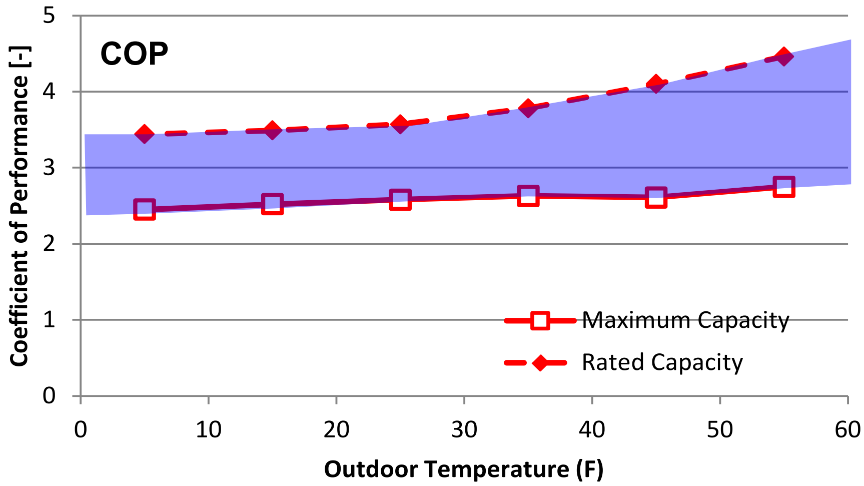


Figure 4. Mitsubishi FE12NA efficiency (COP) at rated and maximum conditions

Manufacturers' data do not include the effect of defrost; if it were included, a "dip" would result in performance in the 25°–35°F range.

3.3 Experience With Single-Head Systems and Costs

Non-ducted MSHPs are a key aspect Transformations' strategy of paying for improvements in the building enclosure/shell by reducing the cost of the mechanical system. For context, these tradeoff costs were discussed by Ireton (2013); the savings from eliminating a conventional heating and cooling system are a significant fraction of paying back the enclosure upgrade costs.

- Total cost increase in enclosure: $14,771
- No traditional heating and cooling system (MSHP savings): $5500.

The builder reports the installed cost of the two MSHPs as roughly $6000 (in new construction), or $3000/head. For reference, the current (2014) retail price for a single MSHP system (without installation) is in the $1600–$1800 range.

In addition, the builder notes largely trouble-free operation of the current generation of MSHP units; he has had very few call-backs based on improperly installed/operating equipment. The exceptions were a simple miswiring error by the installer, and an improperly plumbed condensate line.

The typical installation of the interior ductless wall-mounted head is shown in Figure 5; note that for rough-in, the indoor head is installed on a small section of gypsum board. This is done so that the installation of the interior unit can be completed prior to drywall, and therefore the mechanical contractor needs only one trip to the jobsite (resulting in cost savings). After rough-in (refrigerant lines, electrical and control wires, drain lines), open-cell spray foam insulation is installed in the wall cavity behind the gypsum board, when the unit is mounted on an exterior wall.

Figure 5. MSHP installation at house rough-in (L), and completed installation (R)

Additional photos during installation (Figure 6) show the “plug and play” nature of the equipment.

Figure 6. Unboxing and installation of MSHP equipment (Townsend, Massachusetts)

Infrared images of the indoor (Figure 7) and outdoor (Figure 8) units in heating mode are shown below. In Figure 7, the indoor units had an output temperature in the mid-90°F range (per infrared measurement) during mild outdoor conditions. Even though this might be considered in the risk range for “cold blow” complaints (cold perceived temperatures on skin), it felt sufficiently warm. This is consistent with Transformations’ experience over time. Output temperatures change with fan speed and outdoor temperature; other practitioners report higher output temperatures at colder outdoor conditions (i.e., higher output required).

Figure 7. Indoor MSHP unit in heating mode, showing delivery temperature

The exterior photos (Figure 8) show the "plume" of the cold air ejected from the outdoor unit during heating operation.

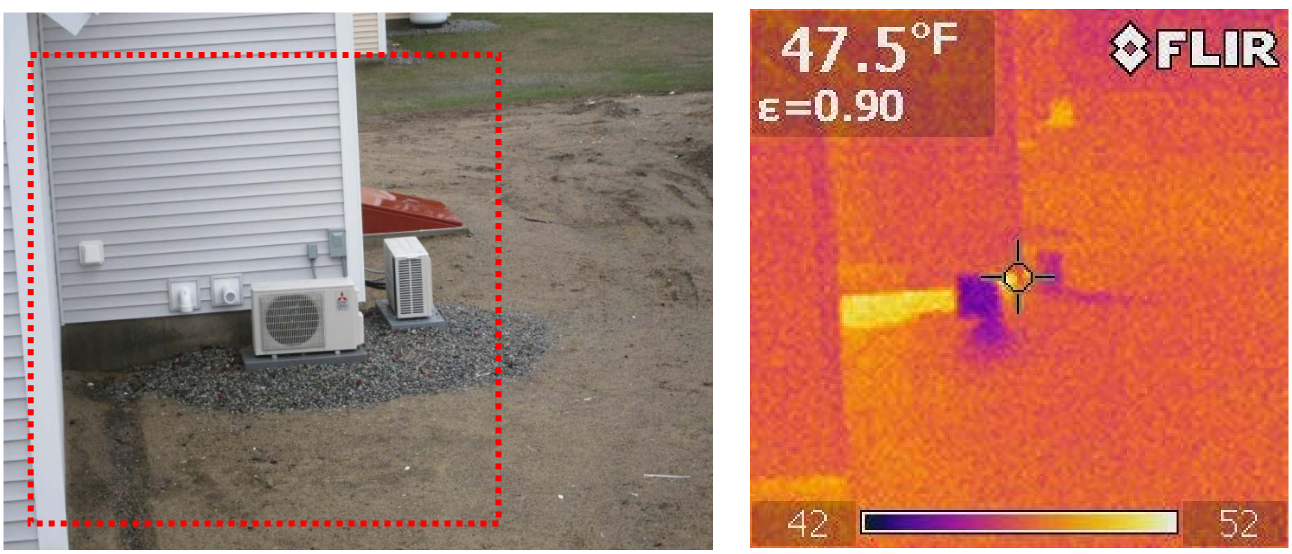


Figure 8. Outdoor MSHP unit in heating mode, showing "cold plume"

3.4 Experience With Multihead Systems

At Transformations' Townsend and Devens developments, there were no substantive comfort complaints in the production houses. However, at the Easthampton development, some comfort complaints began to surface; they are covered in more detail in Section 6.6, "Bonus Room Comfort Issues at Easthampton" . As a response, the builder and the developer jointly decided to take the conservative measure of installing a 3:1 indoor: outdoor MSHP unit for the second floor, in upcoming production (see Figure 9 and Table 7). Indoor heads were installed in each bedroom or room with a door. A single 1:1 MSHP was retained on the first floor.

Figure 9. 3:1 multisplit DHP (Mitsubishi MXZ series) installed at Easthampton

One negative consequence of this switch was the cost increase; based on retail equipment prices, this would be a 50% increase, not counting the increased installation costs.

A larger negative, though, was that the lower efficiency of the 3:1 MSHP (per official ratings) penalizes modeled energy performance. With this new equipment, HSPF drops from 10.6 to 9.3, and SEER drops from 23 to 17.5 (see Table 7); however, the peak summer operating efficiencies (energy efficiency ratios) are closer for the two products (12.9 versus 12.5) (Sooy 2014). In addition, cold weather capacity and efficiency suffer as it is not a cold ambient condition (Mitsubishi “H2i”) unit.

These performance differences resulted in the loss of the Massachusetts Residential New Construction Program Tier III incentive, and a substantially drop to the Tier II incentive (Table 8). These incentives significantly offset Transformations’ energy upgrade costs.

Table 8. Massachusetts Residential New Construction Program Incentive Levels for Single-Family Houses

(MassSave 2014)

Level	Requirement	Incentive
Tier I	15% improvement*	$750
Tier II	30% improvement*	$1,250 (was $3450)
Tier III	45% improvement*	$7,000 (was $8000)

* Minimum percentage improvement over the 2012 Massachusetts baseline home, and compliance with Sections 3 and 5 of the ENERGY STAR Thermal Enclosure System Rater Checklist

To date, the use of multiple MSHP heads in the bedrooms appears to have addressed all comfort complaint issues, but with the negative consequences detailed above.

3.5 Transformations’ Future Space Conditioning Equipment Options

BSC has worked with Transformations on solutions to the problems posed by the Easthampton work, including space conditioning of the bedrooms with closed doors, and the loss of the Tier III incentive. Previous work included the use of transfer fans, which pull warmer air from the conditioned core/hallway, distribute it to the bedrooms, and return via undercuts and transfer grilles. However, these fans had limited effectiveness, especially when run at flow rates that would not result in noise issues.

One excellent solution to the bedroom conditioning problem is the use of a small ducted air handler, recessed into the dropped ceiling of a second-floor hallway. This was used previously in Transformations work (circa 2010) at the Townsend development (Figure 10). Rosenbaum (2014b) listed the advantages of these small ducted systems, which include improved air filtration, possible integration with ventilation (including distribution of ventilation air), reduced noise, and (most importantly) even distribution of temperatures. There is a cost increase associated with ducted air handlers: Rosenbaum (2014b) estimated a cost increase of $2500–$5000; this is consistent with Transformations' increase in the $2000 range (circa 2010). This is a substantial proportional difference compared with the $6000 installed cost of two MSHP non-ducted heads.

Figure 10. Ducted air handler MSHP indoor unit, at Transformations' Townsend development

Rosenbaum (2014a) also recounted his experience with small air handler MSHP systems. He found that dirty filters can significantly reduce airflow (and therefore capacity), because available static pressures in these units are low. The ductwork needs to be exceptionally airtight and well insulated: given the low output of the unit, relatively small duct leaks can result in a substantial loss in capacity. Finally, a very short metal return duct can result in excess noise, so a longer and/or sound-insulated return is recommended.

Ducted air handlers are also more sensitive to poor installation. Figure 11 shows an exceptionally poorly installed MSHP air handler, located in the basement of a deep energy retrofit project in Massachusetts (not associated with Transformations, Inc.). The supply runouts were 4-in. diameter duct with multiple elbows, insulated with only a radiant "bubble wrap" foil product (roughly R-1), extending to the outside perimeter of the house (Figure 11 right). As a result, performance was severely degraded: airflow through the return was below measurable levels in this basement unit, when run at maximum speed.

Another issue with air handler MSHPs is that switching from a wall-mounted ductless system to a small air handler penalizes heating and cooling efficiency. For example, in the Mitsubishi multihead MXZ series (as an example), switching to a mixture of ductless and ducted indoor units reduces SEER by 1.25–1.5, and HSPF by 0.2–0.5. Switching to all ducted units is a further penalty, reducing SEER by 2.5–3, and HSPF by 0.4–1.

Figure 11. Ducted air handler MSHP indoor unit, with excessively long/restrictive ductwork

Despite these issues, the problem of conditioning the bedrooms is significant enough that the team has been exploring options for implementing them. One issue is that the current product lineup does not offer low ambient temperature-capable units (trade name "H2i" or "Hyper Heat") in a 1:1 ducted configuration. Discussions with manufacturer representatives indicated that they had considered this combination, but that management does not consider the market segment large enough for the investment in another product line. Additional correspondence (Sooy 2013) indicated that the manufacturer ran bench top electrical compatibility tests connecting an H2i outdoor unit to a ducted indoor unit. Although this combination appeared to be compatible, this test did not include refrigerant connection and/or running of the system. Furthermore, this combination is not rated by the American Heating and Refrigeration Institute (and is thus ineligible for energy performance rebates), and would not be warrantied by the manufacturer.

One promising option, however, is that the 2:1 and 3:1 MSHP Mitsubishi MXZ series (as used at Easthampton) will be available in the future, with H2i/Hyper Heat low-temperature capacity. A ductless unit could be used on the first floor, and a compact air handler on the second floor; in smaller houses, this may eliminate the need for a separate first-floor system. The product is slated for launch in Q4 2014 (Cefaly 2014).

Another project that was considered by the builder was a set of small townhomes, built with similar characteristics to its current production. This would result in even lower design loads than its current single-family houses. The builder considered a transition to a different manufacturer's 2:1 MSHP system (one head on each floor). BSC analyzed heating output, risk of "cold blow" complaints, and efficiency levels. Key conclusions were that the units would have sufficient capacity at cold temperature, but with some energy performance penalty (roughly 10%–20%), and potential "cold blow" issues at worst-case conditions.

4 Monitoring Setup

4.1 Overview

Monitoring systems were installed in eight houses, as outlined in Table 9 and Figure 12. There was a mixed package of sensors installed in the various houses, which included:

- T/RH in interior spaces and exterior
- Door status sensors (open/closed)
- MSHP electricity use.

Table 9. Summary of Monitoring Packages

Location	Stories-Square Feet	T/RH	Door Open/Closed	MSHP Electricity Use
Devens Lot 3	2-1728	●		●
Easthampton Lot 13	2-1728	●		●
Easthampton Lot 17	2-1239	●	○	○
Easthampton Lot 23	2-1132	●	○	○
Easthampton Lot 30	2-2266	●	●	
Devens Lot 4	2-1728	○	●	●
Devens Lot 7	2-1952	○	●	●
Devens Lot 8	1-1524	○	●	●

● = full dataset; ○ = partial dataset

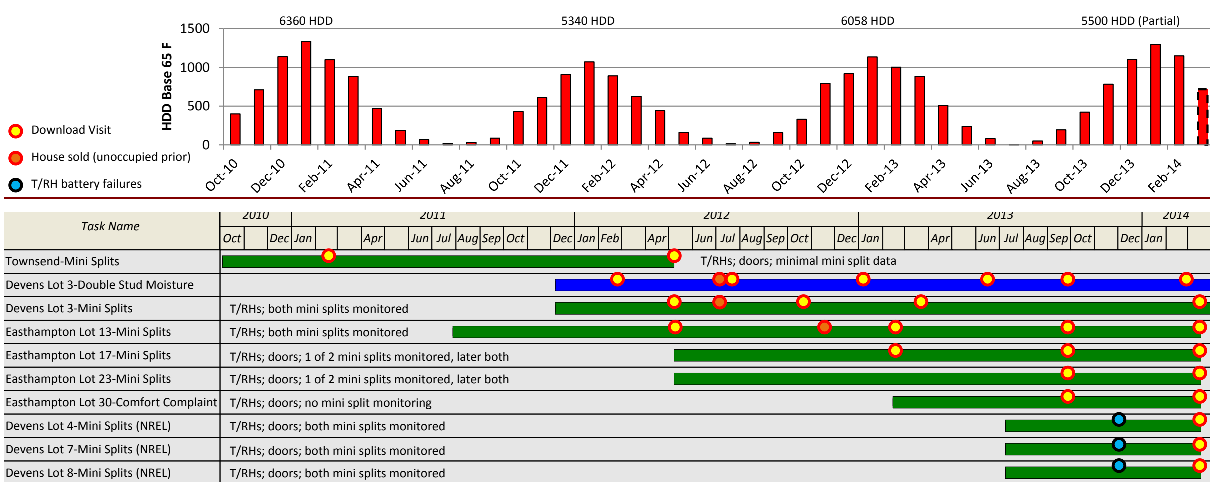


Figure 12. Monitoring summary and timeline with downloads, Devens and Easthampton

These instruments were not all run concurrently: incremental monitoring was added over the course of the project, as outlined in Figure 12. It also shows HDD 65 for the Easthampton site, to allow comparison between winters. The graphic also shows the timeline of download visits, transitions from unoccupied to occupied state (in two houses), and failure of T/RH collection in some Devens houses.

A detailed description of the monitoring equipment is provided in Appendix A, which includes model information and accuracy levels. House-by-house details on the monitoring equipment installation are provided in Appendix C.

There was a mixture of instrumentation in the various houses, and some houses had incomplete datasets, as detailed below:

- Devens Lot 3 and Easthampton Lot 13 had no door sensors. They were initially an unoccupied home and a model, respectively (reducing the value of door sensors), and sensors were not retrofitted later, after occupancy.
- Easthampton Lots 17 and 23 had a second MSHP added to the second floor during the first summer of operation. An additional electricity data logging system was not added until after the equipment's installation, only capturing the final winter (2013–2014). The door status sensors were not functional until the first download trip (roughly 1 year into logging).
- Easthampton Lot 30 monitoring focused exclusively on an investigation of comfort issues at the bedrooms, so the MSHP unit was not monitored.
- Devens Lots 4, 7, and 8 had full set of monitoring equipment, but the interior T/RH recording stopped before the start of winter, due to premature battery failure caused by logger firmware problems.

Figure 13 and Figure 14 show a typical monitoring package, excerpted from Appendix C; it includes the location of the MSHP heads. The closet T/RH sensor was placed in a closet typically left open (per statements by the homeowner).

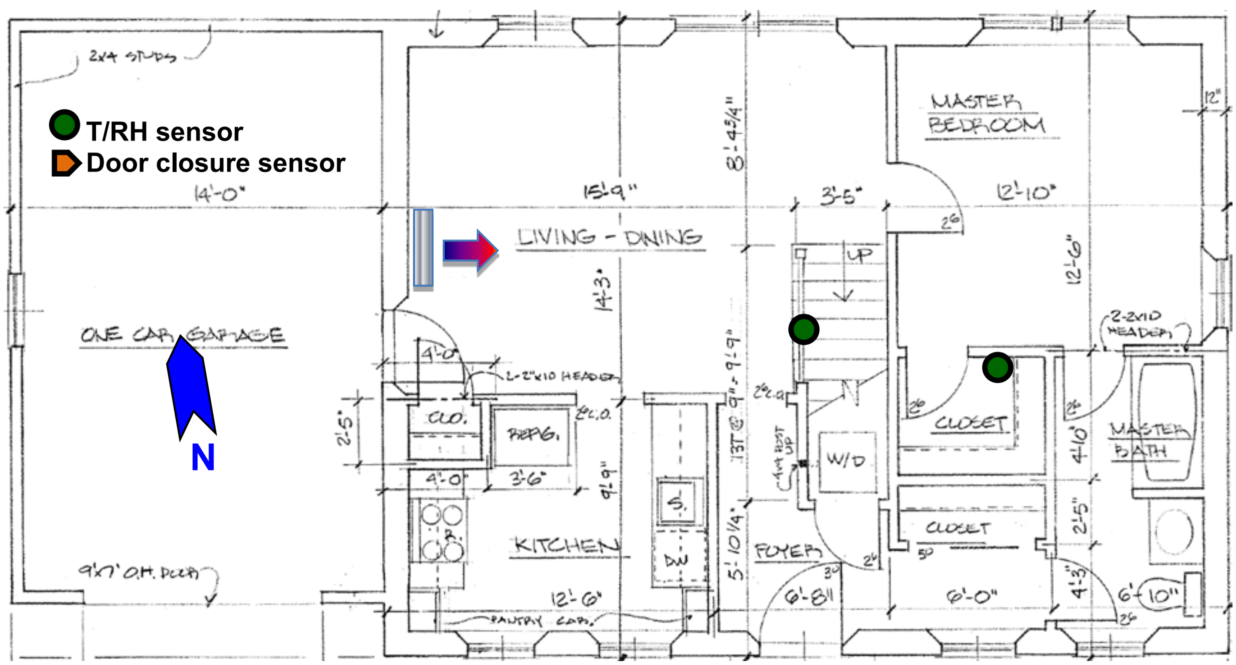


Figure 13. Easthampton Lot 17 first-floor plan, MSHP locations, monitoring locations

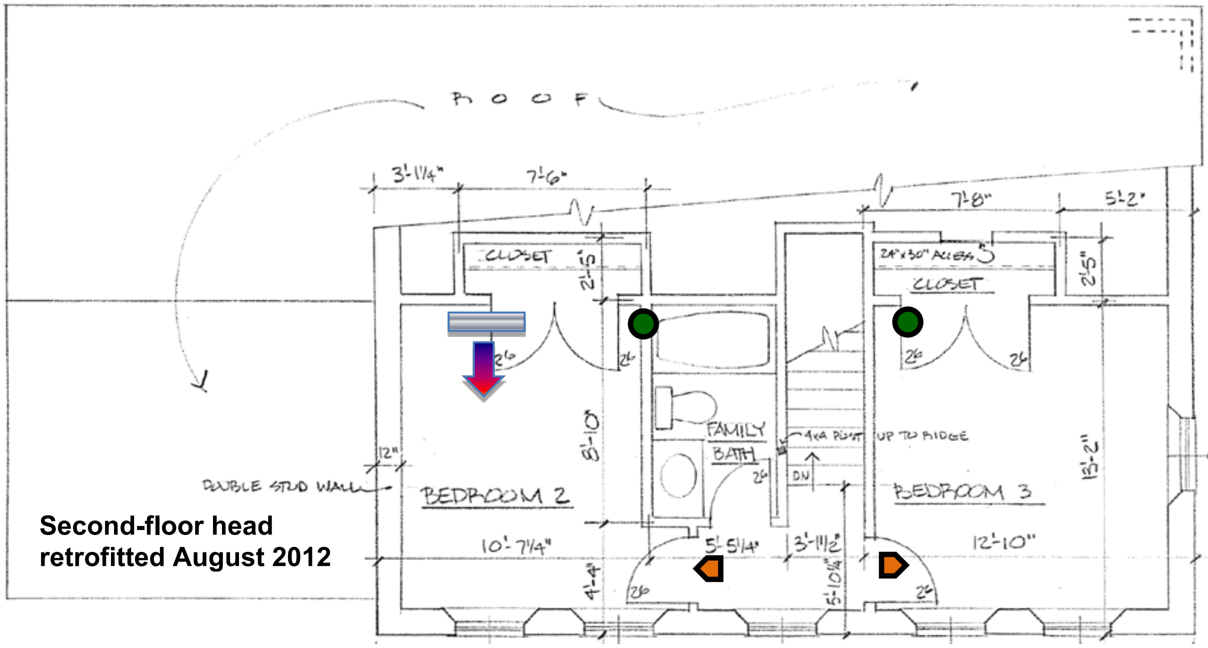


Figure 14. Easthampton Lot 17 second-floor plan, MSHP locations, monitoring locations

4.2 Interior Conditions (Temperature/Relative Humidity)

Interior T/RH measurements were taken with battery-operated loggers, attached to the walls typically 45 in. above finish floor. Logger locations are shown in the floor plans in Appendix C; they were typically located behind the entry door so that they would be concealed in most cases.

Figure 15. Interior T/RH measurements

Of course, the ideal experiment would measure air temperature and radiant temperature in the middle of the room, to avoid any anomalies due to wall placement or proximity to the hallway; however, this level of instrumentation is more suitable to research sites rather than occupied houses. In addition, radiant temperatures and radiant asymmetry are a smaller factor with high-performance enclosures (in particular, triple glazing), and reasonable glazing ratios (per these houses).

4.3 Doors Open/Closed Status

Door open/closed status was measured with a battery-operated state logger, which utilizes a reed switch to sense a magnet mounted to the door frame (Figure 16). The system registers door closed status when the magnet is close to the logger. However, this system does not register a door being partially closed: only “open” (which could include mostly closed) or “fully closed.”

Logger locations are shown in the floor plans in Appendix C.

Figure 16. Door open/closed sensors

4.4 Ductless Heat Pump Energy Use

In most houses, electricity use of the MSHPs was measured with a self-powered, current transformer rated electronic kilowatt-hour meter, connected to a battery-powered pulse count meter (Figure 17). The pulse count meter registers every 10 Watt-hours; loggers were typically programmed to record at 5-minute intervals. Both legs (240 V) of the MSHP were monitored; one kilowatt-hour meter was used per MSHP unit.

Figure 17. MSHP electrical power monitoring at electrical panel

At Devens Lots 4, 7, 8, the MSHP was monitored using a battery-operated multichannel logger set to measure amperage from a split-core current transducer, logging one of two electrical legs at the outdoor unit (Figure 18). Note that this is only a measurement of amperage or electrical current, and does not include power factor correction.

Figure 18. MSHP electrical power monitoring at outdoor unit

4.5 Exterior Conditions (Temperature/Relative Humidity)

Exterior conditions (T/RH) at the Devens site were measured at two locations: one on the north-facing side of Lot 3 (Figure 19, left), and the other within a radiation enclosure between Lot 7 and Lot 8 (Figure 19, right).

Figure 19. Devens measurement of exterior conditions (T/RH)

At Easthampton, outdoor conditions are taken from the weather station at Westfield, Barnes Municipal Airport (KBAF), roughly 8 miles south of the development.

5 Results: Mini-Split Heat Pump Operation and Energy Performance

This section examines the energy performance of the monitored MSHPs; electricity use was monitored in seven of the eight houses (Table 10). Two houses (Easthampton Lots 17 and 23) have only partial data, as a second MSHP was retrofitted after construction; monitoring was procured and installed after the MSHP installation.

The effect of simplified space conditioning distribution on interior temperature variations is covered in Section 6.

Table 10. Summary of Monitoring Packages: Electricity Monitoring Highlighted

Location	Stories-Square Feet	T/RH	Door Open/ Closed	MSHP Electricity Use
Devens Lot 3	2-1728	●		●
Easthampton Lot 13	2-1728	●		●
Easthampton Lot 17	2-1239	●	○	○
Easthampton Lot 23	2-1132	●	○	○
Easthampton Lot 30	2-2266	●	●	
Devens Lot 4	2-1728	○	●	●
Devens Lot 7	2-1952	○	●	●
Devens Lot 8	1-1524	○	●	●

● = full dataset; ○ = partial dataset

5.1 Operation and Energy Consumption Patterns

Some representative sample plots are presented in this section, in order to provide an overview of what the collected MSHP data can reveal, as well as some general patterns that were observed across many monitored houses. Devens Lot 3 is covered in detail below.

5.1.1 Temperature and Mini-Split Heat Pump Electricity Use Plots

A basic way of digesting the collected MSHP data is to plot indoor and outdoor temperatures with hourly power use (Watt-hours per hour, or average wattage for the hour). Figure 20 shows interior and exterior temperatures (left-hand axis) and power use (right-hand axis) for winter 2012–2013 for Devens Lot 3.

This type of plot is used throughout this report to explain the relationship between temperatures and MSHP operation. Full datasets for all houses are provided in Appendix C. Observations from this plot include the following:

- The homeowner maintained a relatively steady set point for the heating season, with most temperatures in the 65°–70°F range.
- The MSHP unit hourly electricity consumption varied up and down as a function of outdoor temperature; during the majority of the winter, there were very few hours with zero power draw.

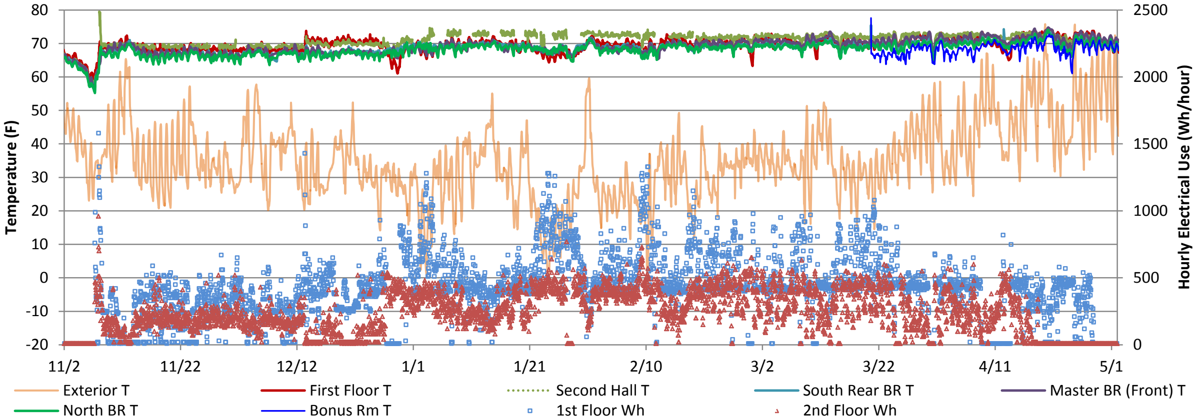


Figure 20. Devens Lot 3 heating season 2012–2013

Plots of the raw 5-minute interval data (Figure 21) demonstrate the modulating output of the MSHP unit. The first-floor unit (left-hand side) modulates higher and lower with temperature. The second-floor unit (right-hand side) also modulates, but appears to have many hours at zero draw. However, this is a function of the instrumentation resolution: the power meters are set to 10 Wh/pulse, which means that low-draw periods will be counted as zeroes. For the purposes of this work, hourly resolution is used for ease of plotting and graph interpretation.

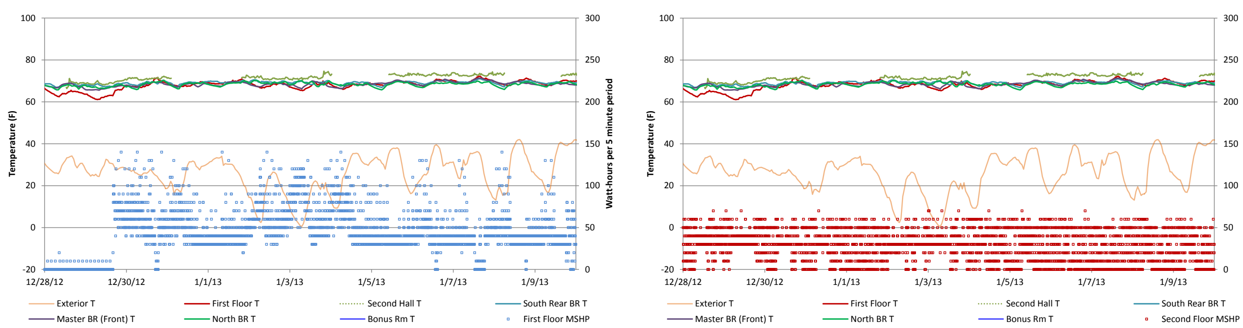


Figure 21. Devens Lot 3 MSHP 5-minute data; winter 2012–2013

- The MSHP electricity consumption varied with outdoor temperature: increasing in colder conditions, and decreasing in milder/warmer conditions.
- The first-floor MSHP unit has greater power draw than the second-floor MSHP, showing that it is providing more than half of the heating, despite temperatures being very similar on the first and second floors. This is likely a thermal buoyancy effect.
- These MSHP units do not reach their maximum power draw of ~2000 W, with peak loads of ~1250 W (assuming constant speed per monitored hour), showing excess available capacity.

A similar example is shown in for a cooling season (summer 2013) at Easthampton Lot 13, in Figure 22. It is clear that cooling is turned on in late May, after some hot weather and interior temperature excursions. At first, the second-floor unit provides most of the cooling, but later, both units are run (early July), resulting in more even interior temperatures (possibly due to lower set point as well).

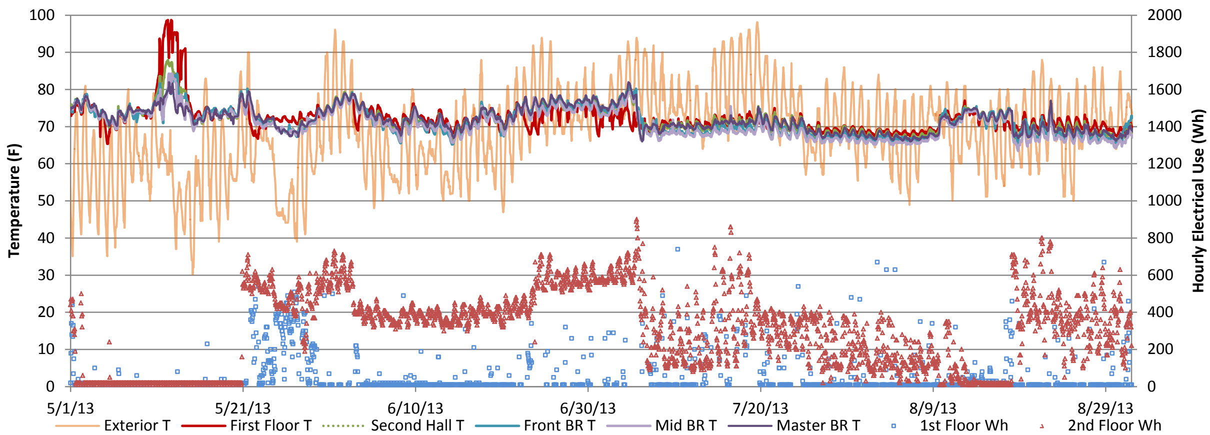


Figure 22. Easthampton Lot 13 cooling season 2013

5.2 Temperature Versus Mini-Split Heat Pump Electricity Use Plots

Further information can be gained by plotting the daily MSHP electricity use against daily average temperature (Figure 23). As would be expected, daily power draw increases with colder temperatures. However, there is substantial scatter, including many low power load days at cold temperatures. This type of scatter plot is also often created using indoor-outdoor temperature difference (ΔT) as the horizontal axis, but with a fixed interior set point, the plot is essentially the same as the outdoor temperature plot (assuming the interior set point is satisfied).

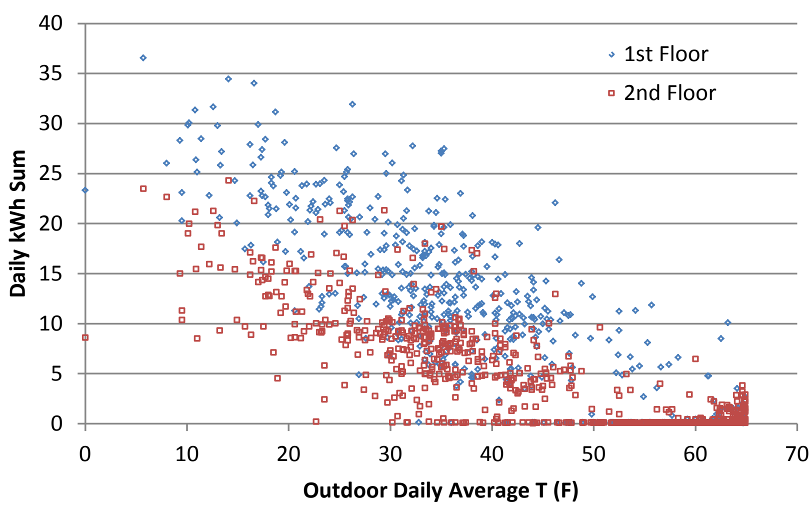


Figure 23. Devens Lot 3 daily kilowatt-hour versus daily average temperature (°F)

Finer grain resolution (albeit with more scatter) can be obtained with hourly plots of MSHP electricity use versus outdoor temperature, as shown in Figure 24 for Devens Lot 3. There are distinct responses for heating versus cooling loads (i.e., two different groups of data). Heating and cooling loads show their expected responses of rising with greater temperature difference.

For reference, the outdoor winter and summer design temperatures are shown, as well as an estimated trend line for heating and cooling responses. There are many hours outside of design conditions (although a count was not used to determine whether they were more or less than 1% of hours). The heating draw very rarely reached ~2000 W (unit maximum capacity), with significant spare margin at outdoor design conditions.

The heating balance point (outdoor temperature at which no heating is required) can be estimated by where the red dotted line crosses the x-axis. It appears to be in the 55°F range, or slightly lower than the typically cited 65°F. This is expected for buildings with high-performance enclosures and normal internal loads.

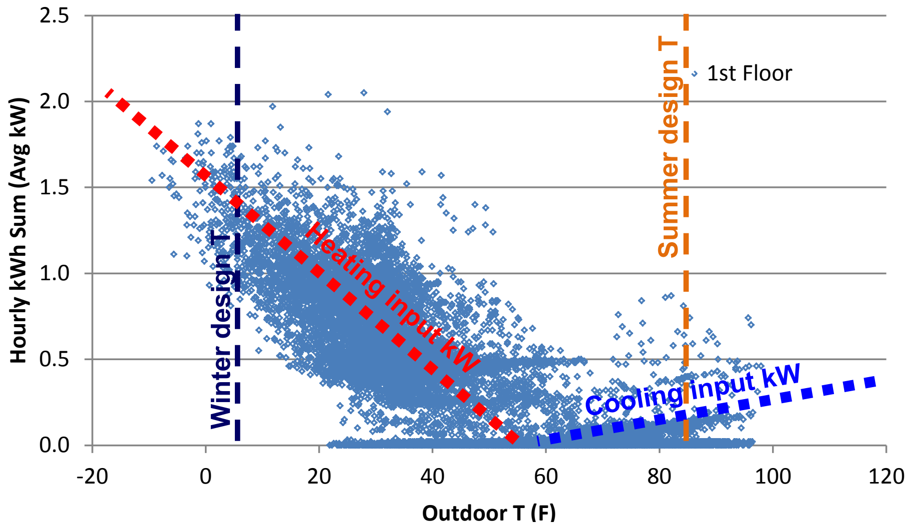


Figure 24: Devens Lot 3 hourly kWh versus outdoor temperature (hourly data)

Given the greater resolution from plotting hourly data (versus daily data), it is primarily used in the sections below.

5.3 Ability To Satisfy Heating Loads

One critical question is whether there were issues with insufficient capacity using MSHPs in a cold climate. Previous literature indicates that these units have excellent output at cold ambient conditions, thus avoiding historical issues with heat pump use in a cold climate.

5.3.1 Design Loads and Equipment Sizing

A first step was to compare the installed equipment sizing with the calculated design heating load. Heating loads were calculated using Architectural Energy Corporation REM/Rate software and the following outdoor design conditions:

- Easthampton (Greenfield, Massachusetts weather station: Winter –2°F/Summer 85°F)
- Devens (Worcester, Massachusetts weather station: Winter 4°F/Summer 84°F).

REM/Rate load calculations typically give smaller results than ACCA Manual J (ACCA 2011) (albeit roughly comparable); REM/Rate loads were chosen due to availability from the energy rater.

Table 11 shows heating design loads, installed equipment capacity, and the "oversizing factor" (installed capacity relative to design load). Installed equipment capacity is stated for outdoor winter design temperature. Several of the houses had MSHP equipment retrofitted and installed after construction; they included a 3:1 MXZ series MSHP at Easthampton Lot 30 (see Section 3, "Builder Mini-Split Heat Pump Experience"), and adding second-floor MSHP unit to Easthampton Lots 17 and 23. Retrofitted equipment capacity is noted in brackets.

Table 11. Heating Design Loads and Equipment Sizing for Devens and Easthampton Houses

Location	Lot	Adjusted Gross Square Feet	Heating Design Load (kBtu/h)	Installed Equipment Capacity (kBtu/h)	Oversizing Factor
Devens	3	1728	16.8	25.0	149%
Devens	4	1728	16.3	25.0	153%
Devens	7	1952	18.2	37.5[a]	206%
Devens	8	1524	13.0	25.0	192%
Easthampton	13	1728	12.1	22.0	182%
Easthampton	17	1239	11.0	11.0 [22.0][b]	100% [200%]
Easthampton	23	1132	10.0	11.0 [22.0][b]	110% [220%]
Easthampton	30	2266	18.1	22.0 [33.7][c]	121% [186%]

Original installed capacity [Retrofitted Equipment Capacity]
[a] 3x 12,000 heads installed at Devens Lot 7
[b] Second MSHP head added on second floor after cooling season issues
[c] Second floor switch from MSHP to 3:1 MXZ-series multisplit (not low-temperature capacity)

It is clear that the equipment is substantially oversized relative to design loads (150%–200% typical), so lack of equipment capacity is not expected. Although oversizing is commonly criticized for cooling equipment, oversizing is beneficial for heat pumps. This is particularly true for MSHPs that modulate their capacity, as their highest efficiency is obtained when the unit is running at the lower end of its capacity range. In addition, these houses have no electric resistance backup heat: the heat pumps are the sole source of heating.

Also, although square footage metrics are a poor method for load calculations, the square footage conditioned by each MSHP head was a matter of some interest. The results are shown in Table 12, including houses retrofitted with additional heads, in brackets.

The table shows that the problem cases occurred at houses with more than 1100 ft^2 conditioned per MSHP head. However, this is too little information to be considered general guidance: it is based on a specific climate, specific construction type, and house geometry.

Table 12. Square Footage per MSHP Head for Devens and Easthampton Houses

Model	Adjusted Gross Square Feet	# MSHPs	ft^2/MSHP
Victorian	1728	2	864
Farmhouse	1728	2	864
Custom Saltbox	1952	3	651
Ranch	1524	2	762
Farmhouse	1728	2	864
Small Saltbox	1239	1 [2]	1239 [620]
Cottage	1132	1 [2]	1132 [566]
Custom Home	2266	2 [4]	1133 [567]

Original installed capacity [Retrofitted Equipment Capacity]

5.3.2 Hourly Power Use Versus Exterior Temperature (Watt-Hour Meter)

Hourly power use versus exterior temperature plots were used to provide a "signature" of the behavior of the eight tested houses; the following four houses were monitored with Watt-hour meters. In all cases except for Easthampton Lot 23, heating draws are typically below the maximum input of 2000 W (with some exceptions), showing that system capacity is not being taxed, even at winter temperatures below design conditions. Lot 23 is discussed in more detail below. All plots show the response of increased power draw with increased temperature difference. The high load hours at Devens Lot 3 appear to be some type of anomaly: either recovery from setback, or possible ice blockage/defrost issues.

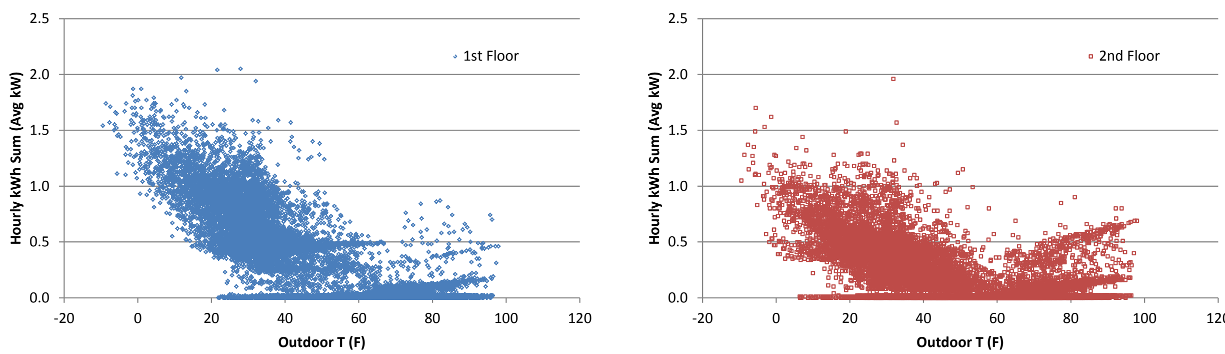


Figure 25: Devens Lot 3 hourly kilowatt-hours versus outdoor temperature

Easthampton Lot 17 (Figure 27) shows minimal runtime of the second-floor MSHP. The second-floor MSHP was retrofitted after the first summer, and the electricity logger was only added in September 2013. However, the electricity logger did capture the end of summer 2013, and winter 2013–2014. This indicates that in this small (1239-ft^2) house, the first-floor MSHP unit provided the majority of the heating.

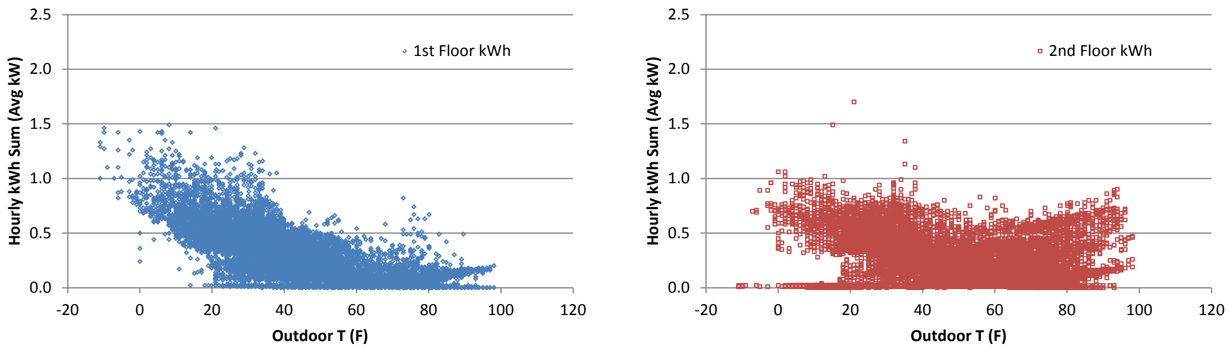


Figure 26. Easthampton Lot 13 hourly kilowatt-hour versus outdoor temperature

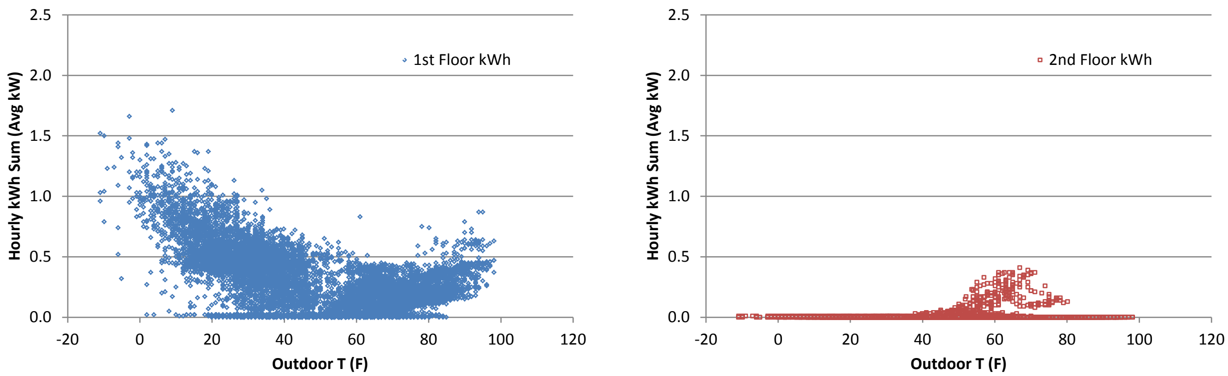


Figure 27. Easthampton Lot 17 hourly kilowatt-hour versus outdoor temperature

Easthampton Lot 23 (Figure 28) shows a substantially different response from the previous houses. Although there is increasing load with lower outdoor temperatures, there are many hours at maximum capacity, even at moderate temperatures.

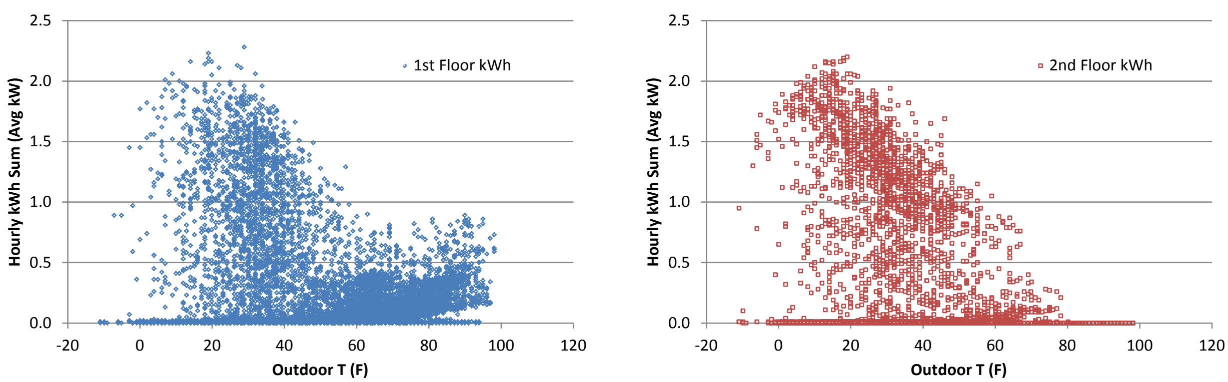


Figure 28. Easthampton Lot 23 hourly kilowatt-hours versus outdoor temperature

This reflects the fact that the homeowner controlled the MSHPs in an "on-off" manner, turning the system on and off based on perceived comfort, rather than letting the thermostat control the unit. The numerous hours at high electricity load reflect the MSHP unit running at maximum capacity, to recover from the deep setbacks (often from 60°F to 70°F^{+}). In addition, controlling the unit in this manner exacerbates peak load issues. The effect of on-off control on interior temperatures is discussed in a later section.

5.3.3 Hourly Power Use Versus Exterior Temperature (Amperage Measurements)

Three houses were monitored with amperage metering, as opposed to kilowatt-hour metering. Therefore, the graphs below should properly have a vertical axis labeled as kVA (thousand volt-amps), as opposed to kilowatt-hours.

At Devens Lot 4, there is a similar relationship between power draw and outdoor temperature. However, there are many more hours at maximum capacity (~2000 W). In addition, there appears to be a "missing band" of data during the heating season, between 0 VA and 200 VA.

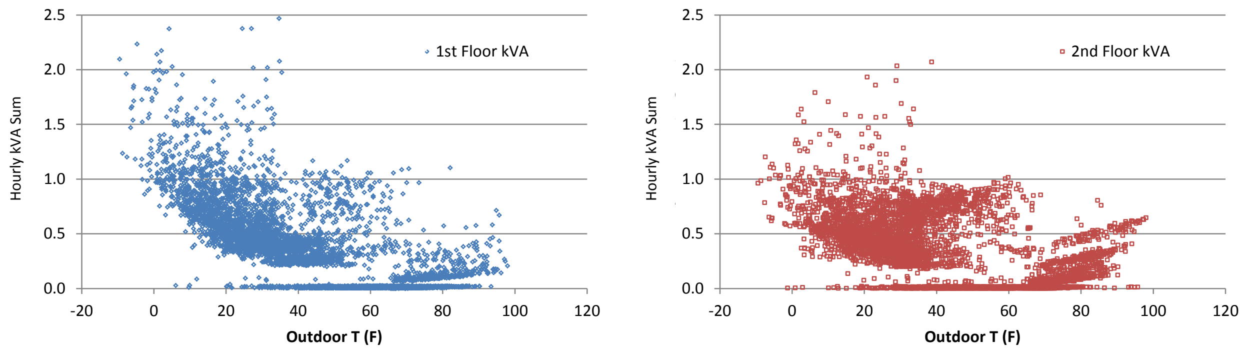


Figure 29. Devens Lot 4 hourly thousand Volt-amps versus outdoor temperature

Devens Lot 7 is a house with three MSHP heads; it shows less correlation than previous graphs between power draw and temperature. In addition, it has a similar "missing band" of data during the heating season.

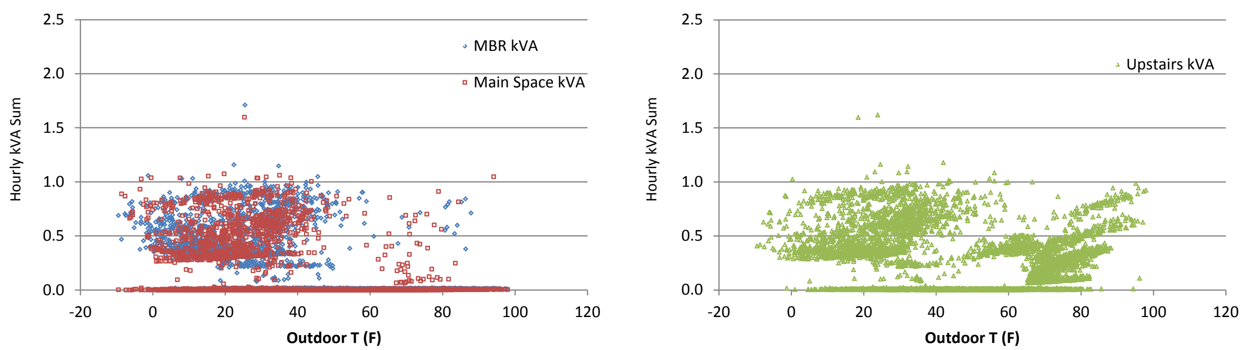


Figure 30. Devens Lot 7 hourly kVA versus outdoor temperature (3 MSHPs)

Devens Lot 8 (Figure 31) showed similar responses to Devens Lot 7, with a lack of correlation between temperature and electricity draw, and the "missing band" of data.

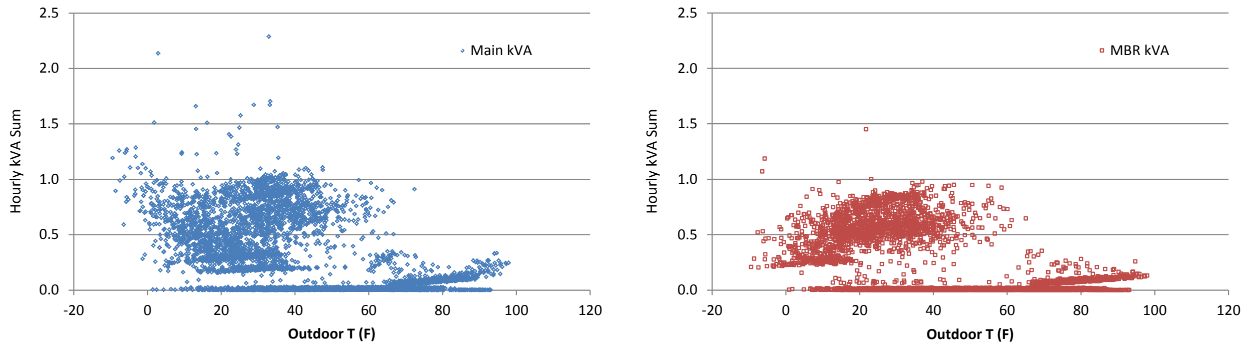


Figure 31. Devens Lot 8 hourly kVA versus outdoor temperature

The hourly temperature and power draw data for Devens Lot 7 (Figure 32) shows the "missing band" issue in the heating season, across all three MSHP units. However, this issue does not occur during the cooling season.

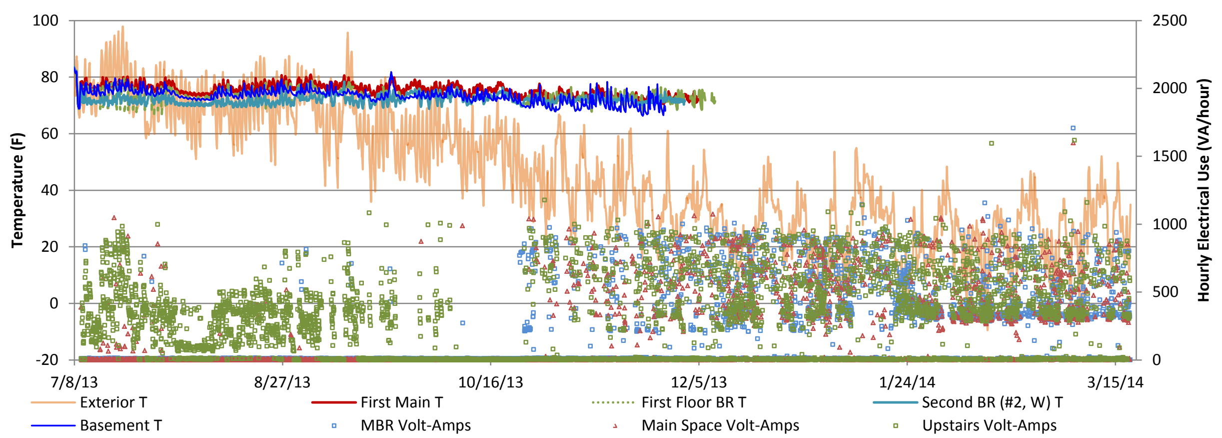


Figure 32. Devens Lot 7 hourly kWh (three MSHPs) and indoor/outdoor temperatures

One possible explanation for these data is the effect of power factor on wattage and amperage measurements. Rosenbaum (2014c) has conducted measurements of MSHPs systems; his anecdotal observations show that power factor is close to 1 when at full power, but a much poorer (lower) power factor when at lower speed (e.g., in 0.15 range). This is consistent with the use of an inverter-driven motor. If raw amperage is used to calculate wattage (without a power factor correction), low power factors would tend to overstate the power draw at low speed. This issue is consistent with the "missing band" of data. However, the "missing band" issue is not seen in the cooling season, which does not match this theory.

If MSHP power factors are as low as those found by Rosenbaum, the Watt-hour/kilowatt-hour measurements are also subject to some inaccuracy at low speeds. The Watt-hour meter states its power factor range as "0.5 to 1.0, leading or lagging."

Another possible source of error is limits of the current transducer; the equipment manufacturer states a minimum measurement of 2 A, or 240 VA (at 120 V). This lower limit is roughly consistent with the "missing band" of data.

The measurement of a single leg of the 240 V MSHP is another potential source of error; however, Harley (2014) found the two legs to be essentially identical in draw.

5.4 Mini-Split Heat Pump Standby Electricity Use

As low-load houses or net zero energy houses reduce their energy use, “always on” or standby energy use becomes a more noticeable fraction of total electricity use.

Several researchers have found that standby loads on MSHPs were higher than would be expected. CARB (2010b) reported an MSHP with a constant 27-W electricity load. Rosenbaum (2014c) noted a standby load of 40 W with a ducted single-zone system (Mitsubishi SEZ/SUZ heat pump).

BSC observed a case of a Mitsubishi MXZ/SEZ heat pump system with a very high standby load. It was a 2:1 system (two indoor heads) that drew 150 W continuously; it was attributed to an incorrectly set up system. Mitsubishi technical representatives noted that the crankcase heater will draw roughly 60 W, but should run only at the temperature range where defrost is required.

Harley observed that the crankcase heater draws an average of 30 W; however, further measurements showed that it operated during the winter only (below 34°F), resulting in a relatively low average load (120 kWh annually, or an average of 14 W for the year).

The logging of multiple MSHPs allowed for the examination of standby use: at Easthampton Lot 13, the second-floor MSHP appeared to be on, but the heating demand was met by the downstairs unit. When the near-zero data were averaged (from late October through March; Figure 33, highlighted in purple), the standby load was determined to be 4 W. It is likely that the unit was periodically running the fan to sample air temperature during this period. Similar results were found at Devens Lot 3 (4–5 W, both units, 2 months’ data), and Easthampton Lot 17 (5 W, one unit, 1.5 months’ data).

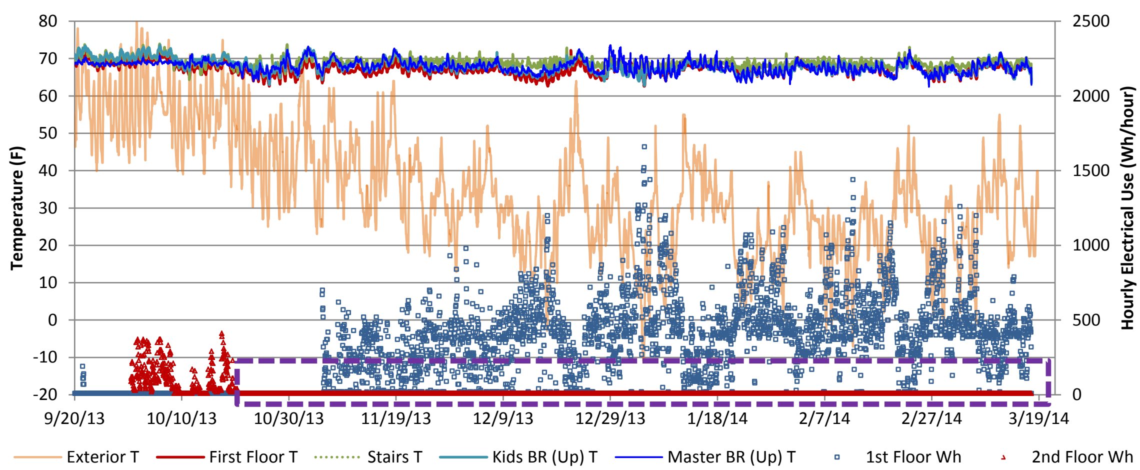


Figure 33. Easthampton Lot 13 standby period (with indoor/outdoor temperatures)

Standby load varies between manufacturers and models; this measurement applies to the monitored MSHPs only (Mitsubishi FE12NA; MUZ-FE12NA + MSZ-FE12NA).

As a point of reference, standby measurements have been taken on conventional space heating equipment. A furnace was measured at 10 W and a boiler at 15 W. Both were gas fired, ~80% annual fuel utilization efficiency, atmospherically vented units with printed circuit board controllers, but no extensive electronics.

5.5 Snow Blockage of Mini-Split Heat Pumps

One risk of using air-source heat pumps in a cold climate is of the outdoor unit being blocked by snow, resulting in diminished capacity at critical periods. All MSHPs examined here were ground mounted, but raised from their pads with timber risers (Figure 34). This is consistent with best practice guidance (Manclark and Thomas 2011), which recommends the use risers to avoid snow issues, and also allows greater drainage of condensate water during the heating season.

The data did not indicate any sign of a lack of capacity during snow events. In addition, when the site was examined after a snowfall (Figure 34), the MSHP outdoor units were clear of the snow level, and it is plausible that fan operation blows away snow that obstructs the face.

Figure 34. Outdoor units raised on wood block risers

An alternate solution to ground-mounted risers is to mount the unit on an exterior wall, using commercially available brackets. There is the potential for transmitted vibration noise through the wall; however, discussions with two practitioners indicated no problems with this option in their experience.

5.6 Energy Consumption and Simulation Comparisons

The following section presents raw plots of monthly MSHP electricity use, then compares results with previous energy simulations (Architectural Energy Corporation REM/Rate output), and normalizes these results by HDD and square footage (per Rosenbaum 2014b).

5.6.1 Monthly Mini-Split Heat Pump Electricity Use Plot

The MSHP electricity data were also aggregated on a monthly basis, and plotted showing first- and second-floor usage. There was no direct measurement of cooling versus heating operation, but there are clear gaps between the two seasons.

Overall metered energy use (including plug load) was not recorded, which would provide an indication of the fraction of space heating being provided by internal loads. However, all houses were originally equipped with all-compact fluorescent lamps or light-emitting diodes and ENERGY STAR® appliances.

Devens Lot 3 (Figure 35) shows patterns that were seen consistently in several of the monitored houses. There is clearly more heating consumption than cooling consumption, as is typical for a zone 5A climate. The second-floor MSHP unit has lower consumption than the first during the heating season, which is consistent with thermal buoyancy effects (the first-floor unit provides most of the heating), and builder observations. Similarly, the second-floor MSHP unit appears to be the majority of the consumption during the cooling season.

The first winter (2011–2012) was the mildest (see Figure 36), but has a higher consumption than the second winter (Figure 35). The reason for this behavior is not clear, but it may be due to the lack of basement insulation, which was only installed in mid-February 2012.

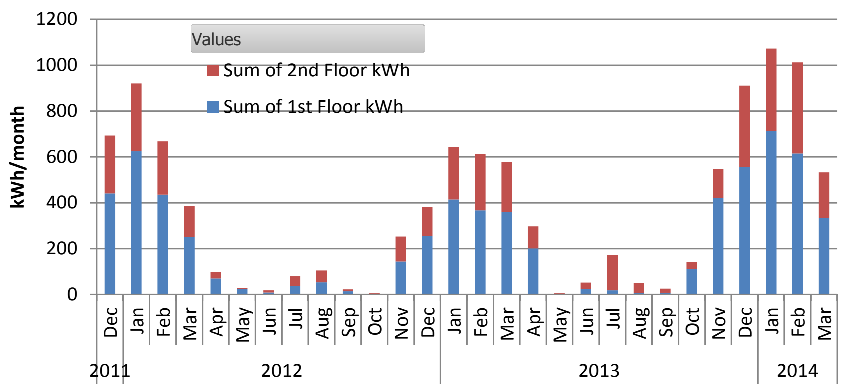


Figure 35. Devens Lot 3 monthly MSHP kilowatt-hour consumption (heating and cooling)

For reference, the monthly HDDs for the Devens site (Fitchburg, Massachusetts, airport, KFIT) are plotted in Figure 36. Electricity consumption normalized by HDDs is covered in a later section.

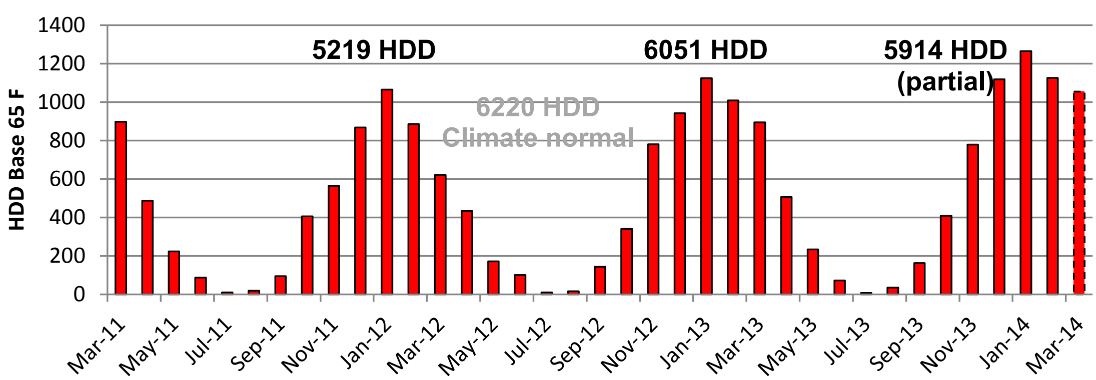


Figure 36. Devens site (KFIT airport) monthly HDDs, 2011–2014

Easthampton Lots 13's monthly consumption is shown in Figure 37. The first winter (2011–2012) has markedly lower consumption than the second (2012–2013) and third (2013–2014) winters. This might be explained by a difference in occupancy: in the first winter, the house was an unoccupied model, but it was occupied by a family of four in the second winter. As shown in the plot of interior and exterior temperatures (Figure 38), a higher set point was used in the second winter (2012–2013, 68°–78°F), and the set point varied much more, compared to the more-constant set point used in the first winter (2011–2012, 67°–71°F). Sharp rises in interior temperature in the second winter are linked to hours with high MSHP electricity consumption (i.e., possible recovery from setback).

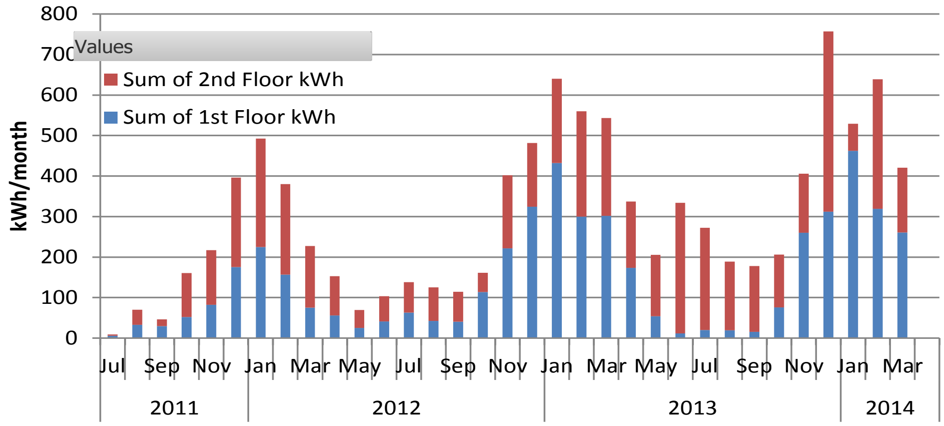


Figure 37. Easthampton Lot 13 monthly MSHP kilowatt-hour consumption (heating and cooling)

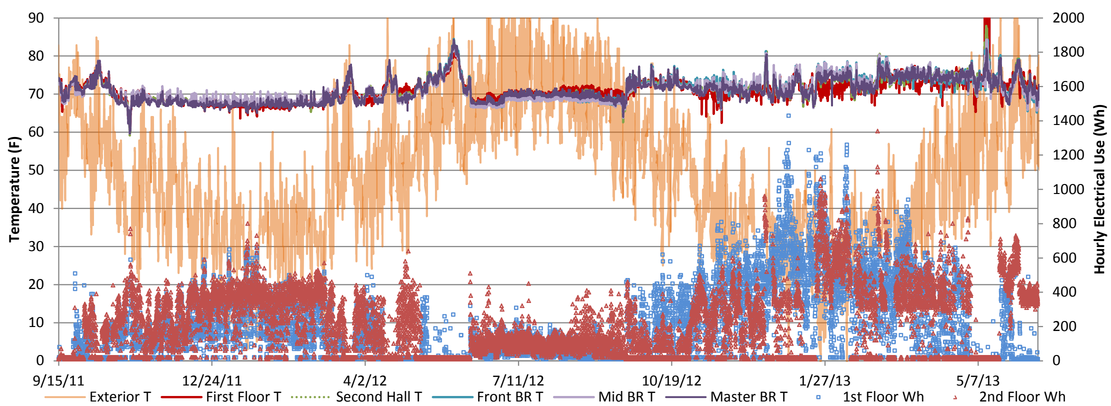


Figure 38. Easthampton Lot 13 hourly temperatures and MSHP electricity consumption, 2011–2013

Easthampton Lots 17's monthly consumption is shown in Figure 39; the second-floor MSHP was installed in August 2012, but it was not instrumented until October 2013. But extrapolating from the monitoring results from winter 2013–2014, the first-floor unit provided the majority of the heating in this house.

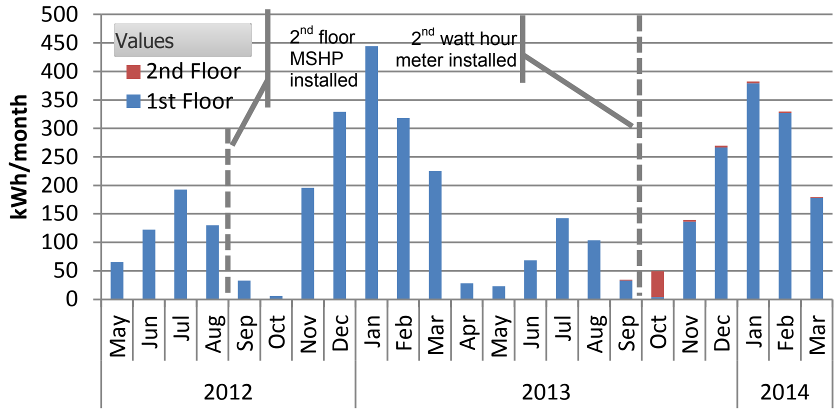


Figure 39. Easthampton Lot 17 monthly MSHP kilowatt-hour consumption (heating and cooling)

Easthampton Lots 23's monthly consumption is shown in Figure 40; again, there was a gap between the installation of the second MSHP and monitoring equipment installation. The MSHPs in this house were operating in an "on-off" manner, instead of using a fixed set point, in an effort by the homeowner to reduce energy use. This is discussed in more detail in a later section, but in short, this results in many hours when the MSHP runs at maximum speed (its least efficient state) to recover temperature set point. Lot 23's performance over winter 2013–2014 can be compared with Lot 17's, which is similar in size (1132 and 1239 ft^2, respectively). Lot 23 consumes much more electricity: peak consumption is ~700 kWh in Lot 23, but ~375 kWh in Lot 17 (note that the vertical axis scale changes between Figure 39 and Figure 40). Lot 17 set points were typically 65°–70°F; Lot 23 temperatures varied widely due to on-off operation, ranging from 60°F to 75°F.

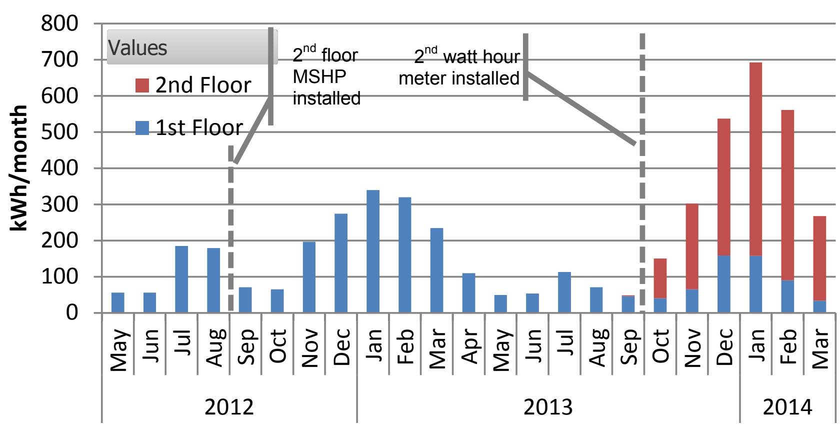


Figure 40. Easthampton Lot 23 monthly MSHP kilowatt-hour consumption (heating and cooling)

For reference, the monthly HDDs for the Easthampton site (Westfield-Barnes Regional Airport, KBAF) are plotted in Figure 41.

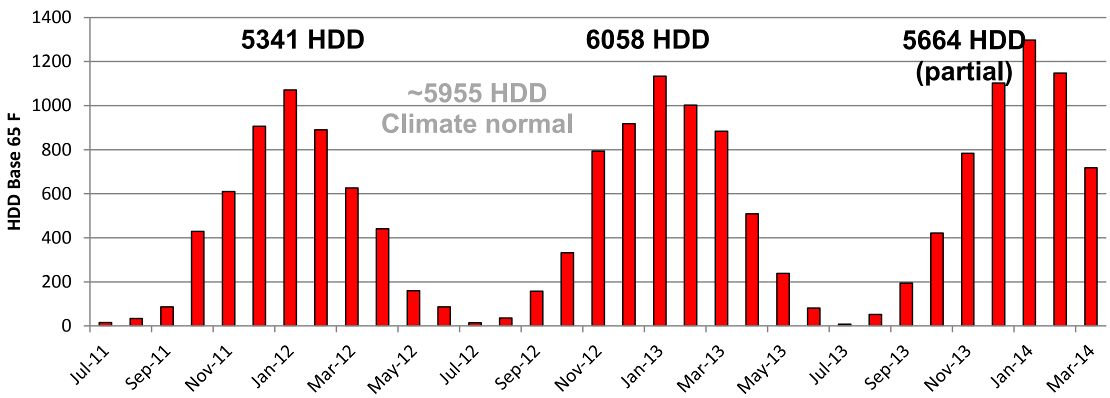


Figure 41. Easthampton site (KBAF airport) monthly HDDs, 2011–2014

Monthly MSHP consumption for Devens Lots 4, 7, and 8 are shown in Figure 42, Figure 43, and Figure 44, respectively. Note that Devens Lot 7 has three MSHP units (two on the first floor, one on the second); the second-floor MSHP provides the majority of space cooling during summer months. Devens Lot 8 is a single-story plan, and had MSHPs located in the main space, and in the master bedroom suite (roughly one fourth of the floor area).

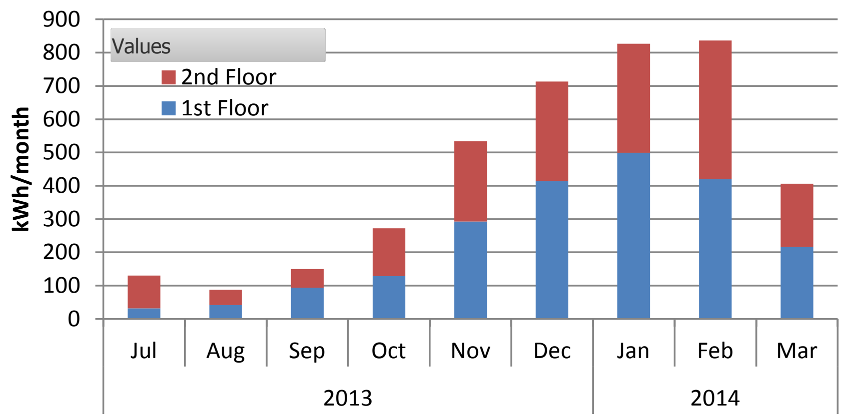


Figure 42. Devens Lot 4 monthly MSHP kilowatt-hour consumption (heating and cooling)

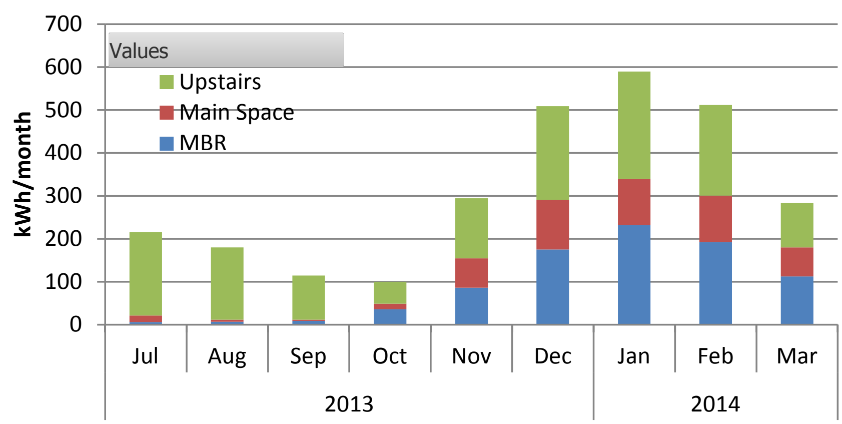


Figure 43. Devens Lot 7 monthly MSHP kilowatt-hour consumption (heating and cooling)

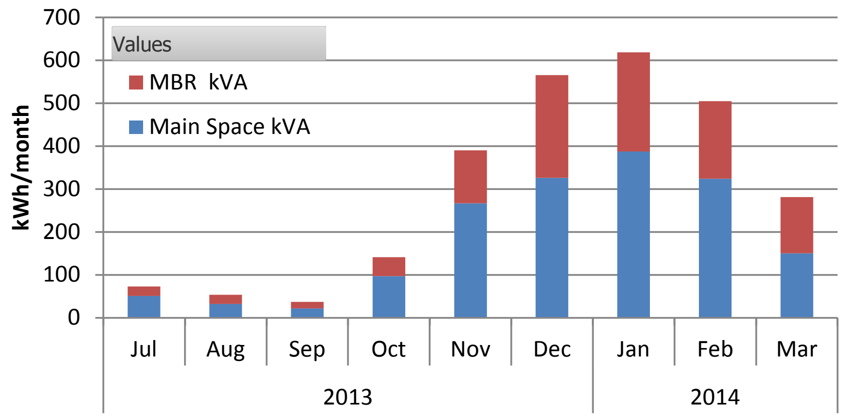


Figure 44. Devens Lot 8 monthly MSHP kWh consumption (heating and cooling)

5.6.2 Heating Degree Day Normalized Use and Comparison With Energy Models

The monthly electricity use can be collated and presented in terms of heating season use. However, these results are not useful in and of themselves, as they are not normalized by the severity of the winter; in addition, several winters have only partial data.

Therefore, the results were normalized in terms of HDD 65°F, and compared with previous energy simulations (Architectural Energy Corporation REM/Rate output). These simulations used custom weather locations; the entered efficiencies for the heat pump systems were 10.5 HSPF/23.0 SEER, per the manufacturer's information (Table 6).

The input values are shown in Table 13; the HDDs 65 for the custom weather stations are shown. The winter season's MSHP electricity use was summed, and the associated HDD shown; partial versus full winters are noted in the table. Partial versus full winters are normalized by adding HDDs from the relevant months only.

Table 13. Devens and Easthampton MSHP Measured (Raw) and Simulated Electricity Use, With HDD

Location	Lot	Square Feet	Identifier	Raw kWh	HDD 65	Dataset Notes
Devens	3	1728	Simulation		6179	
			Winter 2011–2012*	2764	3872	Partial: December-April
			Winter 2012–2013	2794	5738	Full: September–April
			Winter 2013–2014*	4241	5914	Partial: September–March
Devens	4	1728	Simulation		6179	
			Winter 2013–2014*	3738	5914	Partial: September–March
Devens	7	1952	Simulation		6179	
			Winter 2013–2014*	2403	5914	Partial: September–March
Devens	8	1524	Simulation		6179	
			Winter 2013–2014*	2540	5914	Partial: September–March
Easthampton	13	1728	Simulation		6929	
			Winter 2011–2012	2073	5060	Full: September–April
			Winter 2012–2013	3240	5730	Full: September–April
			Winter 2013–2014*	3136	5664	Partial: September–March
Easthampton	17	1239	Simulation		6929	
			Winter 2012–2013	1580	5730	Full: September–April, no logger #2
			Winter 2013–2014*	1385	5664	Partial: September–March
Easthampton	23	1132	Simulation		6929	
			Winter 2012–2013	1611	5730	Full: September–April, no logger #2
			Winter 2013–2014*	2561	5664	Partial: September–March

* Partial winter season as noted, but accounted for in HDD 65

These inputs were then used to normalize electricity consumption by HDD; a simple ratio-based normalization was used. The results are shown in Table 14, with the performance relative to the simulation, in terms of ±%.

Table 14. Devens and Easthampton MSHP Normalized Heating Use, With Comparison to Simulation

Location	Lot	Identifier	kWh (Normalized)		± (%)
Devens	3	Simulation	3722		
		Winter 2011–2012[a]	4411		+19%
		Winter 2012–2013	3009		–19%
		Winter 2013–2014[a]	4431		+19%
Devens	4	Simulation	3224		
		Winter 2013–2014[a]	3905		+21%
Devens	7	Simulation	3390		
		Winter 2013–2014[a]	2511		–26%
Devens	8	Simulation	2579		
		Winter 2013–2014[a]	2654		+3%
Easthampton	13	Simulation	2813		
		Winter 2011–2012	2839		+1%
		Winter 2012–2013	3918		+39%
		Winter 2013–2014[a]	3836		+36%
Easthampton	17	Simulation	2257		
		Winter 2012–2013	1911	[b]	–15%
		Winter 2013–2014[a]	1694		–25%
Easthampton	23	Simulation	1993		
		Winter 2012–2013	1948	[c]	–2%
		Winter 2013–2014[a]	3133		+57%

[a] Partial winter season as noted, but accounted for in HDD 65
[b] 2nd floor MSHP not logged, but winter 2013–2014 suggests minimal runtime 2012–2013
[c] 2nd floor MSHP not logged, significant runtime missed

There is considerable scatter in the simulations: correlations varied from 57% above to 26% below the simulation prediction. However, there are some useful points to be gleaned, and further explanations needed, as follows:

- Devens Lot 3 has three winters of data, some partial. The first winter might have been high due to a lack of basement insulation. The third winter might have been high due to a higher interior set point (high 70s/low 80s; see Figure 53).
- Easthampton Lot 13 also has three winters of data (some partial). The first winter was unoccupied, while the second and third winters were occupied. The first winter was run at a completely fixed set point, possibly resulting in best-case performance, compared to the later winters (per previous discussion, under monthly graphs). The bonus room at Lot 13 was finished and used as conditioned space after construction. However, it was finished between winter 2012–2013 and winter 2013–2014, so it does not explain the difference between these the two similar occupied winters.

- Easthampton Lot 17 had a second-floor MSHP retrofitted after the first summer, but instrumentation was not installed until winter 2013–2014. However, based on monthly consumption data (Figure 39), it appears that the first-floor unit accounts for the majority of the heating load.
- Easthampton Lot 23 also had a second-floor MSHP retrofitted after the first summer, with instrumentation installed just before winter 2013–2014. Based on the final winter, both first- and second-floor MSHPs are being used for heating. The HDD-normalized use for winter 2013–2014 is the worst outlier relative to the model (+57%); this is explained by the use of on-off control of the MSHP by the occupant.

These inputs were then used to normalize electricity consumption by HDD; a simple ratio-based normalization was used. The results are shown in Table 14, with the performance relative to the simulation, in terms of ±%.

Table 14 can also be shown as a scatter plot, comparing the actual use (HDD normalized) with the simulation results. Data points above the diagonal line (1:1 correspondence) indicate actual use greater than the simulation; points below the diagonal indicate the reverse.

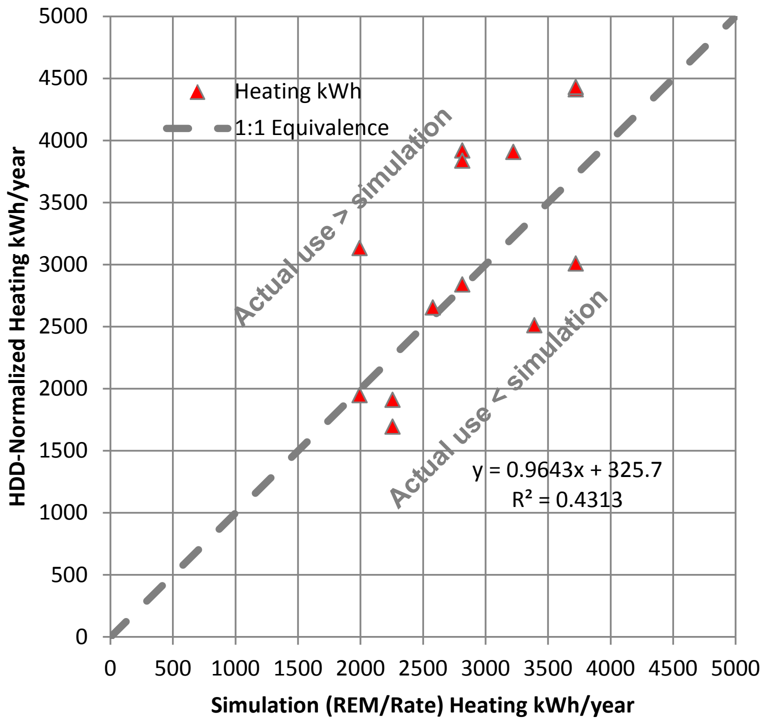


Figure 45. Comparison of simulation (x-axis) and HDD-normalized heating (y-axis) electricity use

Given the limited correlation seen in this plot ($R^2 = 0.43$), it is difficult to draw any conclusions about the accuracy (or lack thereof) of the energy model. However, the average error for the sample is +8% (actual normalized use greater than simulation prediction); it drops to +4% if the outlier (Lot 23) is omitted.

5.6.3 Normalized Consumption Metrics (kWh/ft²·Heating Degree Days 65°F)

Another normalization method, proposed by Rosenbaum (2014b), is to divide heating use by kWh/ft²·HDD 65. The results from Devens and Easthampton are shown in Table 15, showing both simulation and actual use. The normalized figures are shown both excluding and including the basement in the square footage calculation; the Easthampton houses are slab on grade, so they remain unchanged.

Table 15. Devens and Easthampton MSHP Area-Normalized Heating Electricity Use ($kWh/ft^2 \cdot HDD$ 65)

Location	Lot	Square Feet	Identifier	Raw kWh	HDD	kWh/ft^2 HDD 65	Bsmt ft^2	kWh/ft^2 HDD 65 w/Bsmt
Devens	3	1728	Simulation		6179	0.00035	864	0.00023
			Winter 2011–2012*	2764	3872	0.00041		0.00028
			Winter 2012–2013	2794	5738	0.00028		0.00019
			Winter 2013–2014*	4241	5914	0.00041		0.00028
Devens	4	1728	Simulation		6179	0.00030	864	0.00020
			Winter 2013–2014*	3738	5914	0.00037		0.00024
Devens	7	1952	Simulation		6179	0.00028	1256	0.00017
			Winter 2013–2014*	2403	5914	0.00021		0.00013
Devens	8	1524	Simulation		6179	0.00027	1524	0.00014
			Winter 2013–2014*	2540	5914	0.00028		0.00014
Easthampton	13	1728	Simulation		6929	0.00023	0	0.00023
			Winter 2011–2012	2073	5060	0.00024		0.00024
			Winter 2012–2013	3240	5730	0.00033		0.00033
			Winter 2013–2014*	3136	5664	0.00032		0.00032
Easthampton	17	1239	Simulation		6929	0.00026	0	0.00026
			Winter 2012–2013	1580	5730	0.00022		0.00022
			Winter 2013–2014*	1385	5664	0.00020		0.00020
Easthampton	23	1132	Simulation		6929	0.00025	0	0.00025
			Winter 2012–2013	1611	5730	0.00025		0.00025
			Winter 2013–2014*	2561	5664	0.00040		0.00040

* Partial winter season as noted, but accounted for in HDD 65

Statistics for the sample (average, maximum, minimum, standard deviation) are shown in Table 16, for the simulations, and the actual (normalized) consumption.

Rosenbaum's normalized results are shown in Table 17 as a comparison point to the previous results.

Table 16. Devens and Easthampton MSHP kWh/ft²·HDD 65 statistics

Statistic	kWh/ft² HDD 65	kWh/ ft² HDD 65 With Basement
Average (Simulations)	0.00028	0.00021
Maximum	0.00035	0.00026
Minimum	0.00023	0.00014
Standard Deviation	0.00004	0.00005
Average (Actual)	0.00030	0.00025
Maximum	0.00041	0.00040
Mininum	0.00020	0.00013
Standard Deviation	0.00008	0.00008

Table 17. Normalized Electricity Consumption of Inverter-Driven Heat Pumps

(Rosenbaum 2014b)

Description/Location	Square Feet	System Type	kWh/ft²·HDD 65
Single-Family Deep Energy Retrofit, Chilmark, MA	1,258 (over basement)	Ducted single-zone system	0.000281
PassivHaus, Brattleboro, VT	2,392	Non-ducted single-zone system	0.000138
Dormitory/Faculty Apartments, Deerfield, MA	11,000	Multizone VRF system	0.000187

Overall, the consumption figures are on the higher end compared to those measured by Rosenbaum; however, normalized consumptions are relatively consistent with simulations. In addition, Rosenbaum's PassivHaus and dormitory would both have more favorable surface area to volume ratios than single-family homes smaller than 2000 ft². The worst-performing houses (highest kWh/ft²·HDD 65) were Devens Lot 3 (first and third summers, explained earlier) and Easthampton Lot 23 (on-off operation).

5.7 Dehumidification Performance

One reported advantage of MSHPs is that they provide superior control of interior RH levels because they continuously modulate, matching cooling output to house load. This addresses many of the issues with oversizing, which is typically linked to poor humidity control due to short cycle times, and failures to reach cold coil/condensing conditions (Proctor et al. 1995). In addition, many MSHP units have what is referred to as a *dry mode*, which is intended to increase dehumidification capabilities. The unit typically is run at low airflow across the indoor coil, and the coil temperature is controlled by the expansion valve to maximize dehumidification, while limiting dry bulb cooling (Mitsubishi 2007).

At the same time, low load houses have a higher risk of cooling season part load humidity issues. The enclosure improvements (greater airtightness, more insulation, improved windows) reduce sensible cooling loads, resulting in less cooling runtime, while leaving most latent loads unchanged, as discussed by Rudd et al. (2013).

The humidity control metric used by Rudd et al. (2013) and others is a count of the number of hours with interior RH levels over 60%. This threshold was chosen for comfort reasons, indoor air quality, and (at times) material durability (risks of mold or fungal growth). Note that the 60% RH level is not considered a hard limit, but more of a metric used for comparing cases. There is not a prescribed number of hours over 60% that is considered allowable/ideal or pass/fail.

For reference, the dew point of 60% RH air at various interior temperatures is shown below:

- 70°F/60% RH = 57°F dew point
- 75°F/60% RH = 62°F dew point
- 80°F/60% RH = 66°F dew point.

A plot of interior and exterior dew points at Easthampton Lot 13 over the summer of 2012 (Figure 46) shows that mechanical cooling controls interior dew point well below outdoor conditions.

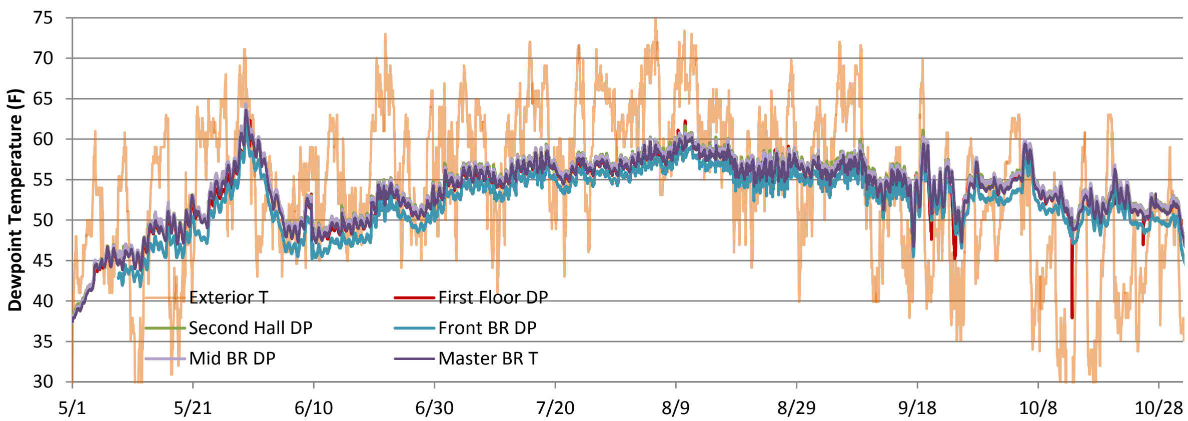


Figure 46. Easthampton Lot 13 interior and exterior dew point conditions, summer 2012

Summer 2013 interior RH levels for Easthampton Lot 13 are plotted in Figure 47, with 60% RH highlighted and exterior temperature for reference. It shows that during peak summer conditions, there are noticeable numbers of hours above 60% RH.

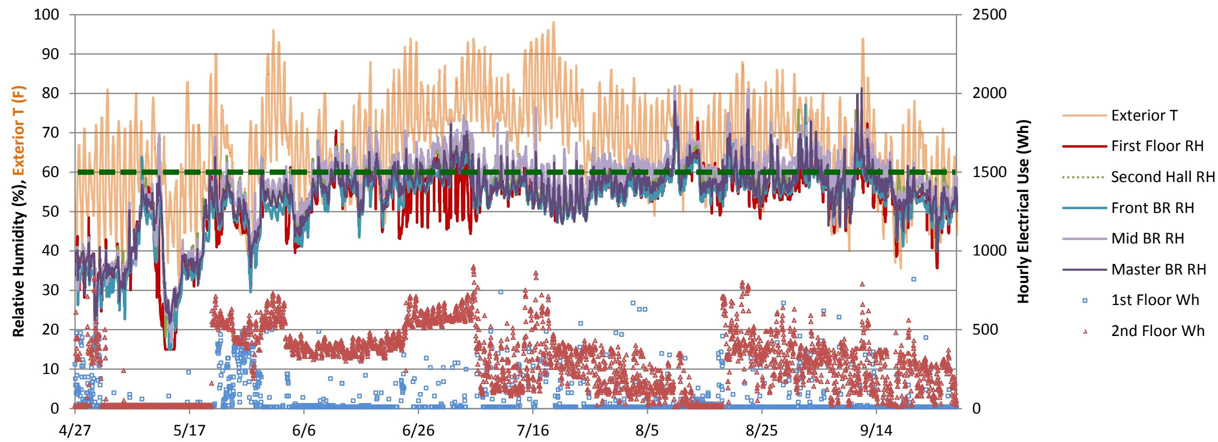


Figure 47. Easthampton Lot 13 summer 2013 interior RH and MSHP power use

This fact is captured in the tabulation of hours over 60% for the full dataset (Table 18).

Table 18. Easthampton Lot 13 Number and Percent of Hours Over 60% RH, Full Dataset

Location	# Hours Over 60% RH	% Hours Over 60% RH
First Floor	6114	13%
Second Hall	9075	19%
Front BR	3637	11%
Mid BR	10903	23%
Master BR	6388	17%

A similar plot for Devens Lot 4 is shown in Figure 48; in this case, many hours appear to be over 60% RH, as reflected in the tabular data (Table 19).

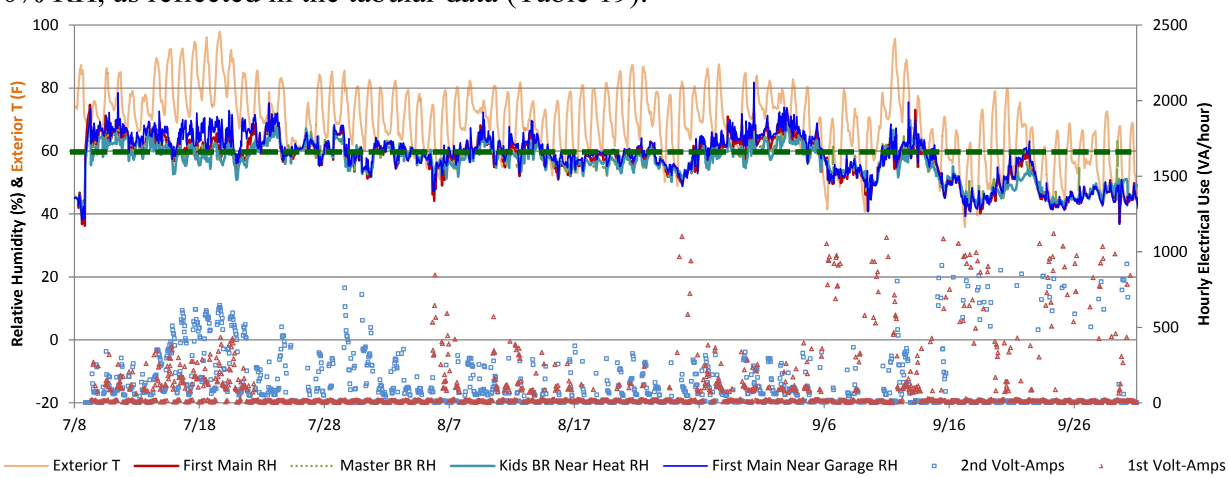


Figure 48. Devens Lot 4 summer 2013 interior RH and MSHP power use

Table 19. Devens Lot 4 Number and Percent of Hours Over 60% RH, Full Dataset

Location	# Hours Over 60% RH	% Hours Over 60% RH
First Main	790	24%
Master BR	700	22%
Kids BR Near Heat	589	17%
Office BR Rear	515	14%
First Main Near Garage	997	29%

A similar plot for Devens Lot 3 (summer 2013) is shown in Figure 49. One noticeable aspect about this house is that the homeowners maintained a higher than average set point (78°–80°F typical range); this is reflected in the limited MSHP runtime. This resulted in fewer hours above 60% RH, likely due to the dew point-RH relationship.

These results are also shown in Table 20, which show the low number of hours above 60% RH. The results for "South Rear BR" are italicized, as they are outliers. The calculated dew point of this room is much higher than all other rooms in the house, which suggests instrumentation (RH sensor) errors.

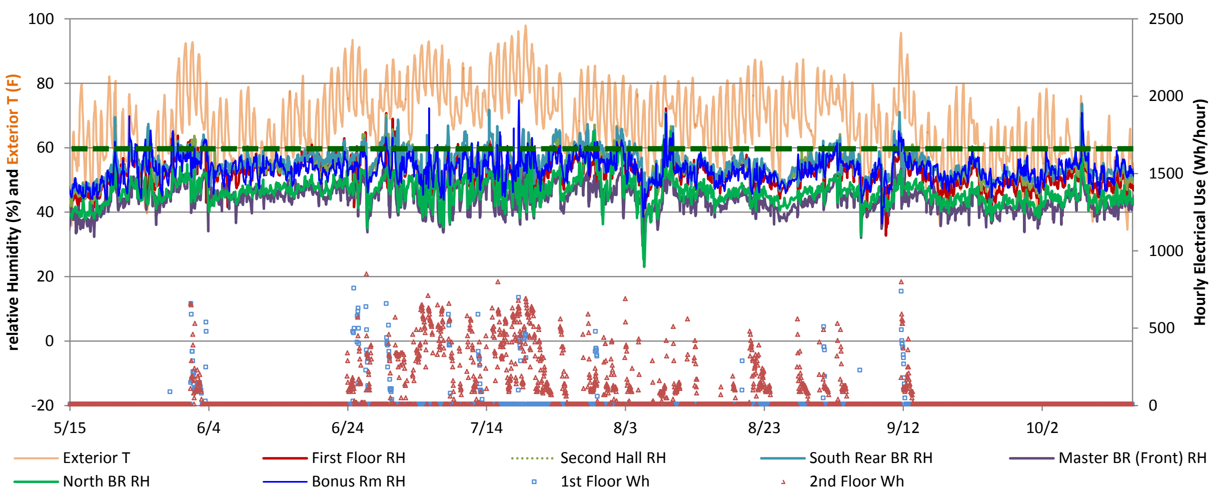


Figure 49. Devens Lot 3 summer 2013 interior RH and MSHP power use

Table 20. Devens Lot 3 Number and Percent of Hours Over 60% RH, Full Dataset

Location	# Hours Over 60% RH	% Hours Over 60% RH
First Floor	157	2%
Second Hall	1574	7%
South Rear BR	*6457*	*21%**
Bonus Rm	170	2%
Master BR (Front)	366	2%
North BR	358	2%

* Possible instrumentation (RH sensor) issue

The results for numbers of hours over 60% RH can be interpreted in light of results from Rudd et al. (2005). He found that in a zone 2A (Houston, Texas) climate, ENERGY STAR-level houses without supplemental dehumidification had RH levels over 60% for 20% of the monitored hours. In contrast, similar houses with supplemental dehumidification systems had RH levels over 60% for fewer than 10% of monitored hours.

These results show that MSHPs are not a panacea for controlling interior RH in high-performance houses in the Northeast. However, these results should be interpreted with some caveats. First, there is no comparison “control” data for similar houses conditioned with conventional split systems; it is entirely likely that MSHPs would have superior RH control to fixed-output (or two-stage) systems. Second, no complaints of high interior RH were reported by homeowners during occupant surveys. Third, there was no indication whether or not any of the systems were run in dry mode to intentionally control RH. Finally, in the Northeast, it is common practice to open windows for more temperate portions of the summer, using ventilation cooling. This practice would tend to increase moisture adsorption (storage) in interior furnishings and finishes, and thus make interior humidity control more difficult.

6 Results: Simplified Space Conditioning

Evaluating the success or failure of simplified space conditioning is covered in several sections below. First, a quantitative method, of the hourly distribution of the maximum temperature difference between spaces (per ACCA Manual RS, ACCA 1997) was used. Then, other variables, such as door open/closed operation, occupied versus unoccupied conditions, and temperature setbacks were examined in more detail. Other issues or problem cases, such as bonus room comfort complaints, thermal buoyancy effects, open-plan first floors, temperature setbacks, and basement temperatures were also examined.

All houses had interior temperature loggers; however, some datasets were more complete. The bulk of this analysis was conducted on Devens Lot 3, and Easthampton Lots 13, 17, and 23; Devens Lots 4, 7, and 8 did not have the wintertime (most critical) data due to logger failure.

Table 21. Summary of Monitoring Packages, Interior Temperatures

Location	Stories-ft^2	T/RH	Door Open/Closed	MSHP Electricity Use
Devens Lot 3	2-1728	●		●
Easthampton Lot 13	2-1728	●		●
Easthampton Lot 17	2-1239	●	○	○
Easthampton Lot 23	2-1132	●	○	○
Easthampton Lot 30	2-2266	●	●	
Devens Lot 4	2-1728	○	●	●
Devens Lot 7	2-1952	○	●	●
Devens Lot 8	1-1524	○	●	●

● = full dataset; ○ = partial dataset

6.1 Interior Temperature Distributions

One quantitative method of looking at temperature distributions is using metrics proposed in ACCA Manual RS (ACCA 1997), which specifies a maximum 4°F difference within a home or zone (highest minus lowest temperature). This method was used in previous work by CARB and IBACOS. It is an objective, quantitative method, but some nuances should be understood when interpreting results. The data cover both occupied and unoccupied spaces: when the occupants intentionally close off unused bedrooms in an effort to conserve energy, this induces failures in this metric even though it is the occupant’s intent.

The first floor was included in the temperature measurements, even though typically, the first floor and second floors each have MSHP heads, and could be considered two separate zones. There were definitely some cases where the first floor was run at a set point different from the second floor, resulting in greater number of hours over the 4°F limit.

The basement and bonus room were not included in this analysis. Although the basement is insulated, it has no intentional space conditioning, and also lacks typical distribution losses (ductwork, radiator piping), which contribute to warmer temperatures. The bonus room was typically not finished by the builder, or was left as a tempered semi-finished space; therefore, it was not included in this analysis.

The data are presented in the form of a histogram of the number of hours of a maximum temperature difference (red bars); the cumulative percentage of hours below the 4°F target is shown on the right-hand axis (blue line).

6.1.1 Devens Lot 3

Devens Lot 3 has the largest dataset, spanning multiple years. If the full dataset is graphed (Figure 50), 67% of the hours are under the 4°F difference.

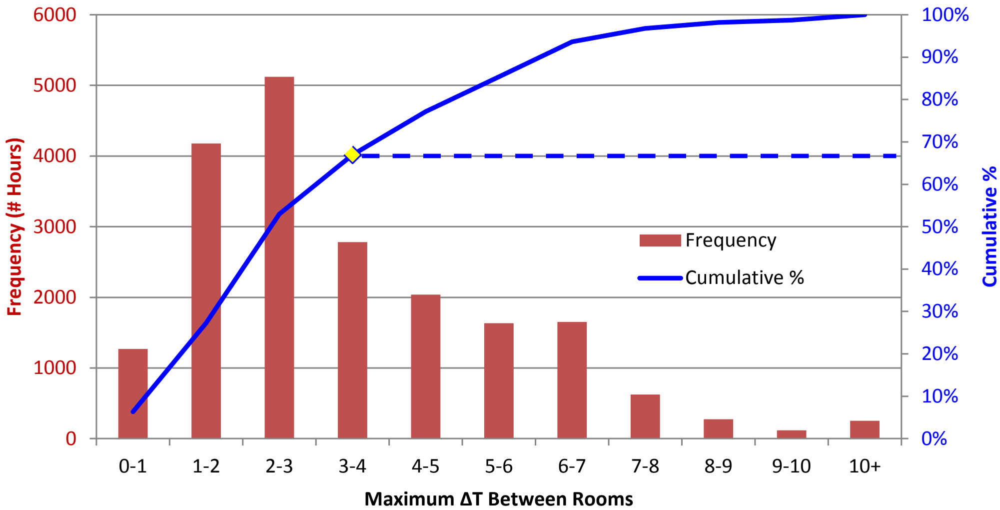


Figure 50.Devens Lot 3 maximum ΔT between rooms, full dataset

However, another way to look at the data is to include only periods when the MSHPs are in operation: it is somewhat unfair to judge the distribution of simplified heating during months when the system is not running. In the winter 2012–2013, based on the electricity consumption logging, the heat pump was in operation from early November through the end of April. With this change, the number of hours below the 4°F difference increases to 73% (Figure 51).

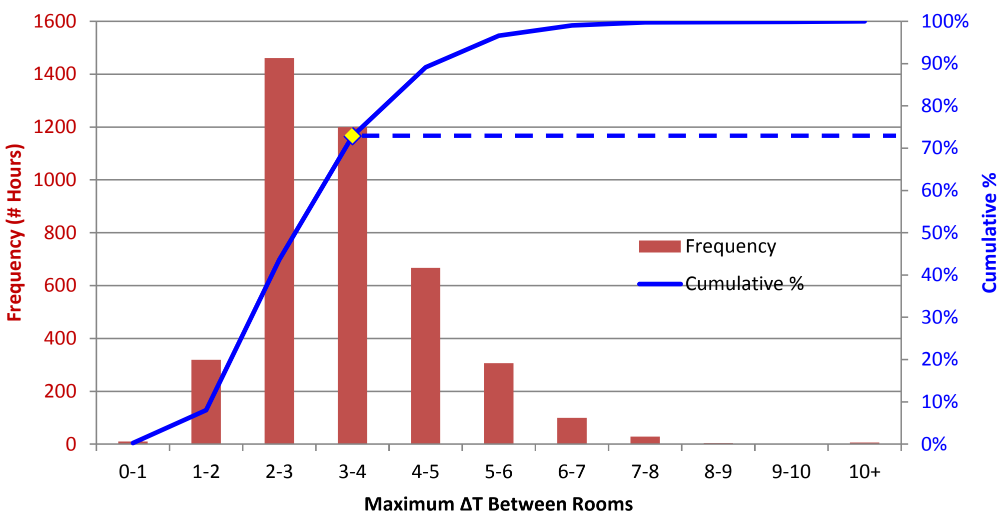


Figure 51. Devens Lot 3 maximum ΔT between rooms, winter 2012–2013 (MSHP in operation)

A similar graph was created for winter 2013–2014 (MSHPs in operation, Figure 52). However, that winter showed much worse performance, with only 19% of hours below the 4°F difference.

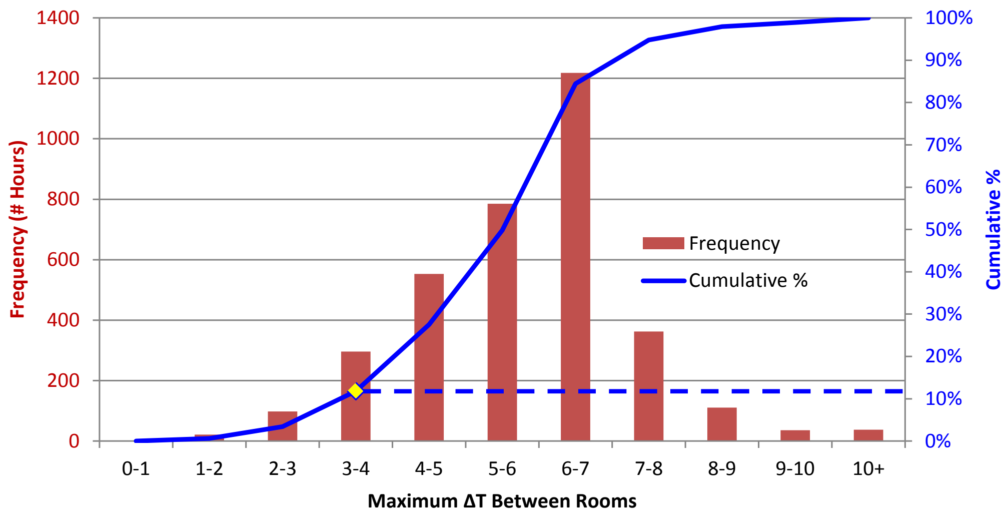


Figure 52. Devens Lot 3 maximum ΔT between rooms, winter 2013–2014 (MSHP running)

When the temperature data are examined more closely, a clear pattern emerges: the hallway (where the MSHP is located) is running noticeably warmer than the bedrooms (Figure 53). The hallway is warmer than typical winter indoor conditions (high 70s/low 80s), but the bedrooms are running at typical set points. Door closure sensors were not installed at this site, so the door status is unknown.

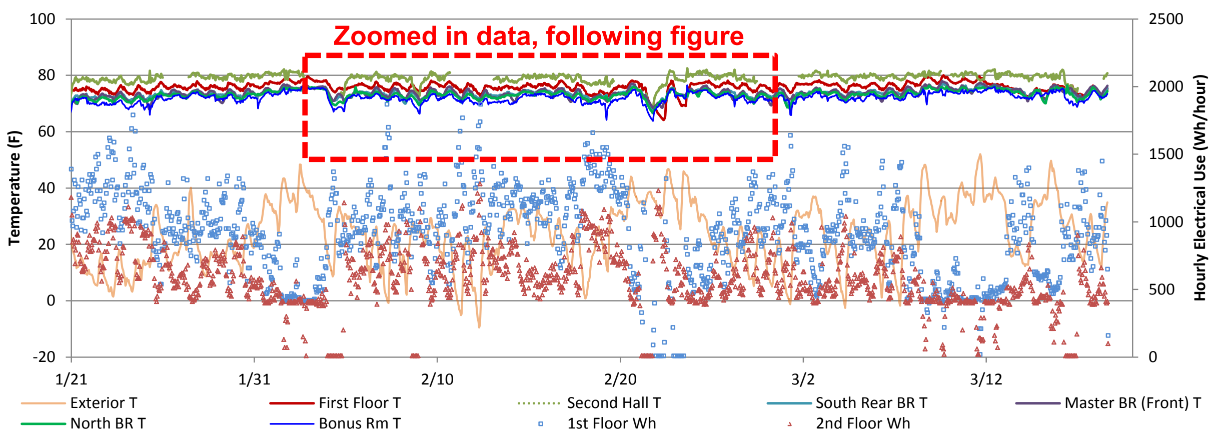


Figure 53. Devens Lot 3 temperatures and MSHP power use, winter 2013–2014

The homeowner, however, did not complain about temperature problems; a closer examination of room temperatures in February 2014 (Figure 54, highlighted in red in Figure 53) shows that the three bedrooms are running in close parallel, with temperatures typically within 1°–2°F. It appears that in essence, the homeowner is using the hallway as a heat distribution plenum, raising the hallway temperature above set point in order to achieve comfort in the bedrooms.

This shows that although the 4°F can be a useful metric, failures do not necessarily indicate comfort problems.

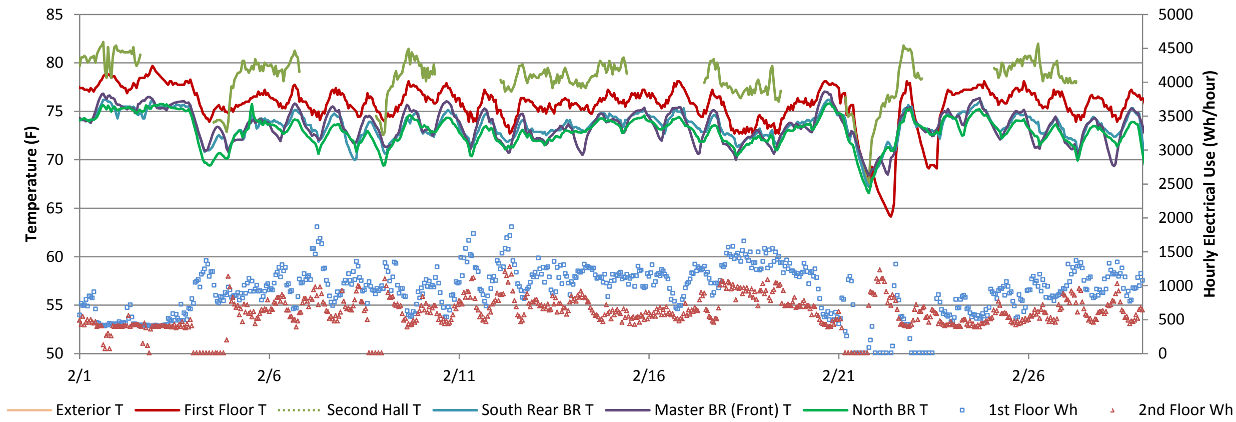


Figure 54. Devens Lot 3 temperatures and MSHP power use, February 2014

The initial winter (2011–2012) was not analyzed here; the basement was uninsulated for a portion of the winter, resulting in colder than normal temperatures on the first floor ("stealing" heat); this was covered in Ueno et al. (2013a).

Another comparison was to examine summer conditions; it was originally theorized that summertime temperature differentials might be greater, given the directionality of solar gain (heating individual orientations), and the rapid heat input rate associated with solar gain through glass. However, when summer 2013 was graphed, for the 2^{+} month period when the MSHP was running (June 25 to September 11), the results show 91% of hours below the 4°F difference (Figure 55). If this time period is expanded (May 1 to October 1), the results improve to 94% of hours.

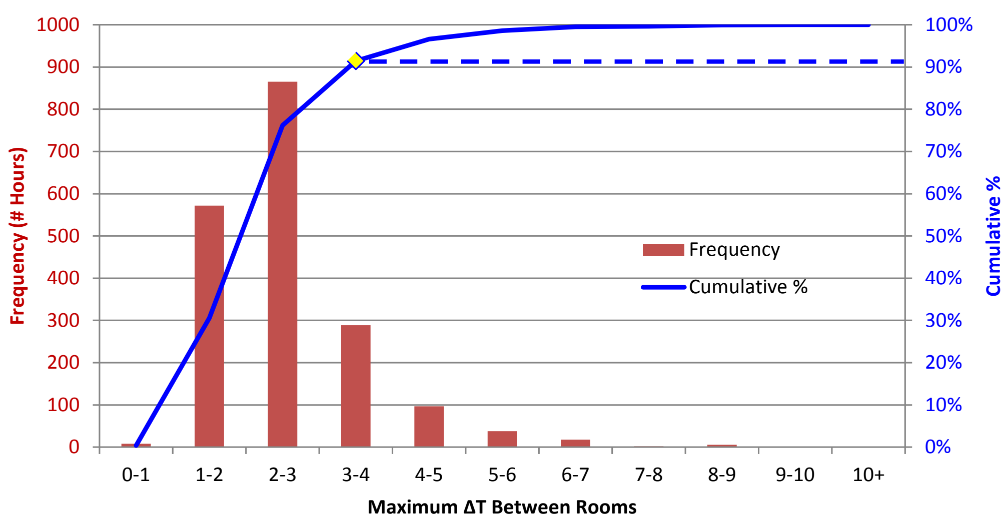


Figure 55. Devens Lot 3 maximum ΔT between rooms, summer 2013 (MSHP running)

This behavior was confirmed by plotting temperature measurements for July 2013 (Figure 56), showing close correspondence between all interior temperatures.

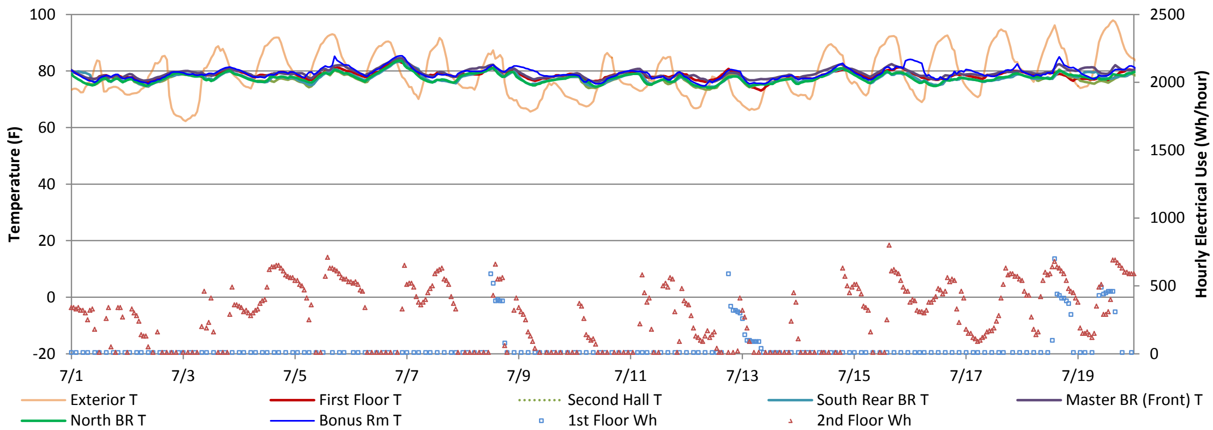


Figure 56. Devens Lot 3 temperatures and MSHP power use, July 2013

Summer 2012 was plotted over the same period (from June 25 to September 11); there was minimal runtime during these months. However, 96% of hours were below the 4°F temperature differential.

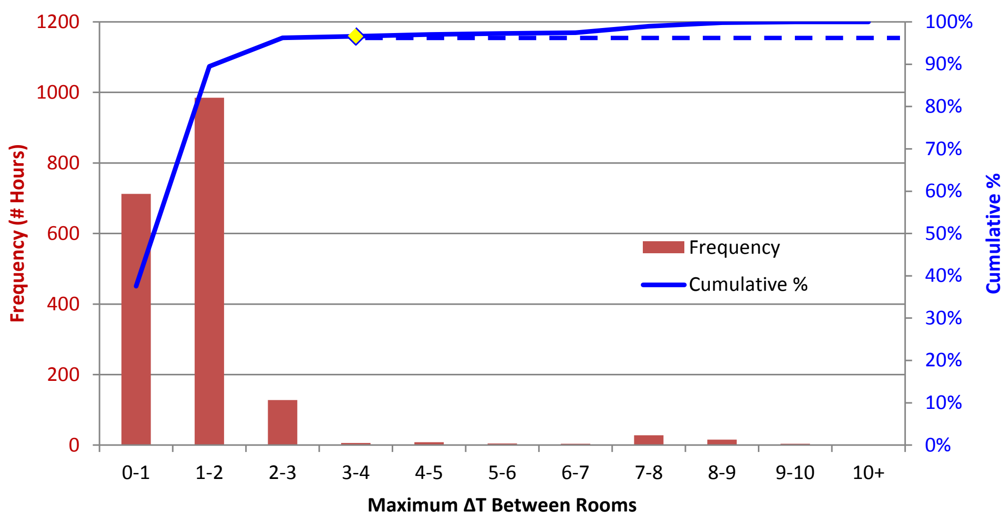


Figure 57. Devens Lot 3 maximum ΔT between rooms, summer 2012

Therefore, it appears that summer conditions are less challenging than winter conditions for simplified distribution, at least given the solar gains (glazing ratios and SHGCs) in these houses. For reference, the triple-glazed windows used here have a relatively low SHGC of 0.17, per the builder's typical practice. This behavior is not very surprising, though, if the indoor-outdoor temperature difference (ΔT) is considered. In this zone 5A climate, ΔTs are much smaller in the cooling season (e.g., 10°–15°F) than the heating season (e.g., 70°F+).

6.1.2 Devens Lots 4, 7, and 8

Devens Lots 4, 7, and 8 were not examined in detail for temperature differences between rooms. Due to data logger failure, measurements were available from July 2013 through November 2013 only, which does not capture cold winter conditions. Wintertime is apparently the greatest challenge for simplified space distribution systems, providing the pass/fail test conditions. However, a cursory analysis was done for Devens Lot 8. When the basement is excluded, 98% of hours have less than 4°F temperature differential; if the basement is included, performance becomes worse, falling to only 77% of hours.

6.1.3 Easthampton Lot 13

At Easthampton Lot 13, 96% of hours were below the 4°F temperature differential. Given these positive results, no further analysis was conducted.

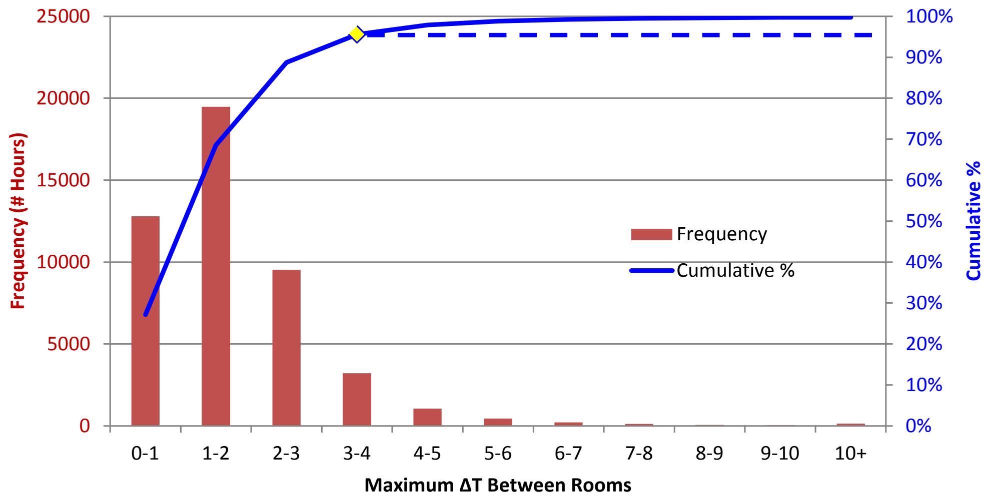


Figure 58. Easthampton Lot 13 maximum ΔT between rooms, full dataset (July 2011–April 2014)

6.1.4 Easthampton Lot 17

At Easthampton Lot 17, 86% of hours were below the 4°F temperature differential (Figure 59); however, this was one of the small houses where a single MSHP unit on the first floor was installed, due to meeting the design heating load. No MSHP unit was installed on the second floor, resulting in comfort complaints during summer cooling season; this issue is covered in more detail in a section below.

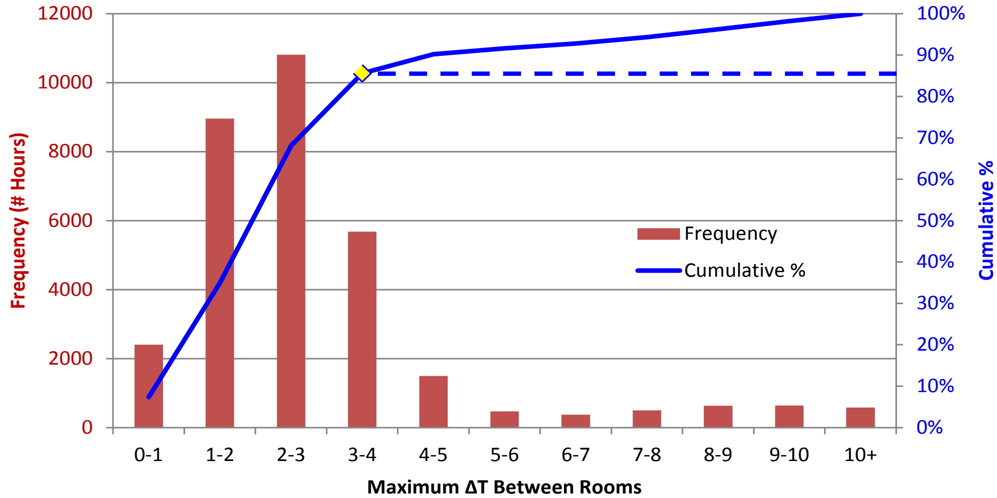


Figure 59. Easthampton Lot 17 maximum ΔT between rooms, full dataset (May 2012–March 2014)

A second MSHP head was installed upstairs in August 2012. Analysis of the data after the retrofit shows 95% of hours under the 4°F difference (Figure 60).

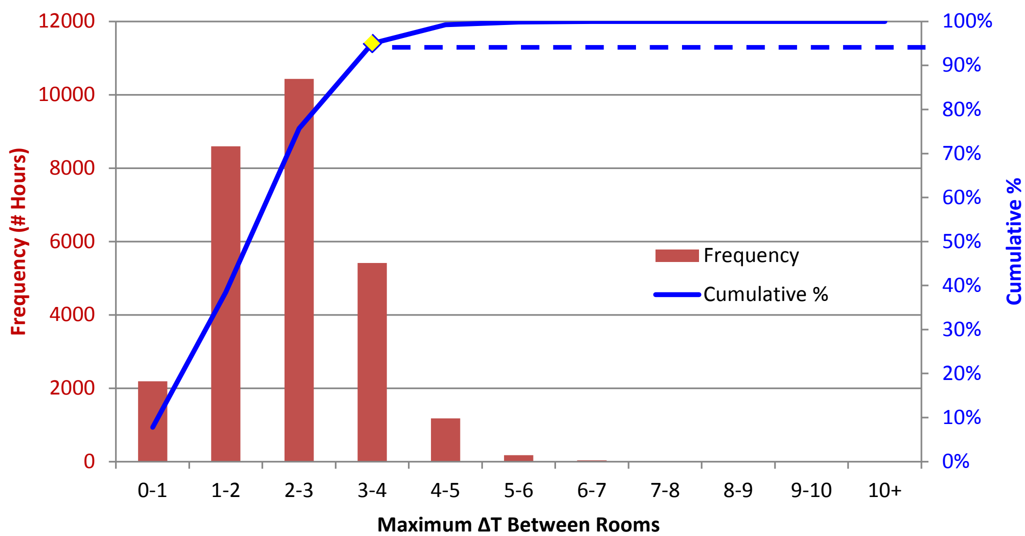


Figure 60. Easthampton Lot 17 maximum ΔT between rooms, post second MSHP retrofit (August 2012–March 2014)

6.1.5 Easthampton Lot 23

Easthampton Lot 23 was another house that originally had a single MSHP on the first floor, with the second-floor unit later retrofitted. However, this house had worse results: 75% of hours below 4°F differential (full dataset; Figure 60), and 82% of hours below 4°F differential (post-retrofit; Figure 61).

The reason for the poorer performance at this house was the use of temperature setbacks, or on-off operation of the MSHP. This is discussed in more detail in Section 6.7, "Temperature Setbacks (On/Off Operation)."

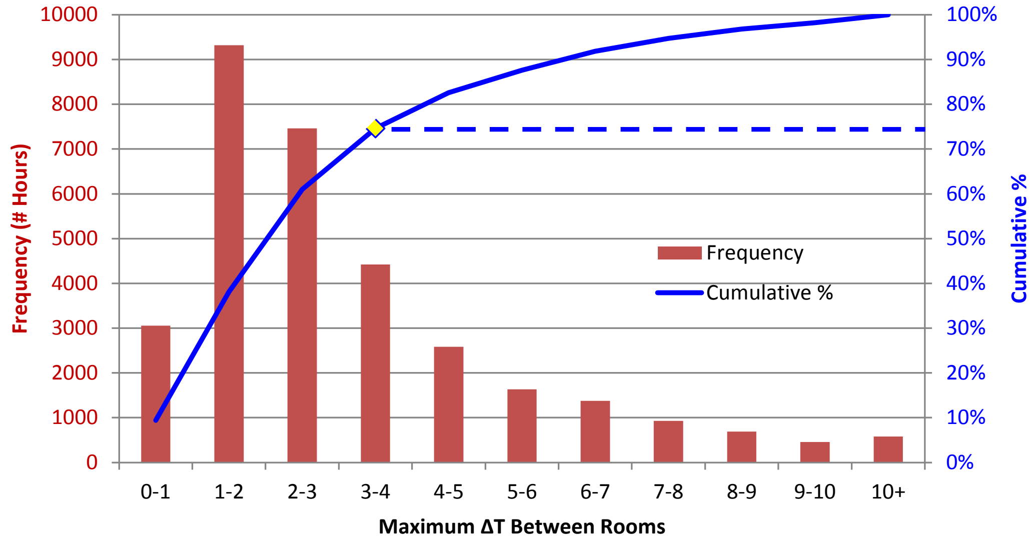


Figure 61. Easthampton Lot 23 maximum ΔT between rooms, full dataset (May 2012–March 2014)

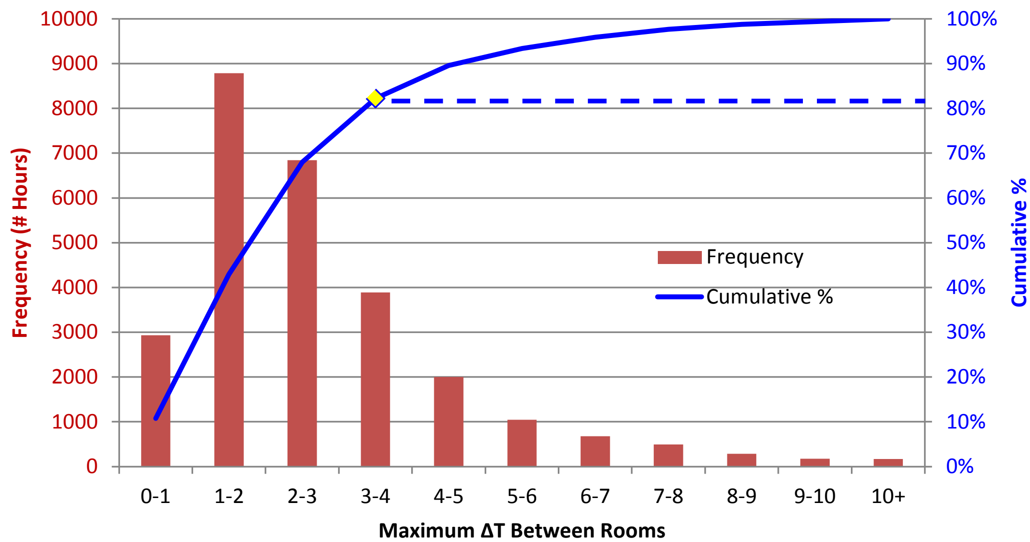


Figure 62. Easthampton Lot 23 maximum ΔT between rooms, post second MSHP retrofit (August 2012–March 2014)

6.1.6 Easthampton Lot 30

Easthampton Lot 30 was a house that was monitored following reports of comfort complaints in this house. A limited period of time was monitored after the complaint, but before a retrofit was carried out. The retrofit was to install MSHP heads in every bedroom, which essentially provides zoning for each room (see Section 3.4, “Experience with Multihead Systems”). Therefore, this house was not analyzed in this manner. The analysis of the comfort complaint issues is covered in Section 6.6, “Bonus Room Comfort Issues at Easthampton”.

6.1.7 Summary

Many histograms of temperature distributions were shown above; a summary of the results is provided in Table 22 below.

Table 22. Percent Hours Below 4°F Temperature Differential, Devens and Easthampton Houses

Location	Lot	Square Feet	% Under 4°F	Sub-Case
Devens	3		67%	Full dataset; bonus room omitted
			73%	Winter 2012–2013, MSHP on
			19%	Winter 2013–2014, MSHP on
			91%	Summer 2013
			96%	Summer 2012
Devens	4	3144	–	Not analyzed (no winter data)
Devens	7	4352	–	Not analyzed (no winter data)
Devens	8	2877	–	Not analyzed (no winter data)
Easthampton	13	1795	96%	Full dataset
Easthampton	17	1348	86%	Full dataset
			95%	After 2nd MSHP retrofitted
Easthampton	23*	1620	75%	Full dataset
			82%	After 2nd MSHP retrofitted
Easthampton	30	2151	–	Not analyzed (1 head per bedroom)

* On-off operation, not steady set point operation

6.2 Occupied Versus Unoccupied Conditions

Devens Lot 3 provided an opportunity to compare performance of an unoccupied house heated with simplified space conditioning systems, versus an occupied house (which will have opening and closing of doors, and possibly set point changes). Lot 3 was unoccupied for its first winter, before it was sold and occupied by a family of four. Figure 63 shows interior temperatures for the first, unoccupied winter (2011–2012).

The three upstairs bedrooms run at almost identical temperatures (within 1°–2°F); the hallway is slightly warmer. This is expected, given that it is the location of the upstairs MSHP.

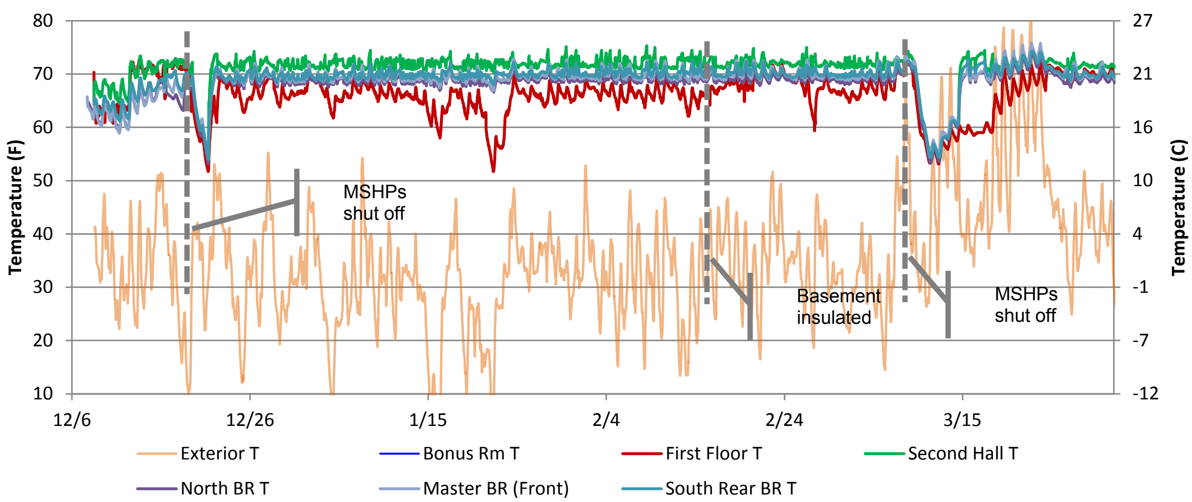


Figure 63. Devens Lot 3 unoccupied winter 2011–2012 data

The first floor runs noticeably cooler than the upstairs rooms at first: this was due to the uninsulated basement; the cold basement effectively “stole” heat from the first floor, via the uninsulated framed floor. There were also several cases where the MSHPs were turned off; interior temperatures decayed/dropped in parallel.

The data can also be presented as a scatter plot, graphing bedroom temperatures against the hallway temperature (Figure 64). The blue dashed line indicates 1:1 correlation; orange and light blue dashed lines indicate a temperature difference of +4°F and –4°F, respectively. The majority of the measurements show temperatures within the 4°F range. The data also include the March 2012 MSHP shutdown, showing all temperatures dropping into the 55°F range; they omit the December 2011 MSHP shutdown.

The house was occupied during the second winter (2012–2013); looking at the temperature plots (Figure 65), there is arguably more variation (likely due to door closures). The occupants reported maintaining a constant set point, which is consistent with the steady temperatures seen in the second-floor hallway.

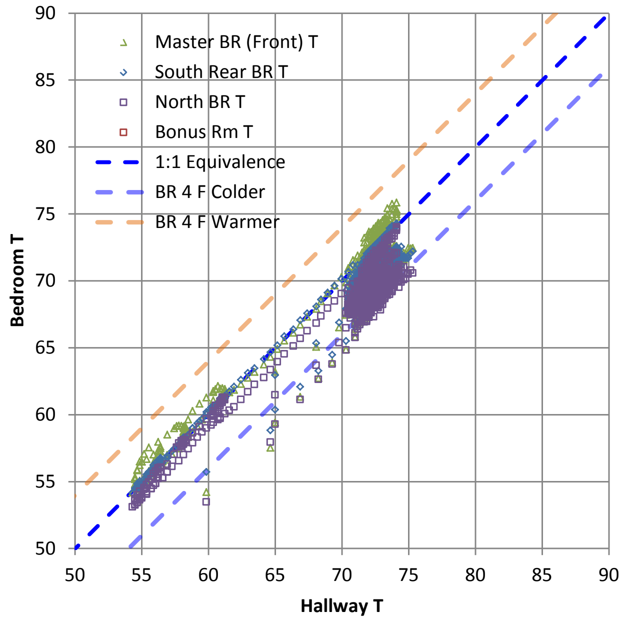


Figure 64. Devens Lot 3 bedroom versus hallway temperature correlation, December 21 through April 1 (unoccupied)

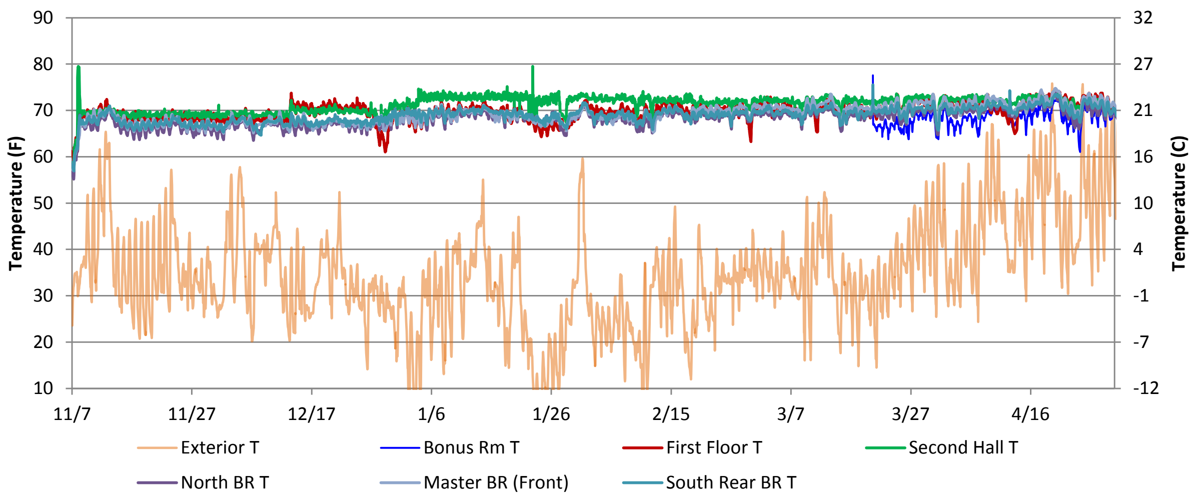


Figure 65. Devens Lot 3 occupied winter 2012–2013 data

The increased variation in temperature is shown in the hallway versus bedroom temperature plot (Figure 66), which shows greater numbers of hours with a greater than 4°F temperature difference. However, the majority of the data are still within 4°F of hallway temperature.

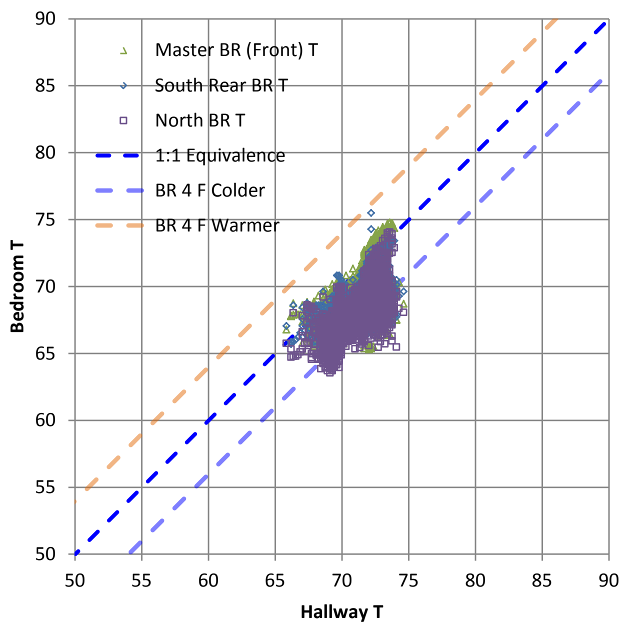


Figure 66. Devens Lot 3 bedroom versus hallway temperature correlation, winter 2012–2013 (occupied)

In the most recent winter (2013–2014), the hallway was set at an elevated temperature (Figure 67): the temperature was likely raised to achieve comfort conditions in the bedroom. It is unknown what difference in operating conditions occurred between this and the previous winter. However, even though there is a large temperature difference between the hall (high 80s typical) and the bedrooms (68°–75°F typical), the bedrooms would still be considered within the typical comfort range. When asked, the homeowner had no complaints about comfort conditions, and did not describe a change in behavior during this winter (versus the previous winter). The hallway-to-bedroom temperature relationship is also apparent in the scatter graph (Figure 68).

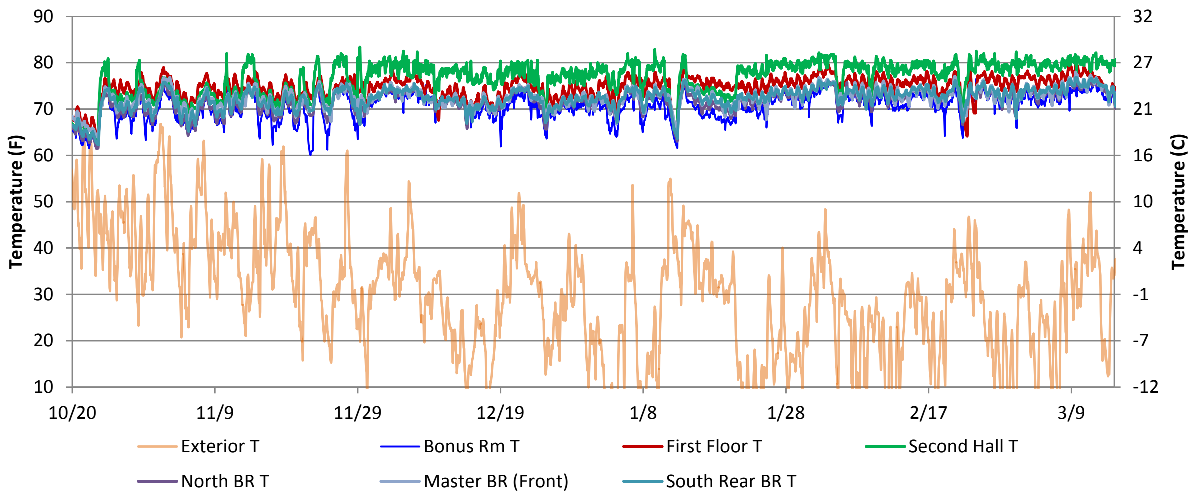


Figure 67. Devens Lot 3 occupied winter 2013–2014 data

The bonus room is noticeably colder, but this is not surprising, given that it is over the garage, and has no space conditioning system.

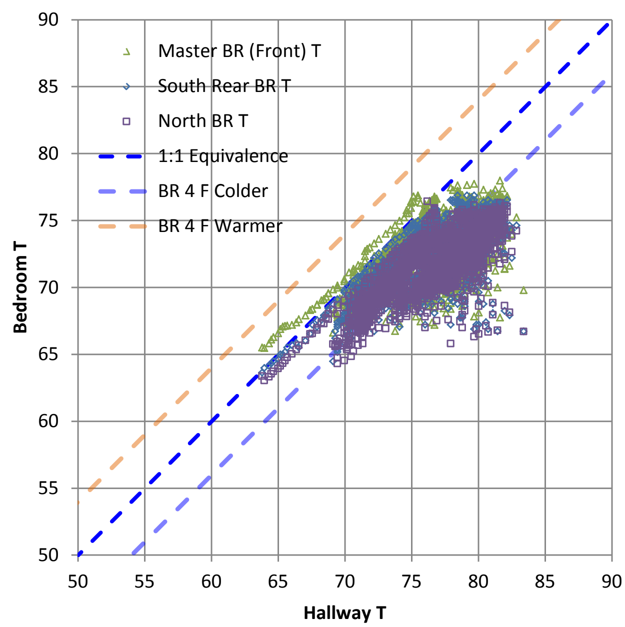


Figure 68. Devens Lot 3 bedroom versus hallway temperature correlation, winter 2013–2014 (occupied)

Overall, this analysis appears to indicate that more even temperatures occur during unoccupied conditions, which is unsurprising, as door closure will tend to increase temperature differences.

Previous analysis of temperature differences indicate that the cooling season is less challenging for simplified distribution, compared to the heating season. This is also apparent in the plots of temperatures (Figure 69) and the scatter plot (Figure 70). The homeowners maintained a relatively high set point throughout the summer, likely due to occupant preferences. The majority of the MSHP runtime was for the second-floor unit, which is consistent with thermal buoyancy issues discussed below.

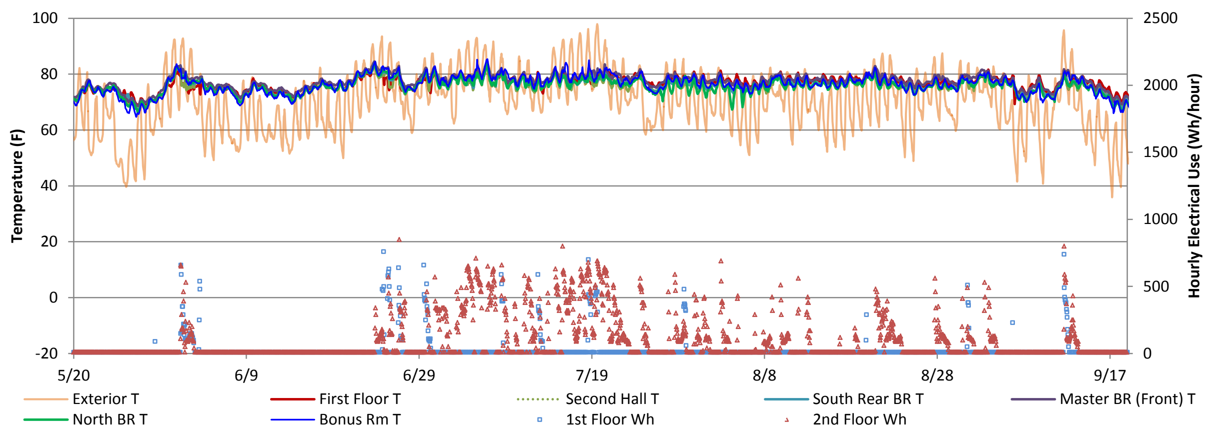


Figure 69. Devens Lot 3 summer 2013 temperature data with MSHP wattage

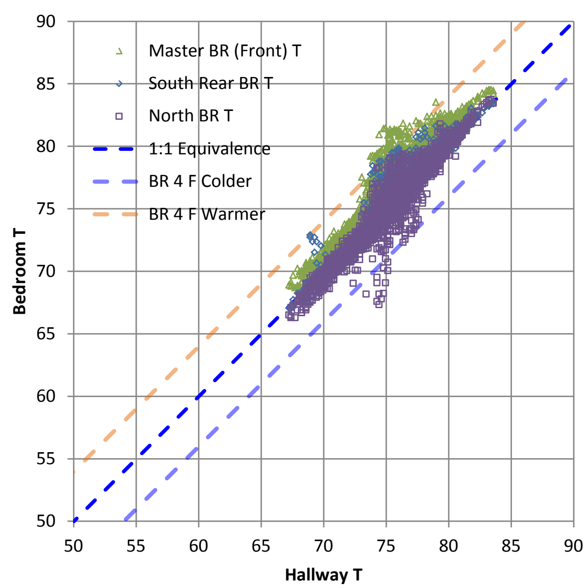


Figure 70. Devens Lot 3 occupied summer 2013 bedroom versus hallway temperature correlation

6.3 Door Operation Effects on Bedroom Temperatures

Door closure sensors were installed in six of the eight houses: this measurement is examined more closely here. The monitored houses are shown in Table 23.

In previous work (Ueno et al. 2013), scatter plots (bedroom temperature versus hallway temperature) were used to demonstrate that bedrooms during closed-door hours had greater differences between hallway and bedroom, compared to open-door hours.

Table 23. Summary of Monitoring Packages, Availability of Door Sensors

Location	Stories-ft^2	T/RH	Doors	MSHP
Devens Lot 3	2-1728	●		●
Easthampton Lot 13	2-1728	●		●
Easthampton Lot 17	2-1239	●	○	○
Easthampton Lot 23	2-1132	●	○	○
Easthampton Lot 30	2-2266	●	●	
Devens Lot 4	2-1728	○	●	●
Devens Lot 7	2-1952	○	●	●
Devens Lot 8	1-1524	○	●	●

● = full dataset; ○ = partial dataset

Easthampton Lot 17 and 23 do not have a complete dataset; the door sensors were not functional due to an installation error until halfway through the monitoring period. Useful data were collected for 1 year, though (February 2013–March 2014). Easthampton Lot 30 was the comfort complaint house, and is covered in detail in a later section.

Devens Lots 4, 7, and 8 have a full door closure dataset, but lack interior temperature information for the winter, when temperature differences are exacerbated. Therefore, they were not examined in detail.

Interior temperatures and door status are plotted for Easthampton Lot 17 in Figure 71. Hours where the bedroom door is closed for more than 50% of the hour are denoted by markers plotted on the right hand axis.

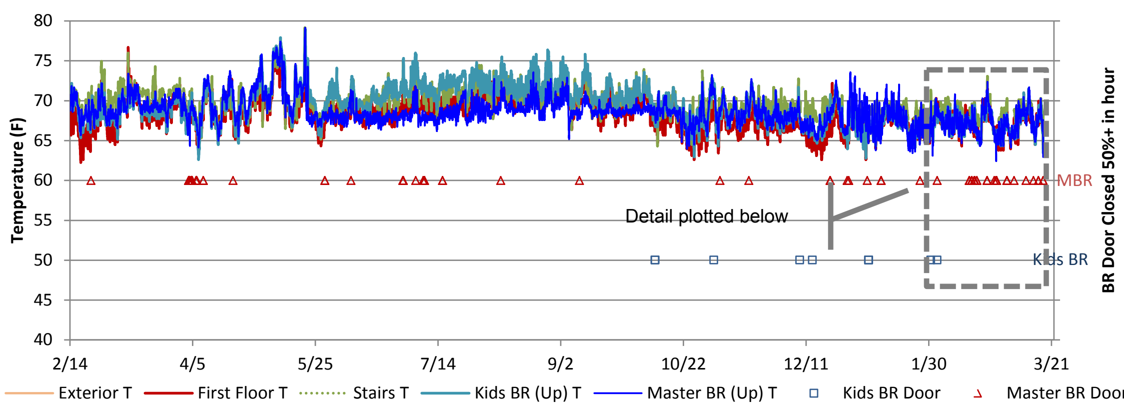


Figure 71. Easthampton Lot 17 interior temperatures and door closures

However, 1 year of data is difficult to interpret, so 1.5 months in winter 2014 are plotted in Figure 72. This close-up of the data shows that the master bedroom door was closed for limited periods (typically 1–3 hours at a time). It is uncertain, though, whether this reflects actual operation or instrumentation limitations. Given these limited hours of door closure, though, minimal temperature differences are expected, which match the temperatures plotted below.

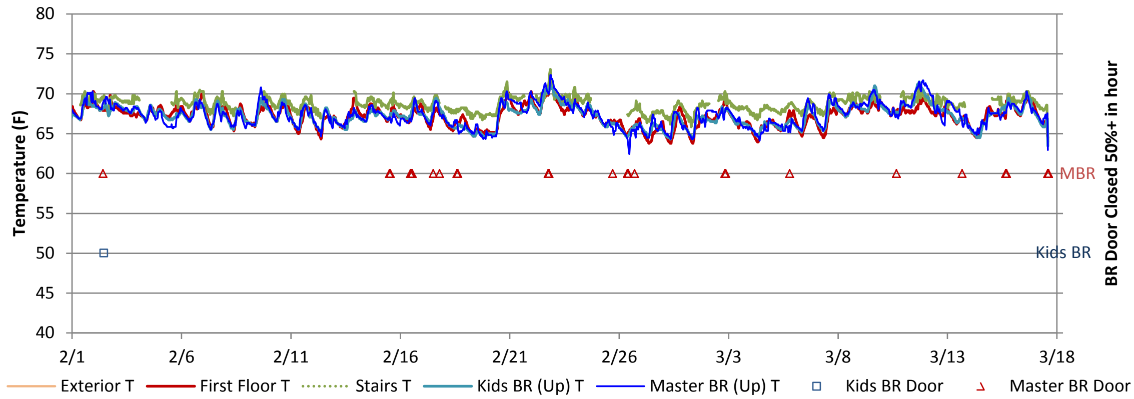


Figure 72. Easthampton Lot 17 interior temperatures and door closures, February–March 2014

A similar plot was generated for Easthampton Lot 23; there are two monitored bedrooms: a first-floor bedroom, and the second-floor master bedroom (which comprises most of the second floor). The second-floor bedroom has its own MSHP unit, so door open-closed status is of minimal interest, as it does not rely on an open door to transfer space conditioning. Therefore, the first-floor bedroom is of greatest interest.

Unfortunately, the homeowner used deep temperature setbacks, and ran the MSHP in an on-off manner, resulting in the wide temperature variations (cycling between 60°–75°F often) seen in Figure 73. The first-floor bedroom door was typically closed for brief periods (1–5 hours). The combination of these factors resulted in few useful data for correlating door status and temperature behavior.

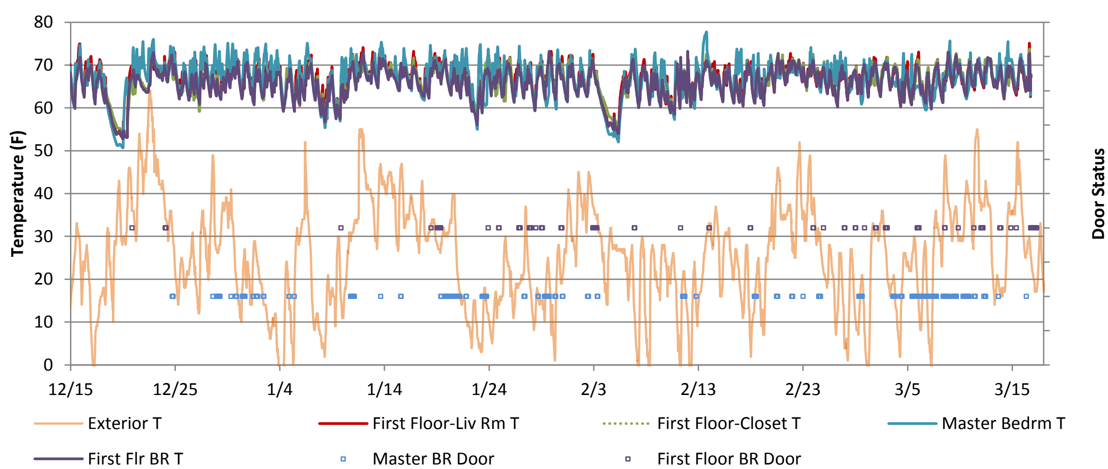
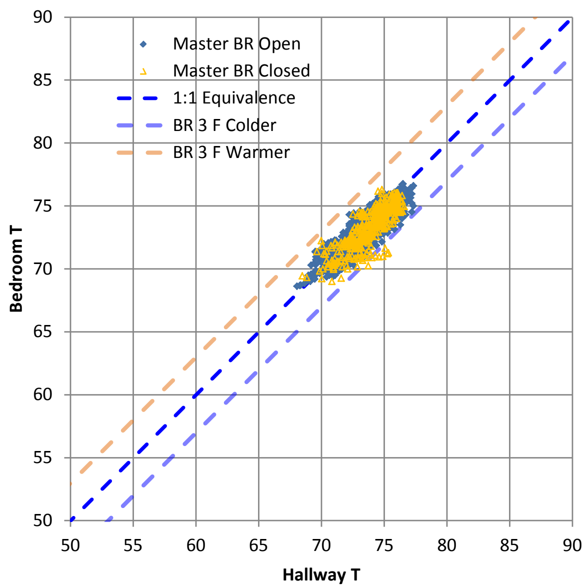


Figure 73. Easthampton Lot 23 interior temperatures and door closures, December 2013–March 2014

As mentioned above, Devens Lots 4, 7, and 8 do not have wintertime bedroom temperature data (which end in early December), so they are of limited use. Devens Lot 8 results are plotted below (Figure 74): the master bedroom shows tight correlation, but there is an MSHP unit in the MBR suite. In the front bedroom, the closed door hours have slightly higher differences from the hallway temperature, but the sets mostly overlap.



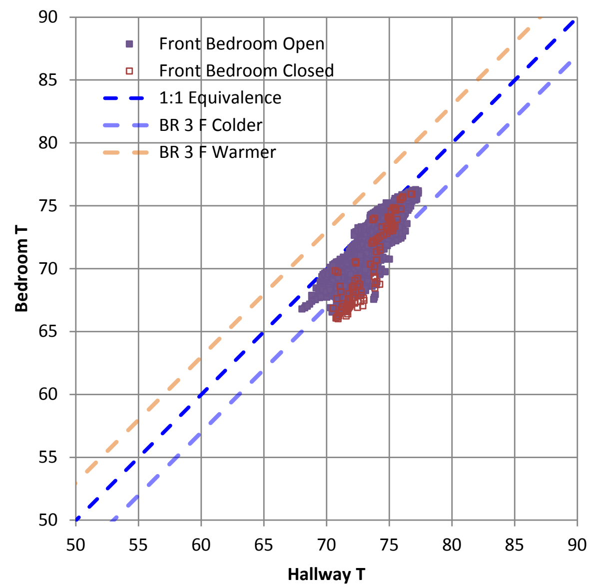
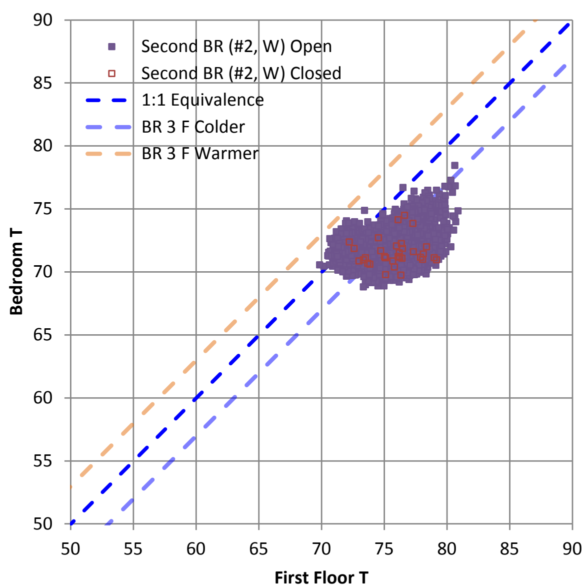


Figure 74. Devens Lot 8 master bedroom (L) and front bedroom (R) temperatures versus hallway

The results for the upstairs bedrooms (#2 and #3) at Devens Lot 7 are shown in Figure 75; bedroom temperatures are plotted against first-floor temperatures, as no hallway temperature was recorded. The door open/closed status appears to have minimal effect, for the non-winter conditions measured.



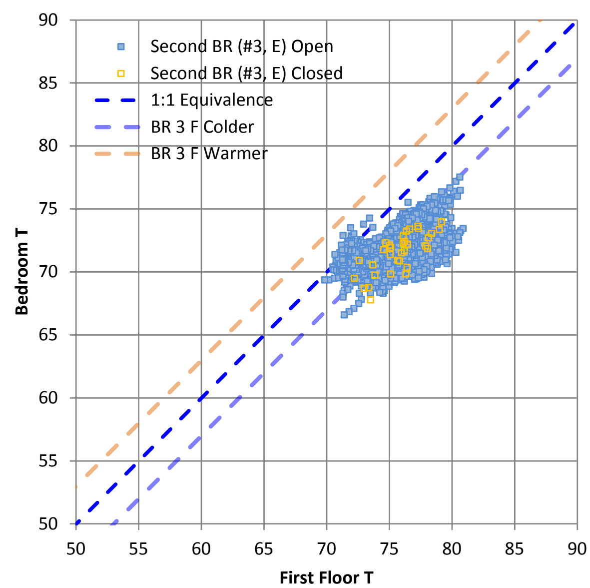


Figure 75. Devens Lot 7 bedroom 2/west (L) and bedroom 3/east (R) temperatures versus first floor

6.4 Thermal Buoyancy Effects (Use of Single Mini-Split Heat Pump on First Floor)

Two houses at Easthampton provide a valuable lesson on the effect of thermal buoyancy on temperature distributions. The two plans were relatively small (1239 and 1132 ft^2), two-story, slab-on-grade houses (Figure 76). Design heating load calculations indicated that they could be heated with a single 12 kBtu/h MSHP head, even at winter design temperatures (Table 11).

Figure 76. Easthampton Lots 17 Small Saltbox (L) and 23 Cottage (R)

As further motivation, the builder had noted over time that the second-floor unit often stays off for most of the winter, with most of the heating provided by the first-floor unit. This is reasonable (thermal buoyancy will drive warm air to the upper floor), and is consistent with observations of Harley (2014) and Rosenbaum (2014a). It was also observed in several cases in the monitored data collected here.

Table 24. Heating and Cooling Design Loads for Devens and Easthampton Houses

Location	Lot	Model	Above Grade Square Feet	Design Loads	
				Heating kBtu/h	Cooling kBtu/h
Devens	3	Victorian	1728	16.8	9.6
Devens	4	Farmhouse	1728	16.3	9.7
Devens	7	Custom Saltbox	1952	18.2	10.6
Devens	8	Ranch	1524	13.0	6.7
Easthampton	13	Farmhouse	1728	12.1	8.7
Easthampton	*17*	*Small Saltbox*	*1239*	*11.0*	*7.3*
Easthampton	*23*	*Cottage*	*1132*	*10.0*	*7.0*
Easthampton	30	Custom Home	2266	27.3	11.3

However, during the first summer of operation, the homeowners reported that the second floor was not cooling down to set point; temperature data (Figure 77 and Figure 78) clearly show this pattern, with upstairs temperatures reaching into the 80°F range, while downstairs set points were closer to 70°F.

In Lot 17, the upstairs bedrooms are "Master BR (Up)" and "Kids BR (Up); their temperatures track identically. The temperature in the stairwell ("Stairs T") tracks between the first floor and upstairs. Although a second MSHP was installed, monitoring equipment was not installed until a later site visit.

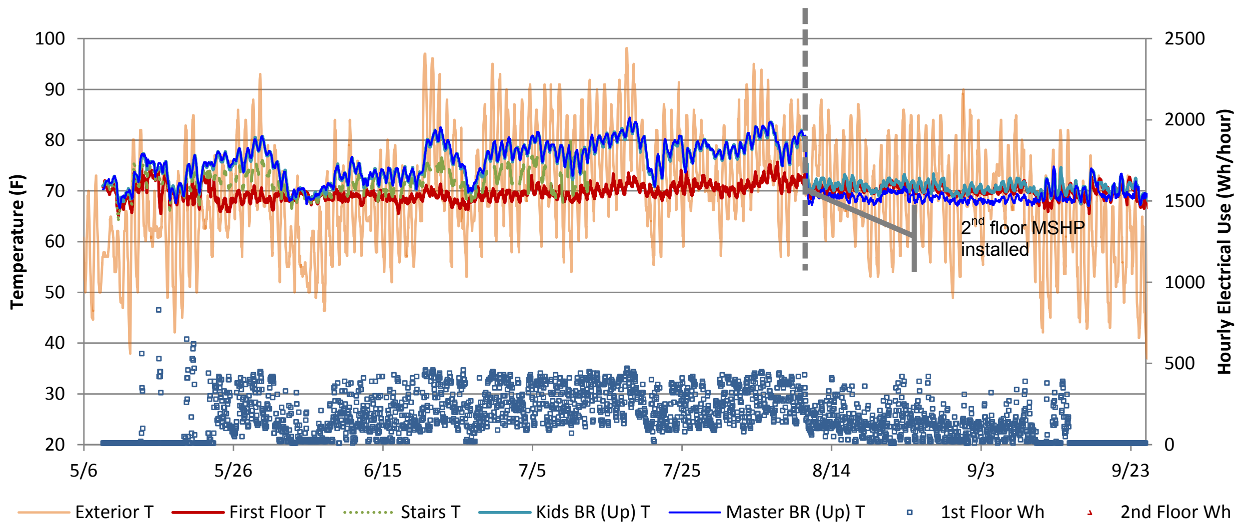


Figure 77. Summer 2012 interior and exterior temperatures at Lot 17, pre- and post-retrofit

These problems continued in Lot 17 despite the presence of a mixing/redistribution fan (40 CFM exhaust fan pulling from the main space, distributing to the bedrooms). The redistribution fan's damper configuration was changed to shift all air to the upstairs master bedroom; this was not sufficient to maintain set point.

In Lot 23, "Master Bedroom" is upstairs; all other temperatures were downstairs. A 40 CFM redistribution fan was also present in this house, split between two bedrooms.

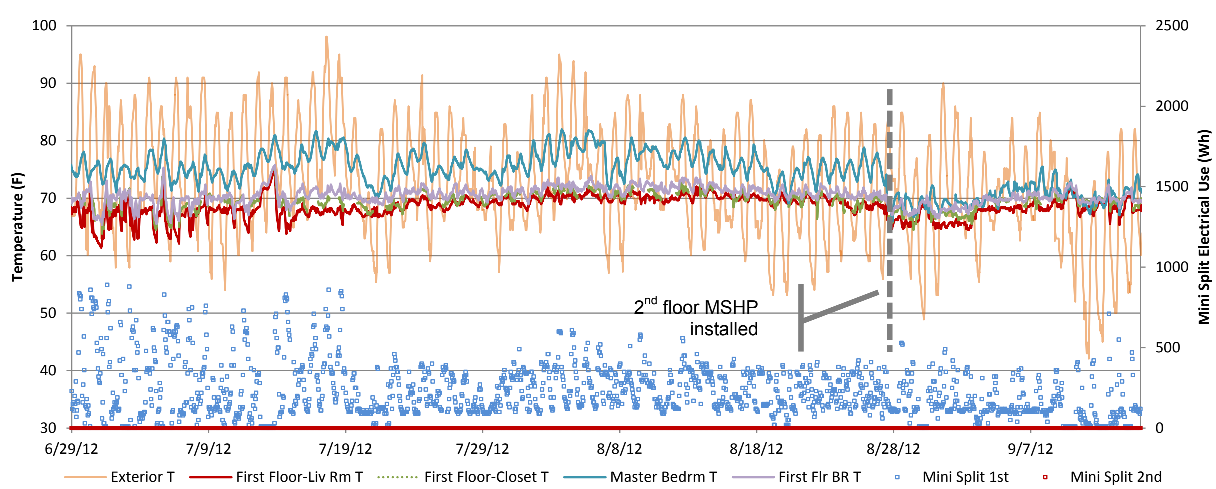


Figure 78. Summer 2012 interior and exterior temperatures at Lot 23, pre- and post-retrofit

Therefore, the builder chose to retrofit a second MSHP unit to the second floor to address cooling issues; the drastic effect is apparent in August, as second-floor temperatures drop to the first-floor set point. Line sets were retrofitted on either the exterior (with a line set hide) or inside the garage (Figure 79).

Figure 79. Retrofitted unit and line set for second-floor MSHP on exterior (L), and in garage (R)

At Lot 17, the second MSHP was installed in the master bedroom; the "Kids BR" tracks in parallel but slightly warmer (Figure 77).

This thermal buoyancy problem has been experienced by other practitioners as well, with similar recommendations for solving the problem (Rosenbaum 2014b).

6.5 Open Plan First-Floor Temperature Distributions

The problem of temperature distribution has primarily been focused on rooms with closed doors, typically bedrooms. In general, the first floors of these houses have had open floor plans, with few reported issues of temperature differences (see occupant surveys in Ueno et al. 2013a).

Therefore, temperature distributions on the first floor were not the focus of the monitoring. The few houses with multiple measurements in the open first-floor plan (Easthampton Lot 23, Devens Lot 4) show minimal differences (1°–2°F typical).

However, there were some exceptions that are worth reporting. The homeowners at Easthampton Lot 17 noted that despite keeping the first-floor bedroom door open, it did not receive sufficient space conditioning, even with the operation of the distribution fan. The homeowners theorized that the open stairwell to the second floor "robbed" heat coming from the MSHP in the winter, intercepting it (via thermal buoyancy) before it could reach the first-floor bedroom (conceptual sketch in Figure 80; photos of stairs and living/dining room in Figure 81).

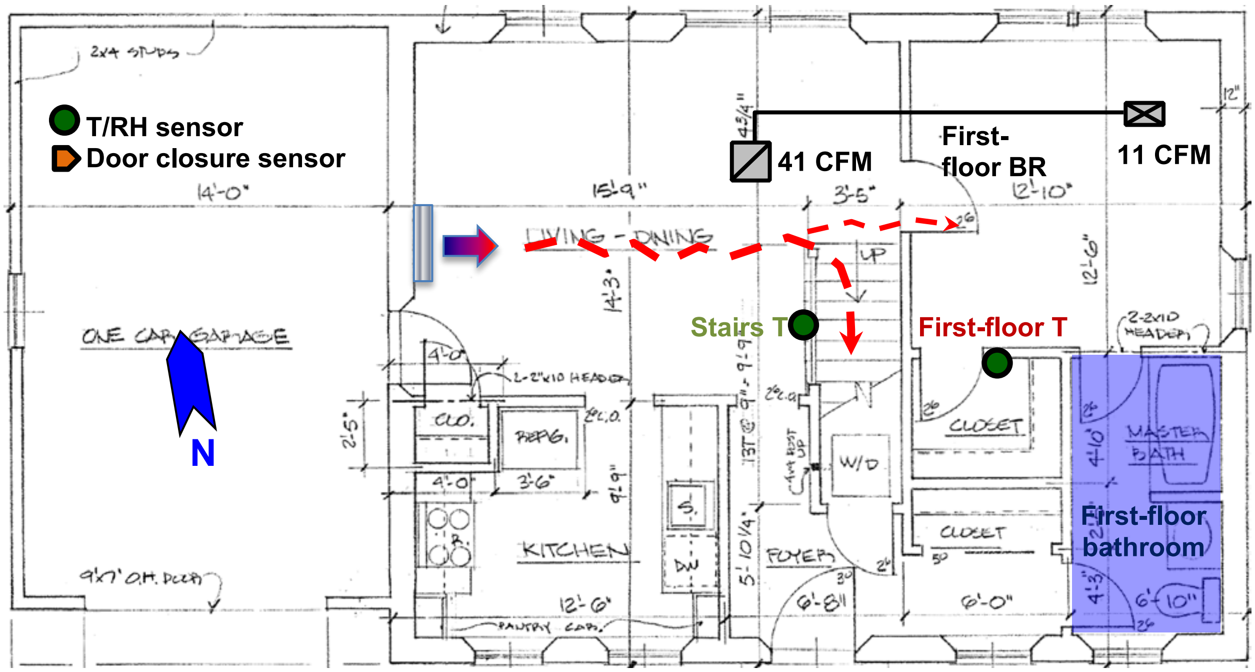


Figure 80. Easthampton Lot 17 first-floor plan, mini split locations, monitoring locations

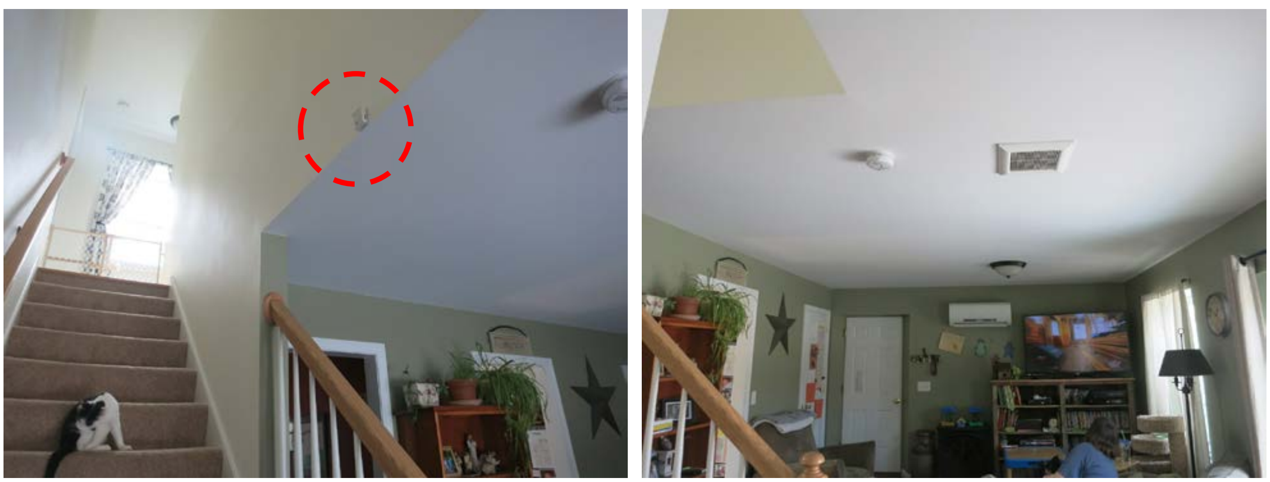


Figure 81. Easthampton Lot 17, view from base of stairs at first floor, stairwell temperature sensor highlighted

The wintertime monitoring data (February–March 2014, Figure 82) show that the first-floor bedroom ("First-Floor T) has temperatures consistent with the upstairs bedrooms. However, the stairwell ("Stairs T") definitely shows consistently warmer temperatures than the room, consistent with the homeowner's theory. Walking from the stairs into the first-floor bedroom would be perceived as a drop in temperature.

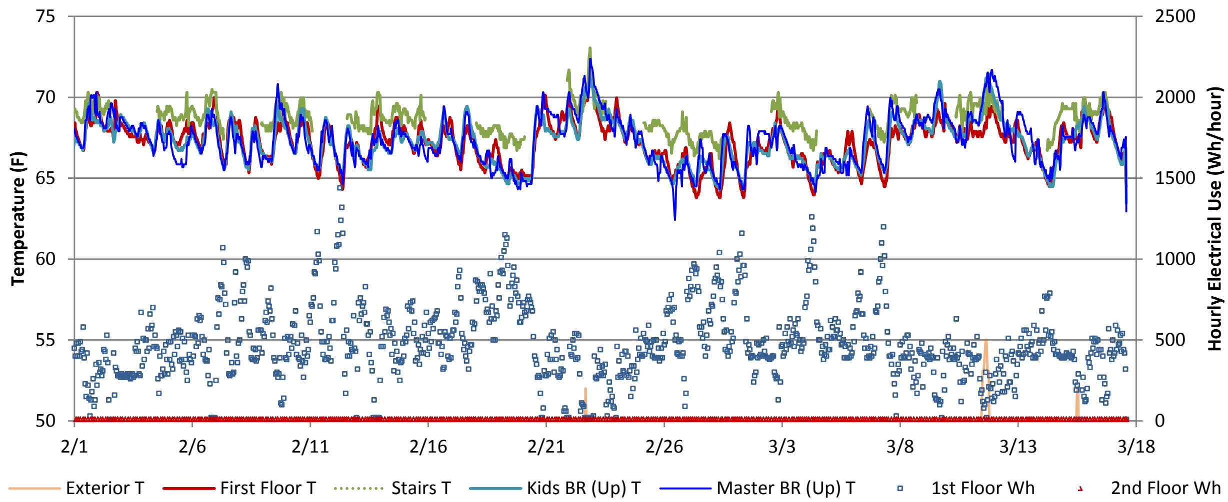
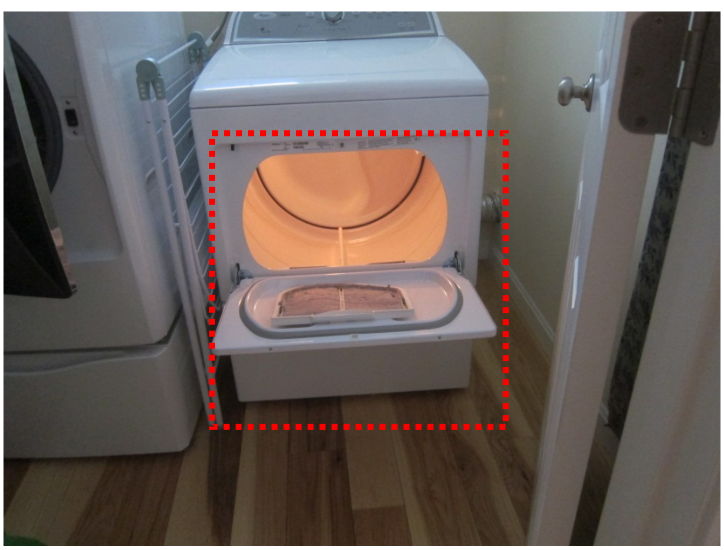


Figure 82. Easthampton Lot 23 interior temperatures and MSHP energy use

In addition, the homeowner noted that the first-floor bathroom was noticeably cold during the coldest wintertime conditions (Figure 80). This is consistent with the geometry of the room (two exterior walls) and the location of the room (furthest location from MSHP).

Another first-floor complaint was at the comfort complaint house (Easthampton Lot 30) covered in more detail below. The homeowners had no issues with first-floor temperatures, except at the laundry room, at the rear corner of the house (Figure 84). They found that with the laundry room door closed, the laundry room would fall to 45°F in the coldest winter conditions. They theorized that this was due to air leakage at the dryer.



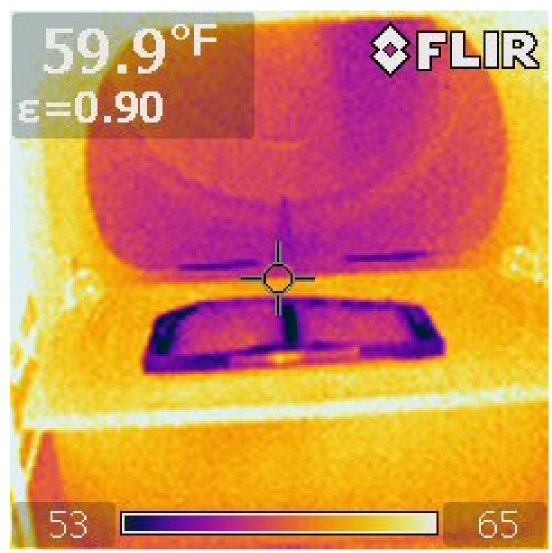


Figure 83. Easthampton Lot 30, air leakage at dryer filter slot

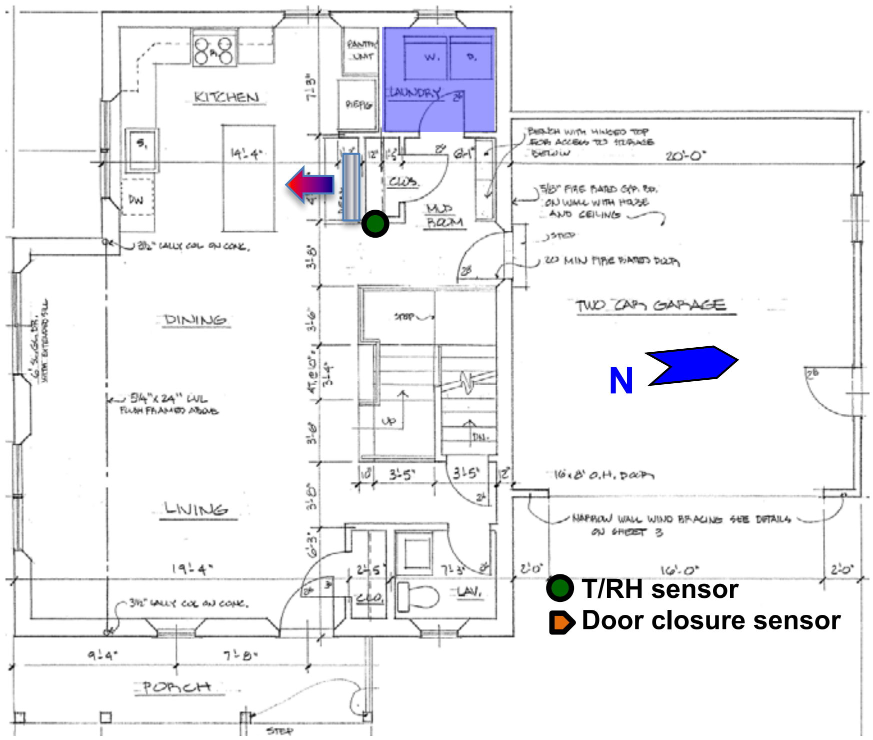


Figure 84. Easthampton Lot 30 floor plans, MSHP locations, monitoring locations

Site observation with an infrared camera and blower door indicated that there was air leakage associated with the dryer duct penetration and the dryer filter slot (Figure 83). It is interesting to note that the first-floor lavatory, despite also having two exposed walls, did not experience similar issues. The recommendation was to add a better sealing dryer vent, and to address any air leakage around the duct.

Overall, one lesson for design is to be aware of the path that the air from the MSHP will take, keeping thermal buoyancy effects in mind. Also, relatively minor localized air leakage can have a more significant effect when using simplified/single point heating.

6.6 Bonus Room Comfort Issues at Easthampton

Another instructive experience was a set of comfort complaints at Lot 30 in Easthampton (Figure 85), in the winter of 2012–2013. The homeowners complained of uneven temperatures in the bedrooms and bonus room over the garage (floor plan shown in Figure 86):

- The front bedroom suite (bedroom 2) stays the warmest/closest to set point; the homeowner ascribed this to placement in line with the MSHP's airflow. The doors to this bedroom suite were normally kept closed, in an effort to try to "push" more heat to the other rooms.
- The rear bedroom suite (master bedroom) is colder than the front bedroom; the homeowner reported that typical cold weather conditions are 5°F colder than the front bedroom with the door open, and 12°F colder with the door closed. This is especially noticeable at the portions near the walk-in closet and bathroom.

- The bonus room/bedroom over the garage (bedroom 3) was much colder, hitting worst-case temperatures in the 50°F range during main space 68°F conditions. If the garage door is accidentally left open, the temperatures in the bonus room are noticeably colder.

The homeowners confirmed that they maintained a constant 68°F set point; they also noted that leaving bedroom doors open for extended periods is not necessarily compatible with their lifestyle and schedule.

Figure 85. Easthampton Lot 30 front and south side views

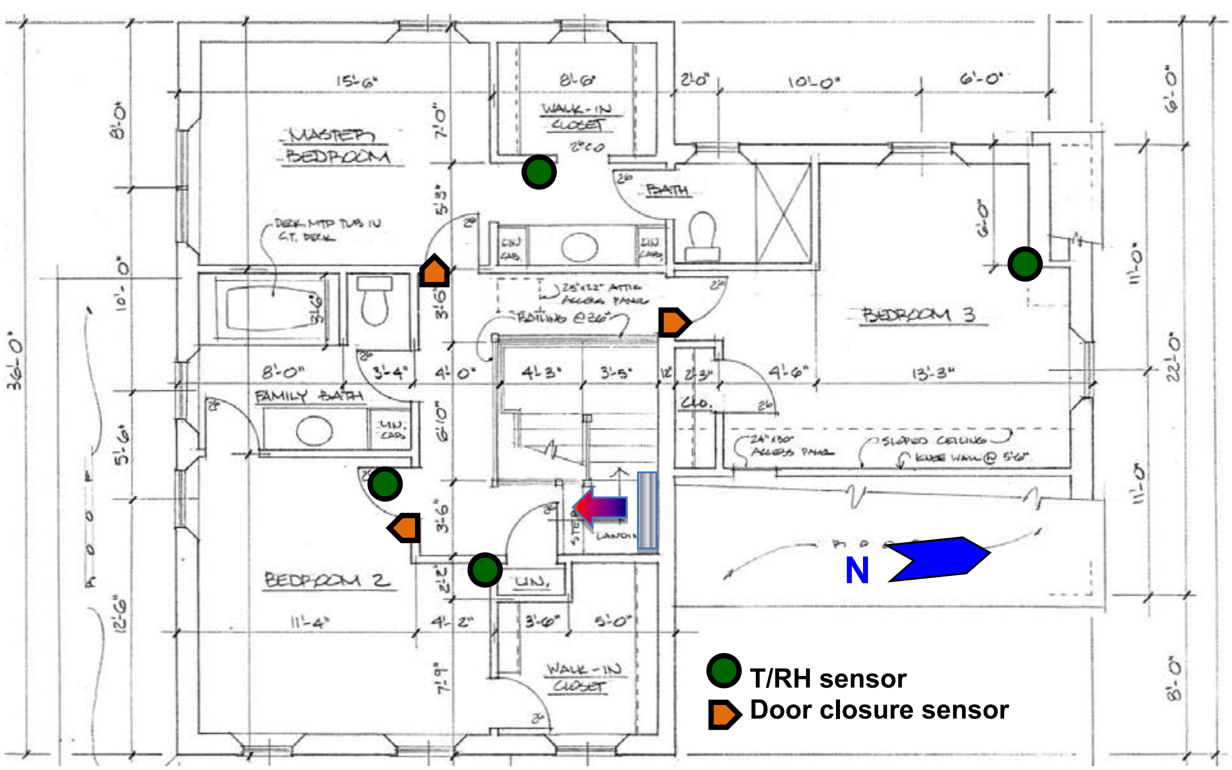


Figure 86. Second-floor plan, showing monitoring and MSHP locations

Due to these comfort complaints, T/RH and door closure sensors were installed in the house in February 2013; in addition, the house was retested for airtightness, with results consistent with the original test (304 CFM 50, or 0.8 air changes per hour at 50 Pascals, or 0.6 in.^{2} equivalent leakage area/100 ft^2). No severe localized air leakage sites were noted, besides the dryer vent covered previously.

One clear difference for this house is its size: at 2300 ft^2, it is noticeably larger than the other houses with two MSHP heads at Devens and Easthampton (1100–1700 ft^2). Devens Lot 7 is larger (2000 ft^2), but has three MSHP heads.

The greater exposure of the bonus room (exterior conditions on five of six sides) is clearly the reason for its extreme temperature excursions. This is also shown in temperature data (Figure 87): when the bonus room and master bedroom doors were closed for extended periods, indoor temperatures dropped into the low 50s and low 60s, respectively.

Scatter plots were generated for the three bedrooms for the period February 26 through April 1 (highlighted in Figure 87), which appears to be closer to "normal" door operation. The results are shown in Figure 88 and Figure 89; colder conditions appear to be linked with door closures, especially at the master bedroom. However, it is not a perfect correlation: the front bedroom has large numbers of hours with door open/more than 4°F colder than hallway. This may be an instrumentation issue, with the door not correctly capturing door closures.

Although the bonus room has few hours outside of the 4°F band, it should be noted that exterior temperatures from February 26 through April 1 are not extreme, with only some excursions below freezing. For reference, the design temperature for this location is –2°F.

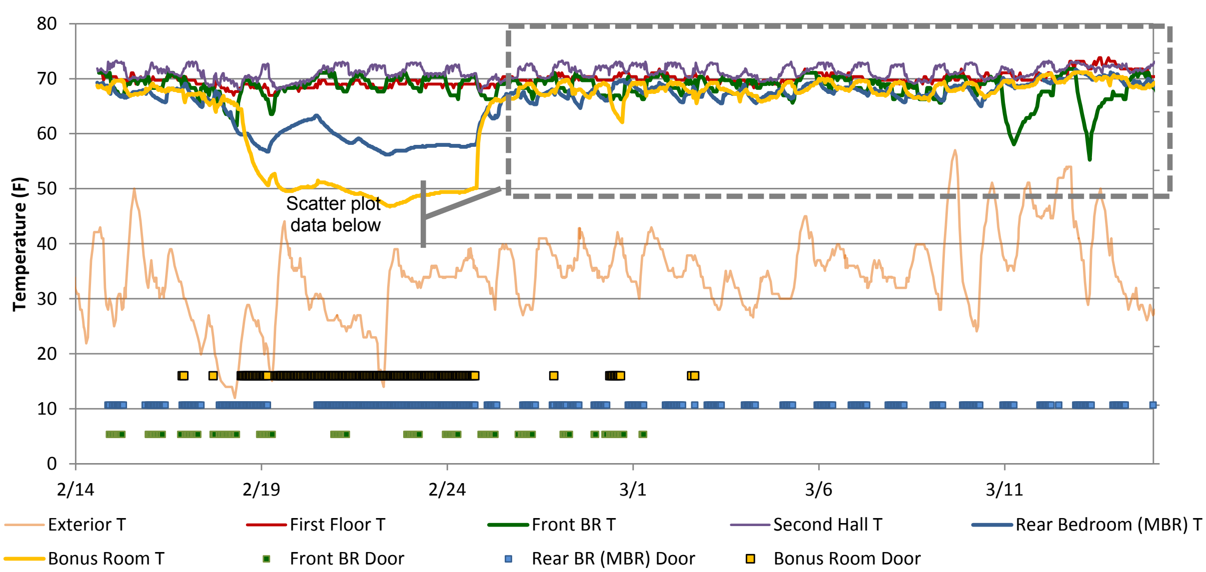
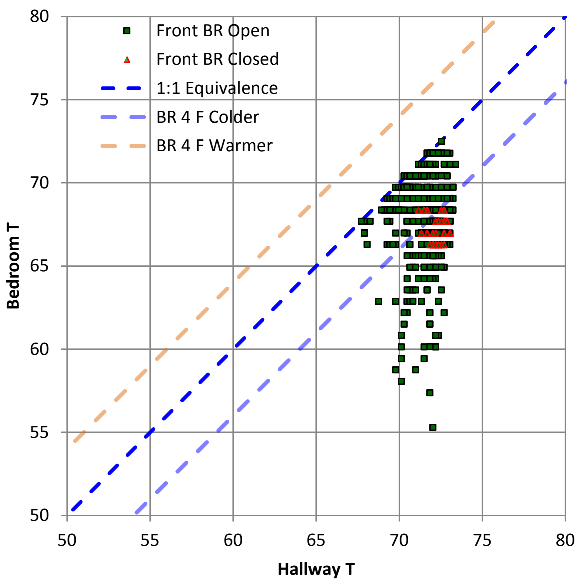


Figure 87. Lot 30 bedroom and hall temperatures, with door status



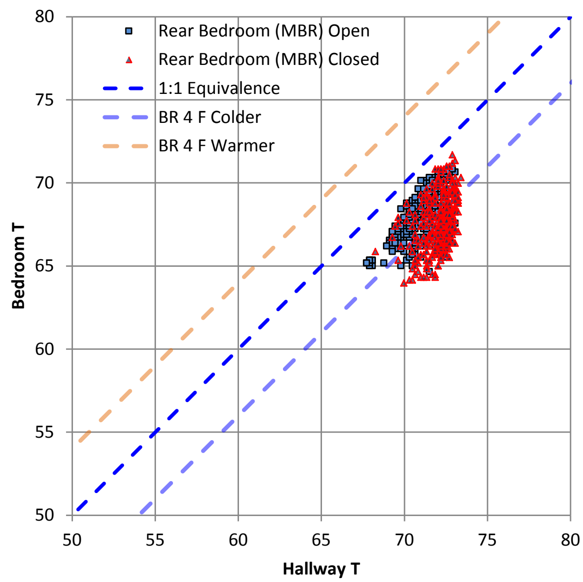


Figure 88. Easthampton Lot 30 front (left) and rear/MBR (right) temperatures versus hallway

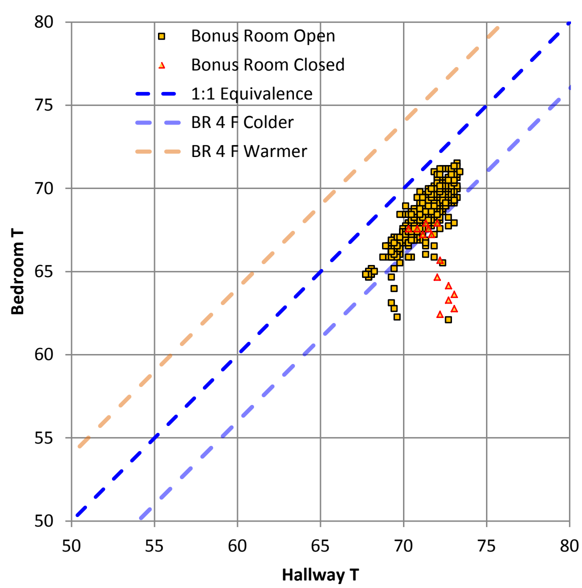


Figure 89. Easthampton Lot 30 bonus room temperatures versus hallway

Previous research has indicated that even with doors closed, heat conduction through uninsulated interior walls has a significant role in ensuring even distributions of heat. The ratio of wall to the exterior versus wall to interior can be compared for the two bedroom suites.

- Front bedroom exterior: interior ratio = 2.3:1 (~57 linear feet exterior; ~25 linear feet interior)
- Rear bedroom exterior: interior ratio = 4:1 (~48 linear feet exterior; ~12 linear feet interior).

These relative proportions are shown in the floor plan in Figure 90. Both of these bedrooms have floors exposed to conditioned space (first floor), and ceiling exposed to exterior (insulated vented attic); these are equivalent conditions for both rooms. The front bedroom suite has two door openings to the hallway (compared to the rear bedroom's one), which likely exacerbates these differences.

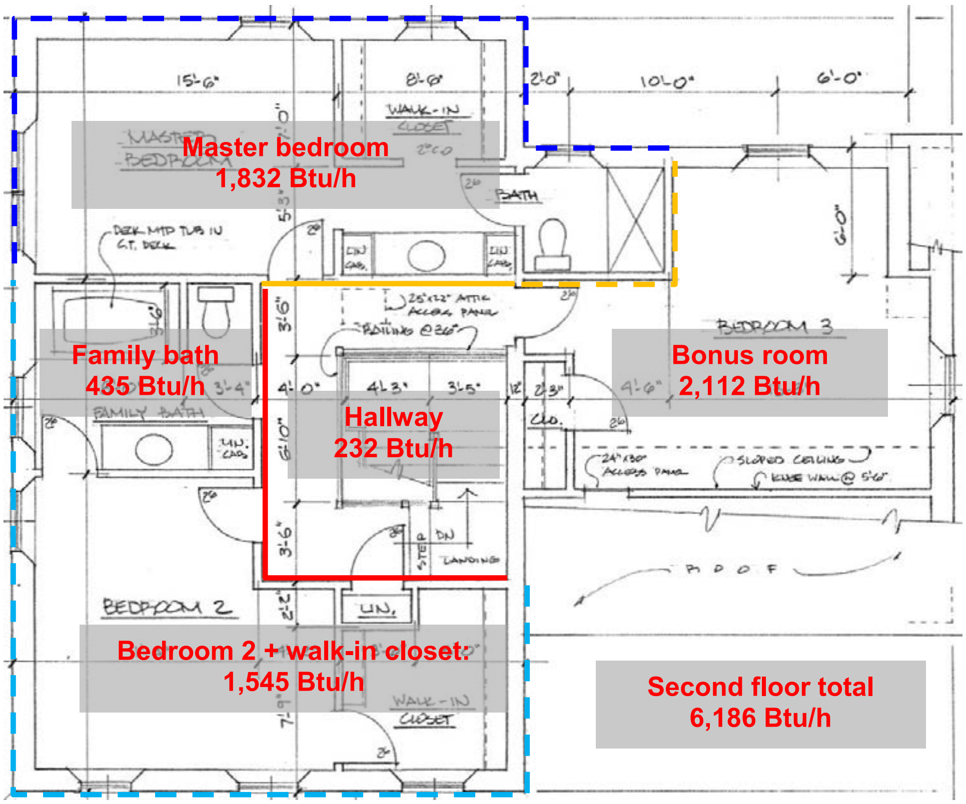


Figure 90. Relative interior/exterior wall areas for bedrooms

This is even worse for the bonus room over the garage: the majority of its surface area is interior-to-exterior, with only a small amount connected to the main hallway interior space (under 10 linear feet interior-to-interior).

These relative exposures are consistent with the reported temperatures, with the front bedroom close to interior main space conditions, the rear bedroom worse (especially at the walk-in closet and bathroom), and the bonus room the worst, especially when the garage door is left open.

A more quantitative method of looking at this problem is to use the spreadsheet calculator of relative heat loss/gain from exterior/interior sources, from Aldrich's work (CARB 2010a).

A room by room heating and cooling load calculation was done (see Figure 90), assuming exterior conditions of –2°F heating, 85°F cooling, and interior conditions 70°F heating, 75°F cooling. The calculations indicated that the installed equipment had sufficient capacity to meet loads, but distribution of the heat was the issue. For instance, the second floor (6.2 kBtu/h) was conditioned with a 12 kBtu/h (nominal) MSHP.

- Heating load: 18,147 Btu/h
- Cooling load: 11,340 Btu/h (9,223 sensible; 2,117 latent).

The solutions suggested to the builder included:

- Installation of an additional MSHP head to directly condition the bonus room, to ensure that it is at set point conditions. This would have the additional benefit of changing the wall to the adjacent master bathroom (dashed gold line) to interior set point conditions. As a result, the wall to the bathroom will be a net heat gain instead of heat loss. To put it in perspective, the ratio for the rear bedroom changes to 2.0:1 exterior: interior, if the dashed gold line is included in "interior" conditions (Figure 90).
- Installation of electric resistance heating in the bonus room bedroom, per Rosenbaum (2011). This should easily bring the bedroom up to set point (assuming it is controlled by an effective remote thermostat). Of course, it has the pro/con of lower installation cost/higher operating cost, relative to an MSHP system. In addition, it will not address any complaints during the cooling season.
- Installation of some type of distribution or "air share" fan, to redistribute heat from the main space into the bonus room. However, previous calculations have shown that attempting to heat using ~68°F air is not a very effective solution. It may be plausible to draw air from the ceiling near the second-floor MSHP head; however, it is a complex system that will be a penetration through the exterior enclosure. Depending on airflow, a return air path might be required as well.

The builder originally selected installation of electric resistance heating; however, the homeowner noted that summertime comfort issues were occurring as well. The builder therefore decided on installation of a 3:1 MSHP, with indoor heads in all three bedrooms. No comfort complaints had been noted since this retrofit.

Data were available for one other bonus room as a comparison, at Devens Lot 3 (Figure 91).

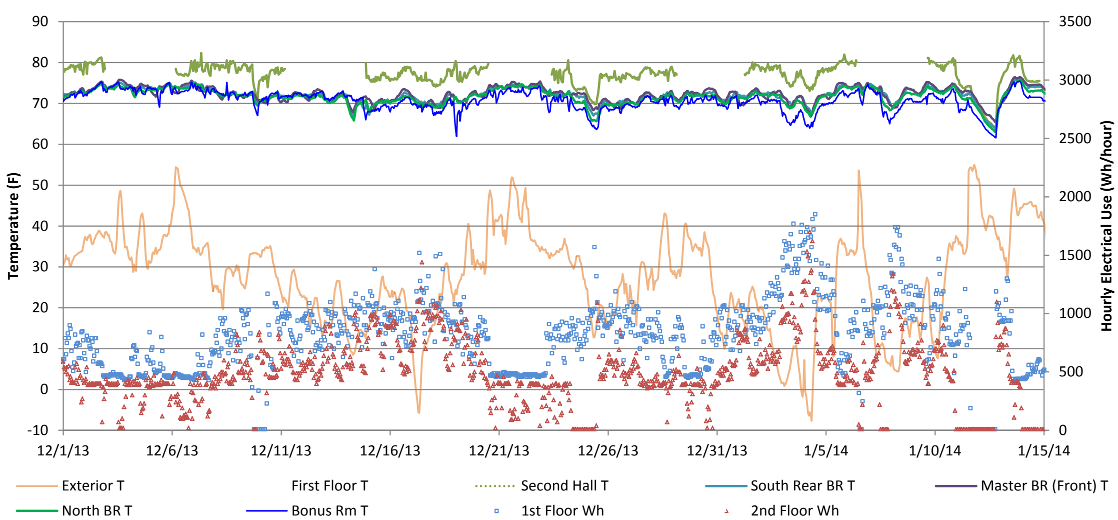


Figure 91. Devens Lot 3 interior temperatures (December 2013–January 2014)

Data were plotted for a cold period in winter 2013–2014 (December–January), which included several excursions below 0°F. The bonus room was definitely colder than other second-floor bedrooms, but by a smaller margin than Easthampton Lot 30. Typical temperature differences during cold periods were in the 2°–3°F range, with worst-case periods of 8°F. No space heater was used in this room. This bonus room might have had a more favorable geometry, because the second-floor hallway MSHP faces toward the door of the bonus room.

Overall, larger houses, rooms with disparate interior/exterior geometries (e.g., bonus rooms over garages), and extended operation with doors closed require caution when using simplified or single-point space conditioning systems, even with high-performance building enclosures with excellent airtightness. Use of a relative heat flow calculator (per CARB 2010a) is a reasonable first step to examine potential problems. However, although bonus rooms are a risk case, the Devens data show that they are not always a problem.

6.7 Temperature Setbacks (On/Off Operation)

Previous work (Ueno et al. 2013a and others) indicated that on-off operation (or deep temperature setbacks) of simplified distribution systems can exacerbate temperature unevenness issues. By using setbacks, there are many times when no heating is required, as the house cools to set point, and other times when the heat pump works at maximum output to recover from setback. During these cooling-off and warming-up periods, there can be large room-to-room differences. In addition, on-off operation also forces the MSHP to run at maximum output to meet set point, which is its least efficient condition (per Winkler 2011).

One homeowner at Easthampton (Lot 23) complained of uneven temperatures in rooms; the monitored data were examined more closely to determine potential causes. A plot of interior and exterior temperatures with MSHP electricity use (Figure 92) makes the operation clear: the temperature swings between under 60°F to over 70°F. More importantly, the pattern of MSHP electricity use shows large spikes near maximum input (~2000 W), when recovering from temperature setbacks. For instance, in early February, both MSHPs were shut off entirely (highlighted box), and the second-floor system was turned on, resulting in several hours at maximum capacity.

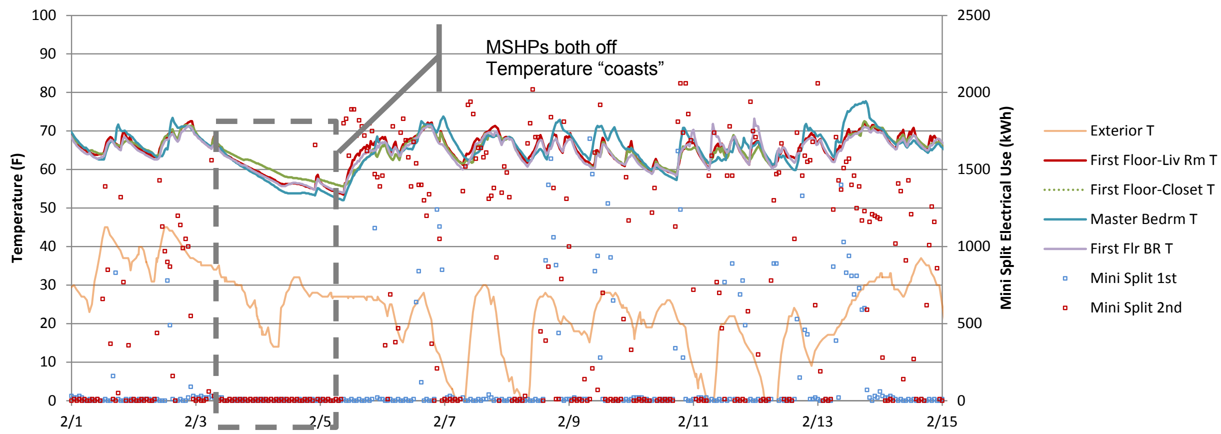


Figure 92. Easthampton Lot 23 February 2014 excerpt (on/off operation)

This type of system operation was confirmed by the homeowners during a site visit; they would turn the unit on and off based on perceived comfort, rather than allowing constant thermostat control.

The electricity and temperature behavior can be contrasted with Easthampton Lot 13, which used a constant set point. The same time period is plotted in Figure 93); the electricity use of the MSHPs track to exterior temperatures, with increased consumption at colder outdoor conditions. In addition, the peak wattage draw never exceeds 1000 W in this period, compared with many hours at 2000 W for Lot 23.

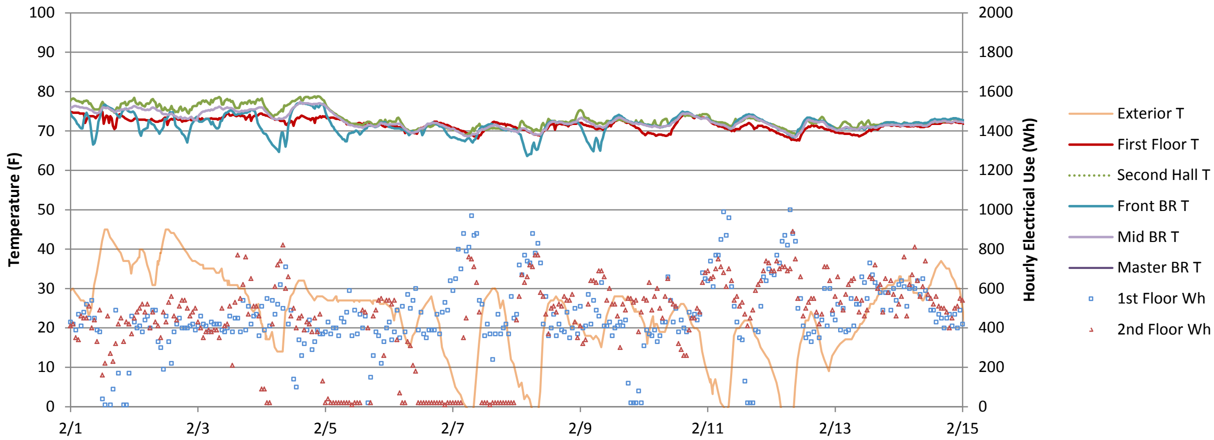


Figure 93. Easthampton Lot 13 February 2014 excerpt (constant set point)

Previous analysis shows that on-off operation or deep setbacks result in much worse energy performance (i.e., monthly kWh comparison between Easthampton Lots 23 and 17).

It appears that Devens Lot 4 might have also used some degree of setback operation, but with a much smaller variation in temperature. Devens Lot 4 was logged with amperage measurements, so the power measurements might be somewhat suspect.

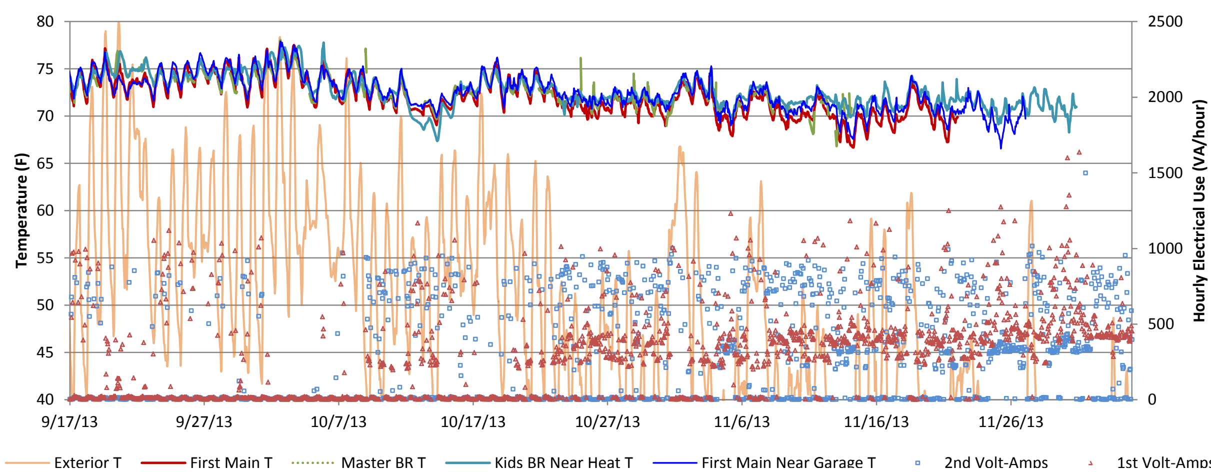


Figure 94. Devens Lot 4 fall excerpt (some possible setback use)

The operation of windows during the cooling season (or swing seasons) is somewhat analogous to thermostat setbacks. Opening of windows and night flushing during favorable outdoor temperature conditions could be used to minimize compressor-based cooling. However, improper timing of window opening could result in higher interior “starting temperatures,” exacerbating temperature unevenness issues and temperature recovery issues. In addition, night flushing in moist climates runs the risk of loading interior finishes with moisture, which would then be removed during cooling operation, thus negating some savings.

Window operation during cool swing seasons effectively increases the localized air leakage in a room; it results in greater heat loss from bedrooms, and lower temperatures.

6.8 Basement Temperatures (Unconditioned Spaces)

Most of the houses at Easthampton were slab on grade, but the Devens houses were all built on insulated (R-20 walls/R-10 slab) basements. The use of MSHPs for space conditioning eliminates typical sources of incidental/unintentional heating of the basement, such as distribution losses (ductwork and radiator piping) and boiler/furnace shell losses.

The builder had previously experimented with excluding the basement from the conditioned space, with insulation at the basement ceiling. However, including the basement within the conditioned space (insulating at the basement walls) often results in improved airtightness (normalized by either volume or surface area; Ueno and Lstiburek 2012), and provides more semi-heated storage or ancillary interior space.

The resulting temperature for this space was a matter of some curiosity; in particular, whether the basement would be cold enough to cause comfort complaints on the first floor. No comfort complaints were reported due to “cold floor” issues. A representative set of temperatures is shown in Figure 95 (Devens Lot 3); the basement walls were insulated during the monitoring period. After insulation, the coldest basement temperatures were typically in the low 60s/high 50s, which is colder than comfort conditions, but adequate for storage.

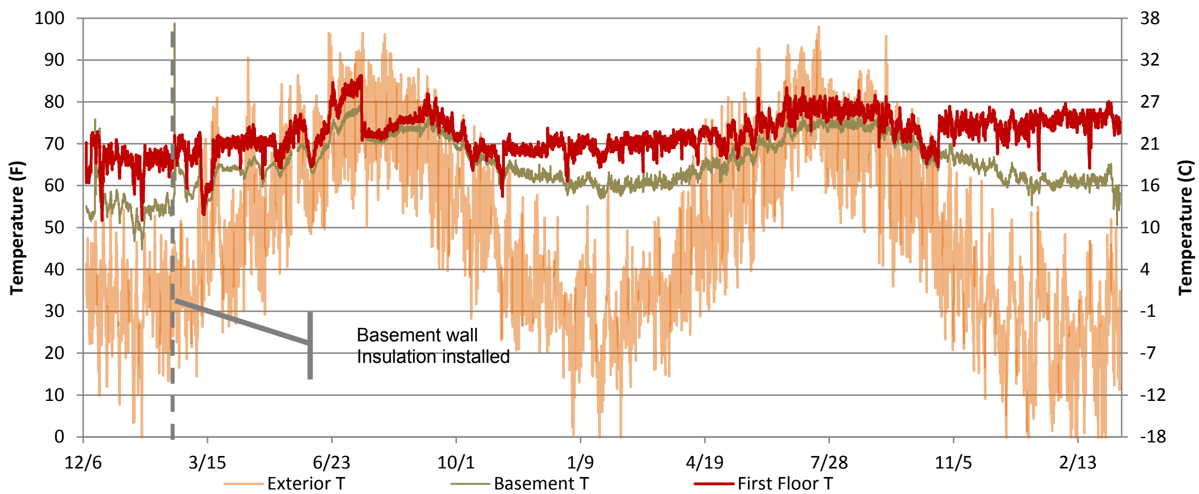


Figure 95. Devens Lot 3 first floor, basement, and exterior temperatures

Limited basement temperature information was available for Devens Lots 7 and 8; Figure 96 shows Lot 7 data through early December. The basement temperature appears to be on a similar trajectory, but the loggers failed before the coldest portions of winter.

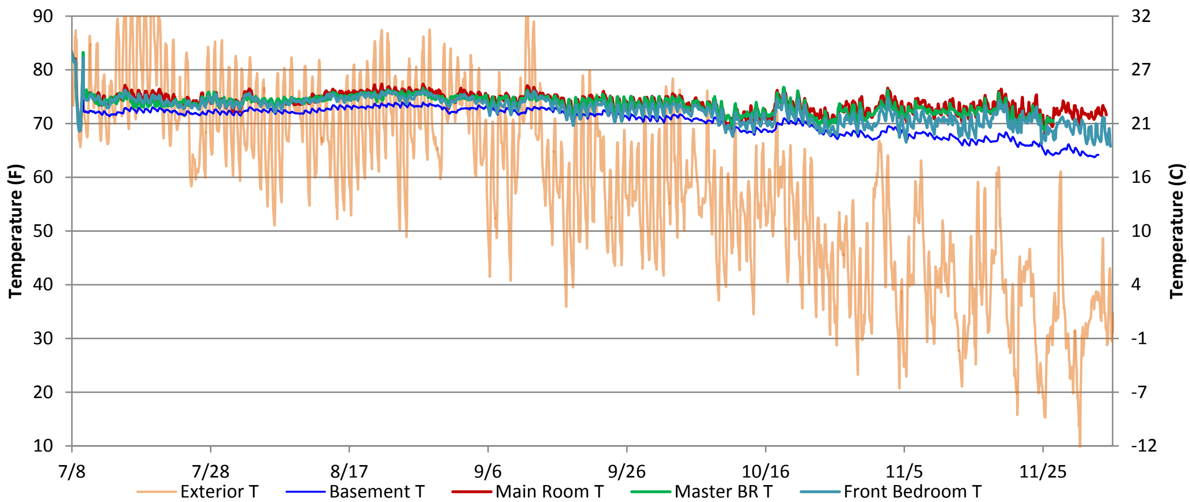
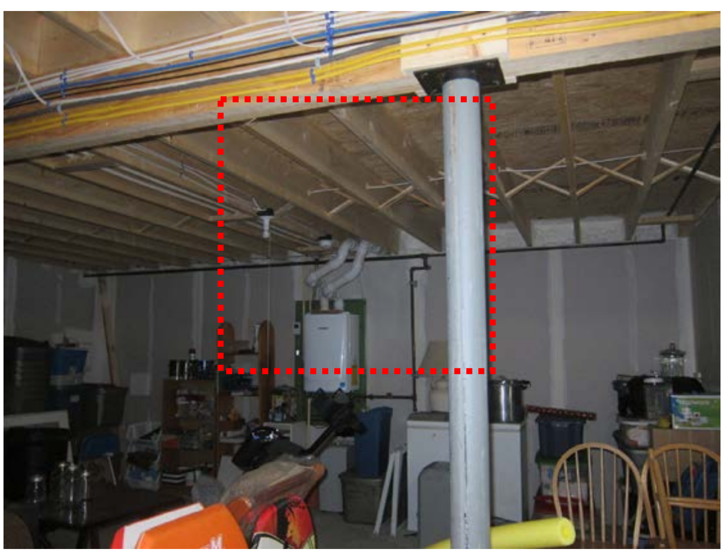


Figure 96. Devens Lot 7 first floor, basement, and exterior temperatures

An infrared image of an insulated basement (Figure 97) shows that the basement ceiling/first floor is warmer than the basement, and emitting heat to the basement.



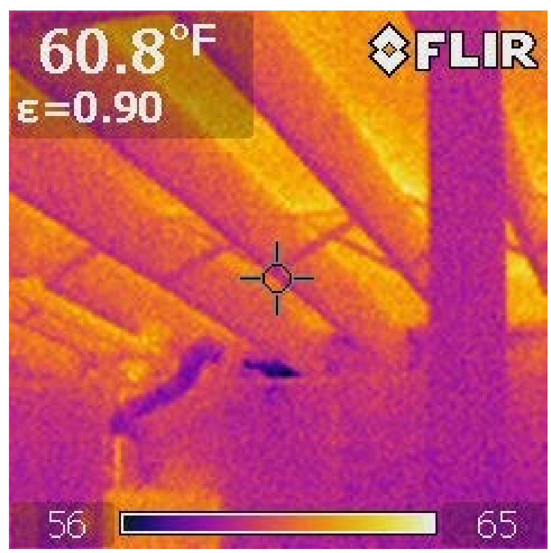


Figure 97. Ceiling of first floor from basement infrared image, Easthampton Lot 30

Overall, basement temperatures were not a source of complaints from homeowners. In addition, if the basement were to be heated, it could be added easily. A load calculations shows a design load in the 3500 Btu/h (1000 W) range, which is the typical size for an electric resistance space heater.

7 Conclusions and Further Work

Conclusions from the field monitoring work are covered below followed by opportunities for further research.

7.1 Conclusions

Monitoring eight houses over 3 years has provided a wealth of data when combined with the builder's experiences. Overall, the work demonstrates that simplified space conditioning distribution using MSHPs can provide excellent performance in a cold (zone 5A) climate, in moderate-sized houses (with 1 MSHP per <1000 ft^2). However, there are some cases and situations that designers should be aware of as potential failures. Occupant operation can have significant impacts on performance as well.

7.1.1 Mini-Split Heat Pump Operation and Capacity

General MSHP operation patterns. Some patterns were seen over many of the monitored houses; it was useful to confirm expected behavior for the equipment. When a constant interior set point is used, the MSHP modulates up and down with outdoor temperature, running almost continuously throughout the winter to meet load. The first-floor unit provides the majority of the heating (compared to the second-floor unit), due to thermal buoyancy. Conversely, in the summertime the second-floor unit often provides the majority of the cooling. As would be expected in a zone 5A climate, heating consumption far outweighs cooling consumption.

Equipment capacity, sizing, and square footage. There were no cases where there were issues with equipment sizing or lack of capacity, indicating that these cold-temperature heat pumps are a viable strategy as a single heat source in cold climates. This was confirmed by the monitoring: the MSHPs seldom hit maximum power draw, indicating substantial excess capacity even during worst-case winter conditions (much colder than local design temperatures).

These results are consistent with the installed capacity of the equipment: the oversizing (compared to calculated loads) typically ranged from 150% to 200%. Although oversizing cooling equipment is commonly criticized, oversizing of heat pumps (for wintertime loads) can be beneficial. This is particularly true for MSHPs that modulate their capacity as their highest efficiency is obtained when the unit is running at the lower end of their capacity range.

There were some problem cases with heat distribution within the space (covered below). The square footage per MSHP head was calculated: all problem cases had over 1100 ft^2 conditioned per head. However, this is too little information to be considered general guidance: it is based on a specific climate, specific construction type, and house geometry.

Summertime humidity control. One reported advantage of MSHPs is that they provide superior control of interior RH levels due to capacity modulation. At the same time, low-load houses have a higher risk of cooling season part-load humidity issues: enclosure improvements reduce sensible cooling loads while most latent loads are unchanged. Calculation of hours over 60% RH (per Rudd et al. 2013) showed relatively high numbers of summertime hours over 60% RH, indicating that MSHPs are not a panacea for controlling interior RH in high-performance houses in the Northeast. However, these results were not compared with similar houses conditioned with conventional split systems; it is entirely likely that MSHPs would have superior RH control to fixed-output (or two-stage) systems. In addition, no complaints of high interior RH were reported by homeowners during occupant surveys.

7.1.2 Mini-Split Heat Pump Energy Use

Normalized use versus simulations. MSHP heating use was tabulated for the various houses, normalized by heating degree days, and compared with simulation predictions for heating use. Several houses had multiple winters (some of them partial), but partial winters are accounted for by the HDD normalization. There is considerable scatter in the results: correlations varied from 57% above to 26% below the simulation prediction. Possible explanations were provided for various individual houses being above or below simulation predictions. Given the limited correlation seen between actual and simulated use ($R^2 = 0.43$), it is difficult to draw any conclusions on the accuracy (or lack thereof) of the energy model. However, the average error for the sample is +8% (actual normalized use greater than simulation prediction).

Normalized use (kWh/ft^2·HDD 65). The heating electricity use was also normalized by HDD and square footage (per Rosenbaum 2014b). Average consumption was 0.00030 kWh/ft^2·HDD 65, which is reasonably close to simulations predictions of 0.00028 kWh/ft^2·HDD 65 without basement. This information also provides a comparison metric for other houses heated with MSHPs.

Amperage meters versus kilowatt-hour meters. Three houses had MSHPs monitored with amperage meters (versus root mean square kilowatt-hour meter used at other sites). Inconsistent results were found, which were suspected to be due to power factor issues (which are not captured by amperage meters); other researchers have found that MSHP power factors vary strongly with load. Future monitoring of MSHPs should be done with true root mean square power meters.

Standby use. Other practitioners have measured the standby use of other MSHPs at higher levels than ideal for low-load houses (30–40 W continuous). However, long-term measurements of the Mitsubishi equipment used here showed low standby use (4–5 W average).

7.1.3 Simplified Space Conditioning and Temperature Distributions

Interior temperature distributions (4°F difference). ACCA Manual RS (ACCA 1997) recommends a maximum 4°F difference within a home or zone (highest minus lowest temperature); the temperature data were evaluated using this criterion. Results spanned a wide range; looking specifically at wintertime operation, results ranged from 96% of hours within the 4°F band to only 19% of hours. However, some weaknesses of this metric were pointed out. In addition, summertime data were analyzed; they indicate that summer conditions are less challenging than winter conditions for simplified distribution, at least given the solar gains (glazing ratios and 0.17 SHGC windows) in these houses.

Occupied versus unoccupied conditions. One house was monitored during winters at both occupied and unoccupied conditions. Occupied conditions resulted in less even temperature distributions, as would be expected with door closures and set point changes.

Door operation effects on bedroom temperatures. Previous work showed that bedrooms during closed-door hours had greater differences between hallway and bedrooms, compared to open-door hours. The current data were analyzed; however, limited conclusions could be drawn. Many houses had very few closed door hours, which might reflect actual operation or instrumentation issues. Another house operated their MSHPs in an on-off manner (instead of constant set point), resulting in little usable data for evaluating door operation.

Basement temperatures (unconditioned spaces). The use of MSHPs eliminates typical sources of incidental/unintentional heating of the basement, such as distribution losses (ductwork and radiator piping) and boiler/furnace shell losses. The basements are well-insulated (R-20 walls/R-10 slab); the resulting winter temperatures dropped to the low 60s/high 50s, which is colder than comfort conditions, but adequate for storage. No comfort complaints were reported due to "cold floor" issues on the first floor.

7.1.4 Simplified Space Conditioning Problem Cases

Thermal buoyancy effects (use of single MSHP on first floor). Two small houses were equipped with a single MSHP on the first floor, due to their small loads and observations that the second-floor unit often does not run in the winter. However, during the first summer of operation, the second floor did not cool down to set point (10°F warmer than the first floor), even with the use of transfer fans. These issues are clearly due to thermal buoyancy: conditioned air rises from the first-floor unit in the winter, but it stays on the first floor during cooling operation. To correct this issue, an additional MSHP was retrofitted to the second floor. In general; providing both heating and cooling from a single point in a two-story plan is problematic due to thermal buoyancy issues.

Open-plan first-floor temperature distributions. In general, open-plan first floors had few issues. The few exceptions were because of geometry issues and thermal buoyancy (an open stairwell intercepting heating air before it could reach across the space), and localized air leakage (dryer vent), resulting in a single cold room.

Comfort complaint house (bonus room). One house experienced comfort issues that are instructive; the owners complained of a bedroom suite and a bonus room that were consistently cold in the wintertime. A constant set point was used, but leaving doors open was not compatible with their lifestyle and schedule. Monitoring confirmed that extended winter periods with closed doors resulted in temperatures in the high 50s in the bedroom suite and high 40s in the bonus room. This house is larger than other monitored houses (2300 ft^2, versus 1100–1700 ft^2 for others); in addition, it has unfavorable geometries in the problem areas. The bedroom suite has a limited amount of interior-to-interior wall area, compared to the non-problem rooms. The bonus room had more severe conditions, of exterior temperatures on five of its six sides. Calculations indicated that this was not an equipment undersizing issue but a heat distribution issue. The problem was resolved by installing a 3:1 (indoor units: outdoor unit) MSHP, with indoor heads in all three bedrooms. In general, the geometry of rooms (e.g., interior wall/floor versus exterior wall/floor) should be examined to ensure that simplified space conditioning can work.

Temperature setbacks (on/off operation). Previous work has shown that deep temperature setbacks of simplified heating systems can exacerbate temperature unevenness issues. One homeowner complained of temperature unevenness; when the data were examined, it was clear that they operated their MSHP in an "on-off" manner rather than using a fixed set point. This resulted in wide swings in interior temperature (between 60°F and 70°F^{+}). The electricity use showed many hours with the MSHP running at maximum capacity (~2000 W), followed by periods with the unit shut off. When operated in this manner, the MSHP is heating at its least efficient (maximum output) state. Electricity consumption was by far the worst among all monitored houses; when compared with simulations, it was the worst-performing house (heating use 57% higher than simulation).

7.2 Further Work

In terms of simplified space conditioning with MSHPs, this long-term field research project (eight houses/3 years) and field deployment of this technology in quantity have demonstrated that it can work in many cases, but that there are potential cases when failure is more likely. However, applying these results in wider situations should be approached cautiously: this research specifically examined single-family, modestly sized, wood-frame, high-performance housing in a cold climate (zone 5A). Further research may be worthwhile in other climate zones (e.g., hot-humid/mixed-humid) or with other construction types. For instance, multifamily construction (with fewer exposed exterior walls) is a promising use case for simplified space distribution.

Another potential research opportunity is if compact MSHP air handlers with low ambient temperature capabilities ("H2i" or "Hyper Heat") become available, as projected for Q4 2014. They appear to be an ideal solution for handling bedroom space conditioning, as opposed to relying mostly on open bedroom doors for space conditioning distribution, or partially effective transfer fans. Of course, the price differential will be a key issue on whether this type of system will be adopted. Confirming the effectiveness of this equipment (in terms of energy use, efficiency measurements, temperature distributions, and/or user experience) may be a worthwhile research topic.

The spreadsheet tool (CARB 2010a) is a useful method for gauging potential risks of using simplified space conditioning in a given space. Further adoption of this tool (and/or making it more user-friendly) might be a worthwhile use of resources.

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Appendix A: Instrumentation Details

Sensors used at the instrumented houses included a mixture of the following:

- T/RH in the main spaces (first floor, second-floor hallway typical)
- T/RH in the bedrooms
- T/RH in the basement (selected houses)
- Door open/closed status
- Electrical power use for the DHPs
    - True root mean square power measurements at most sites
    - Amperage only at Devens Lots 4, 7, and 8.

Onset Computer HOBO loggers were used for T/RH measurements. Differing models were used at some houses, due to the manufacturer's model change and availability.

At Devens, outdoor temperature is measured on site; in Easthampton, outdoor conditions are taken from the weather station at Westfield, Barnes Municipal Airport (KBAF), roughly 8 miles south of the development.

Table 25 and Table 26 provide detail on the sensors package.

Table 25. Instrumentation Listing

Measurement	Interval	Instrument	Accuracy
T/RH	1 h	Onset Computer Corporation HOBO U10-003	T: ± 0.95°F from 32° to 122°F RH: ± 3.5% from 25% to 85% over the range of 59° to 113°F
T/RH	1 h	Onset Computer Corporation HOBO H08	T: ± 1.25°F from 32° to 104°F RH: ±5% over the range of +41°F to +122°F
Outdoor T/RH (Devens)	1 h	Campbell Scientific HMP60 T/RH Probe	T accuracy: ±1.1°F (-40° to +140°F) RH accuracy at 32° to 104°F: ±3% RH (0 to 90% RH) ±5% RH (90 to 100% RH)
Door Open/Closed Status	1 h	Onset Computer Corporation HOBO State Logger U9-001	Time accuracy approximately ± 1 minute per month at 77°F
Electrical Power (Meter)	n/a	Leviton Dual Element Watt Hour Meter MK240-1SW	Revenue-grade 0.3% accuracy class 0.1A solid core current transformers Set at 10 Wh per pulse resolution
Electrical Power (Logger)	5 min	Onset Computer Corporation HOBO 4-Channel Pulse Data Logger UX120-017	Time accuracy ± 1 minute per month at 77°F

Table 26. Instrumentation Listing (Devens Lots 4, 7, and 8)

Measurement	Interval	Instrument	Accuracy
T/RH	1 h	Onset Computer Corporation HOBO UX100-011	T: ±0.21°C from 32° to 122°F RH: ±2.5% from 10% to 90% typical to a maximum of ±3.5% including hysteresis
Door Open/Closed Status	1 h	Onset Computer Corporation HOBO State Logger UX90-001	Time accuracy ± 1 minute per month at 77°F
Electrical Power (Data Collection)	1 h	Onset Computer Corporation HOBO U12-008 4-Ext. Channel Logger	Voltage accuracy: ± 2 mV ± 2.5% of absolute reading ± 2 mV ± 1% of reading for data logger-powered sensors
Electrical Power (Current Measurement)	n/a	Onset Computer Corporation CTV-A 20 A Current Transducer	Accuracy with U12: ±4.5% of full scale, or ±0.9 amps. Minimum measurement: 2A

Appendix B: Development Descriptions and Timeline

A description of the Transformations developments, the locations of monitored houses, and a timeline of the monitoring work are covered below.

The Devens development is a net zero energy community located in Harvard, 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.

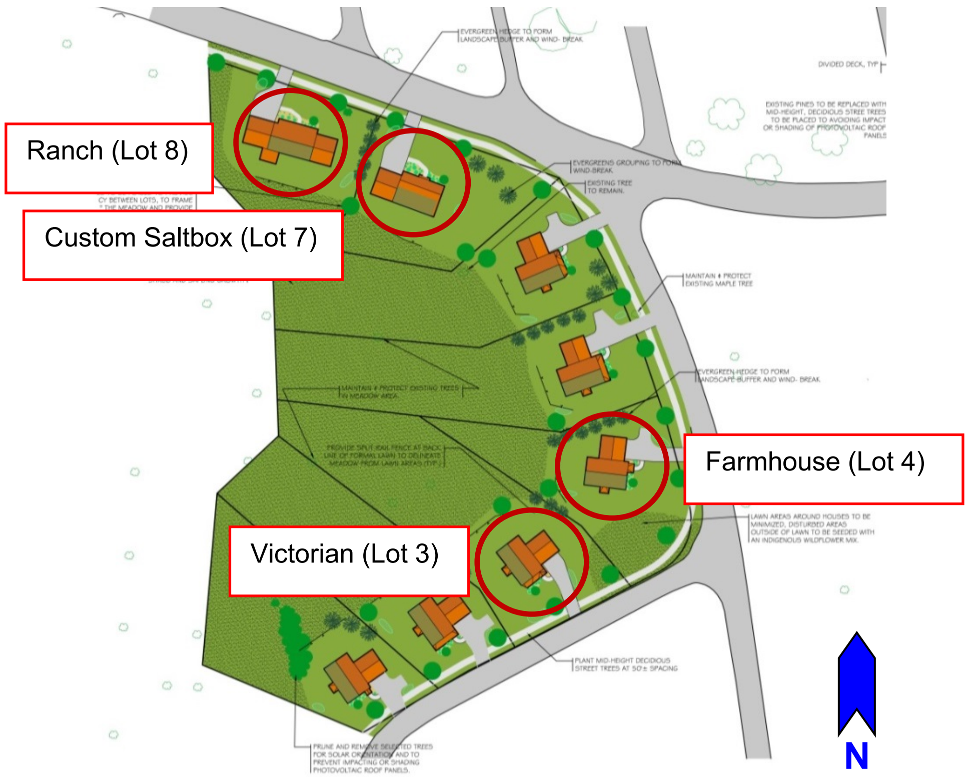

Image Courtesy of Transformations, Inc.

Figure 98. Devens sustainable housing site plan; monitored houses highlighted

Figure 99. Overview of Devens site, showing PV arrays

The Easthampton development is a net zero energy ready 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 100). The houses feature two, three, or four bedrooms; the development includes market-rate as well as affordable units.

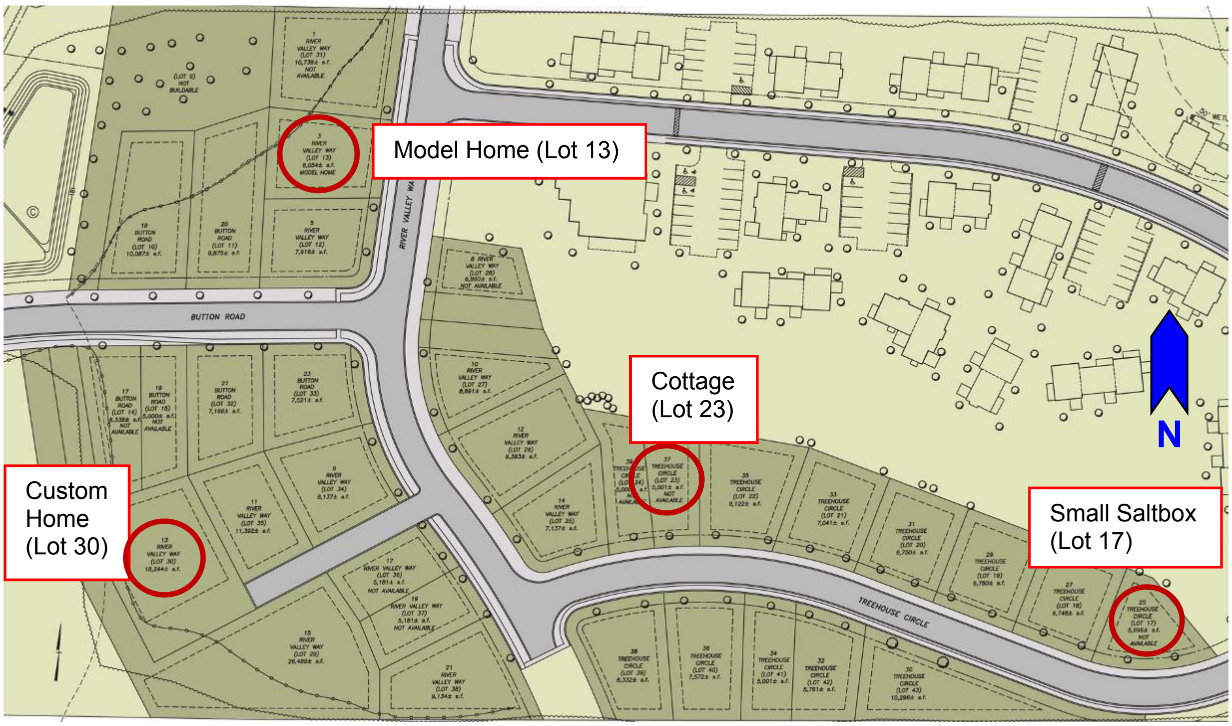

Figure 100. The homes at Easthampton Meadow site plan; monitored houses highlighted

Figure 101. Overview of Easthampton site, showing continuing construction (March 2014)

An overview of the timeline of the monitoring work, including installation, download, and removal times, is shown in Figure 102. Two houses (Devens Lot 3 and Easthampton Lot 13) were sold during the monitoring period, switching from unoccupied to occupied condition, as noted on the timeline. In addition, three houses at Devens lost T/RH data from early December onward due to a premature battery failure, as shown.

HDD 65°F for Westfield-Barnes Regional Airport (KBAF, near the Easthampton site) are plotted for reference. March 2014 was a partial month of data collection (through March 18), so the HDDs shown cover the beginning of the month only.

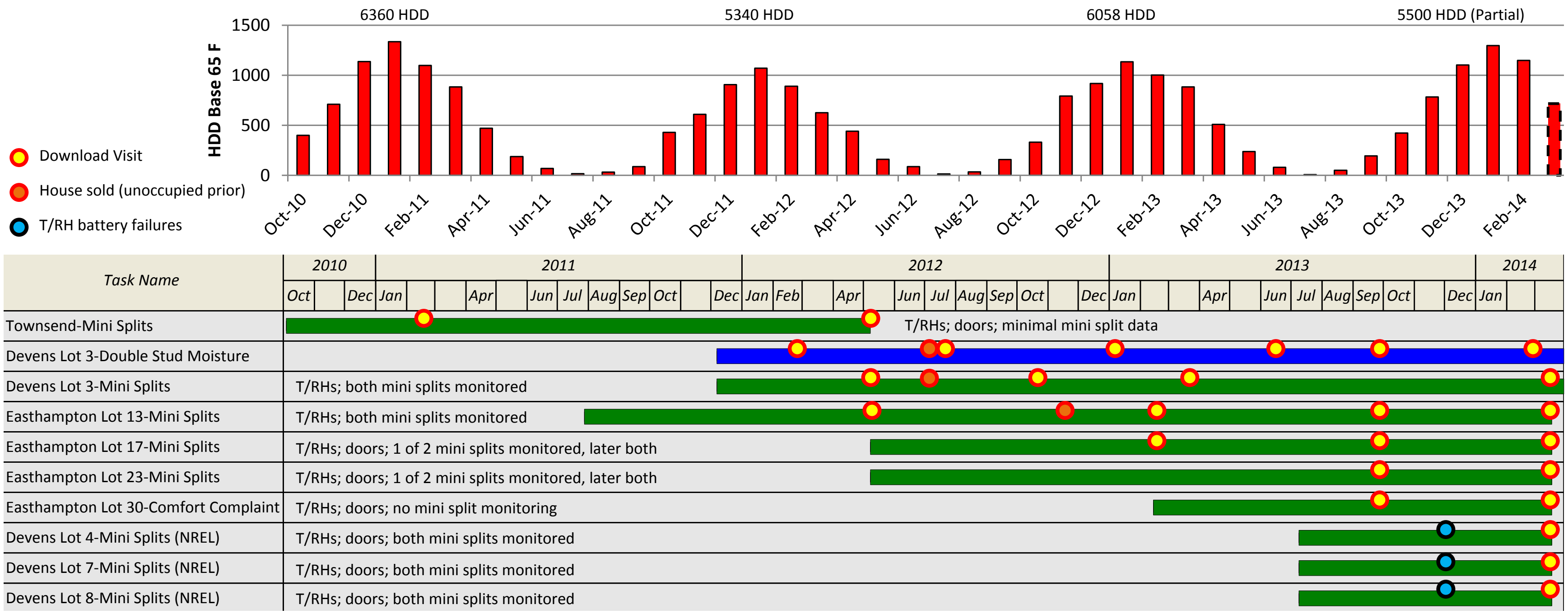

Figure 102. Monitoring timeline with downloads and HDDs for KBAF (Easthampton)

Appendix C: House Characteristics and Data Overview

The characteristics of the eight test houses are covered in the sections below; in addition, an overview plot of the collected data is included for reference.

Devens Lot 3 (Victorian)

Figure 103. Devens Lot 3 front and side views

This house is also the location of the double stud wall moisture monitoring experiment; several sensors are "piggybacked" off the monitoring system used in that work (T/RH for basement, MBR, bedroom 2). This house was unsold for the first winter and spring, and then occupied by a family of four.

Table 27. Characteristics of Devens Lot 3

Characteristic	Value
Stories	2
Foundation Type	Basement
Square Footage (w/o bonus room)	1728 + 864 basement
Bedrooms	3
Occupants	2 adults, 2 children
Bonus Room Status	Finished, semi-heated

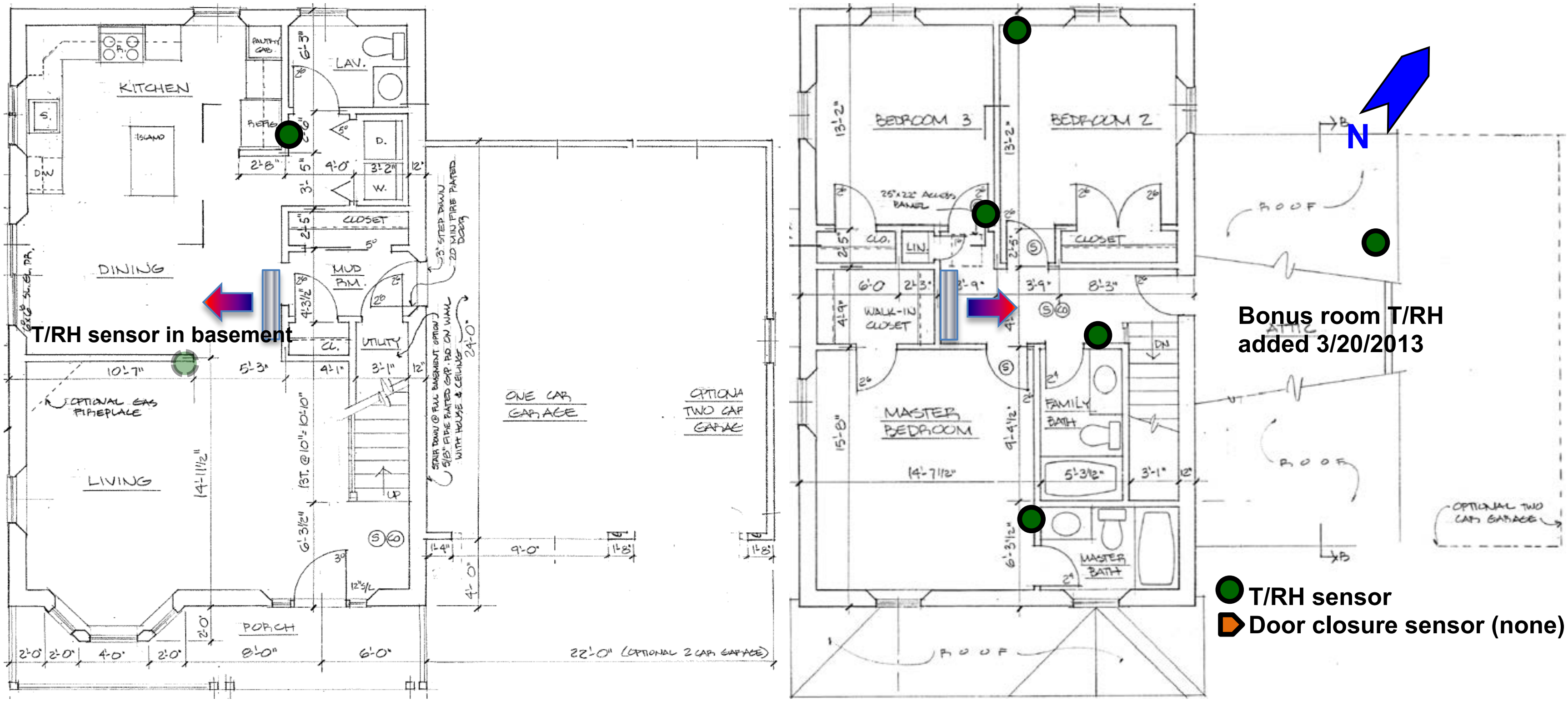

Figure 104. Devens Lot 3 floor plans, MSPH locations, monitoring locations

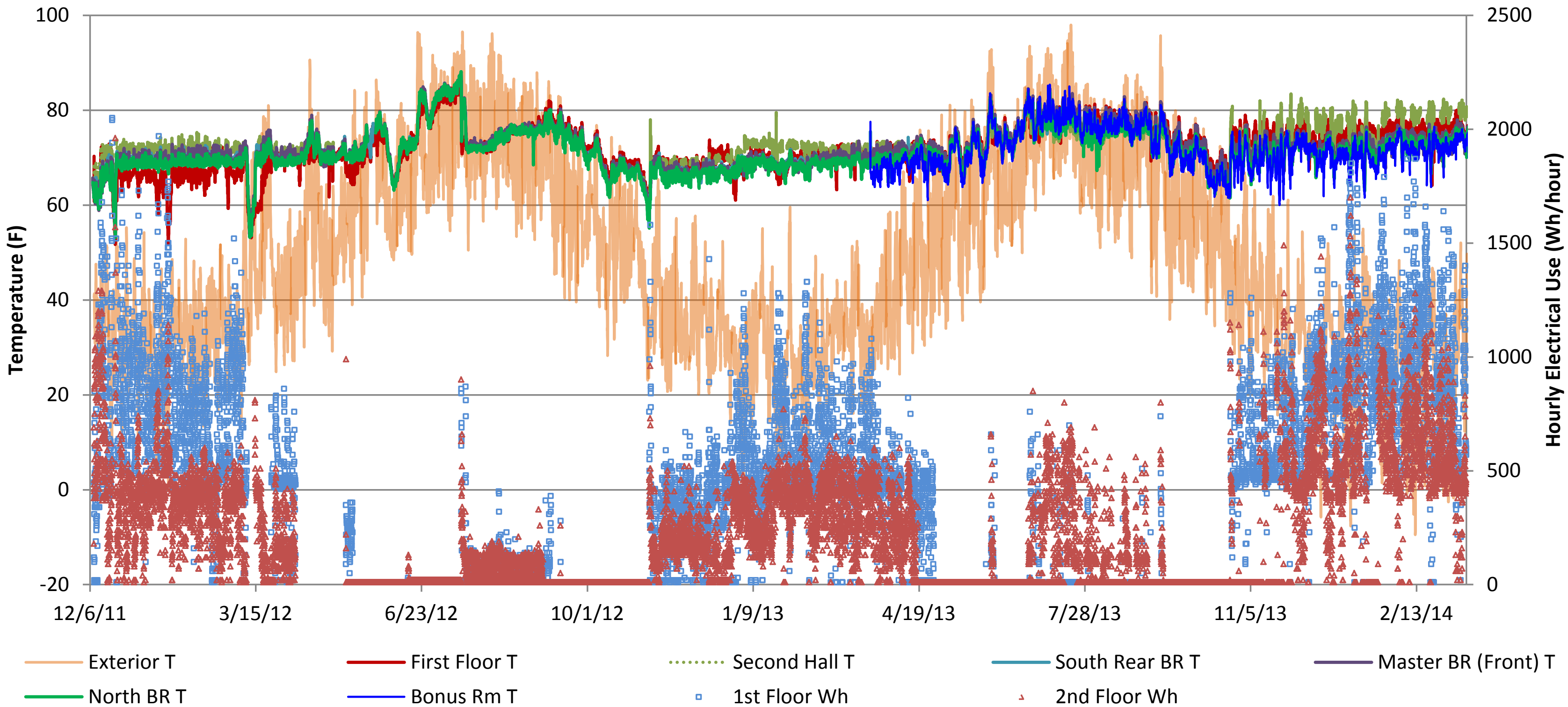

Figure 105. Devens Lot 3 interior and exterior temperatures, with MSHP hourly electricity use

Devens Lot 4 (Farmhouse)

Figure 106. Devens Lot 4 front and side views

This was one of three houses that were monitored from July 2013 through March 2014. Unfortunately, the interior T/RH loggers malfunctioned in November/December 2013; therefore, no temperature data were available for winter conditions. The MSHPs were logged with amperage measurements of one power leg.

Table 28. Characteristics of Devens Lot 4

Characteristic	Value
Stories	2
Foundation Type	Basement
Square Footage (w/o bonus room)	1728 + 864 basement
Bedrooms	3
Occupants	2 adults, 2 children, 1 senior
Bonus Room Status	Finished by homeowner, used as home theater

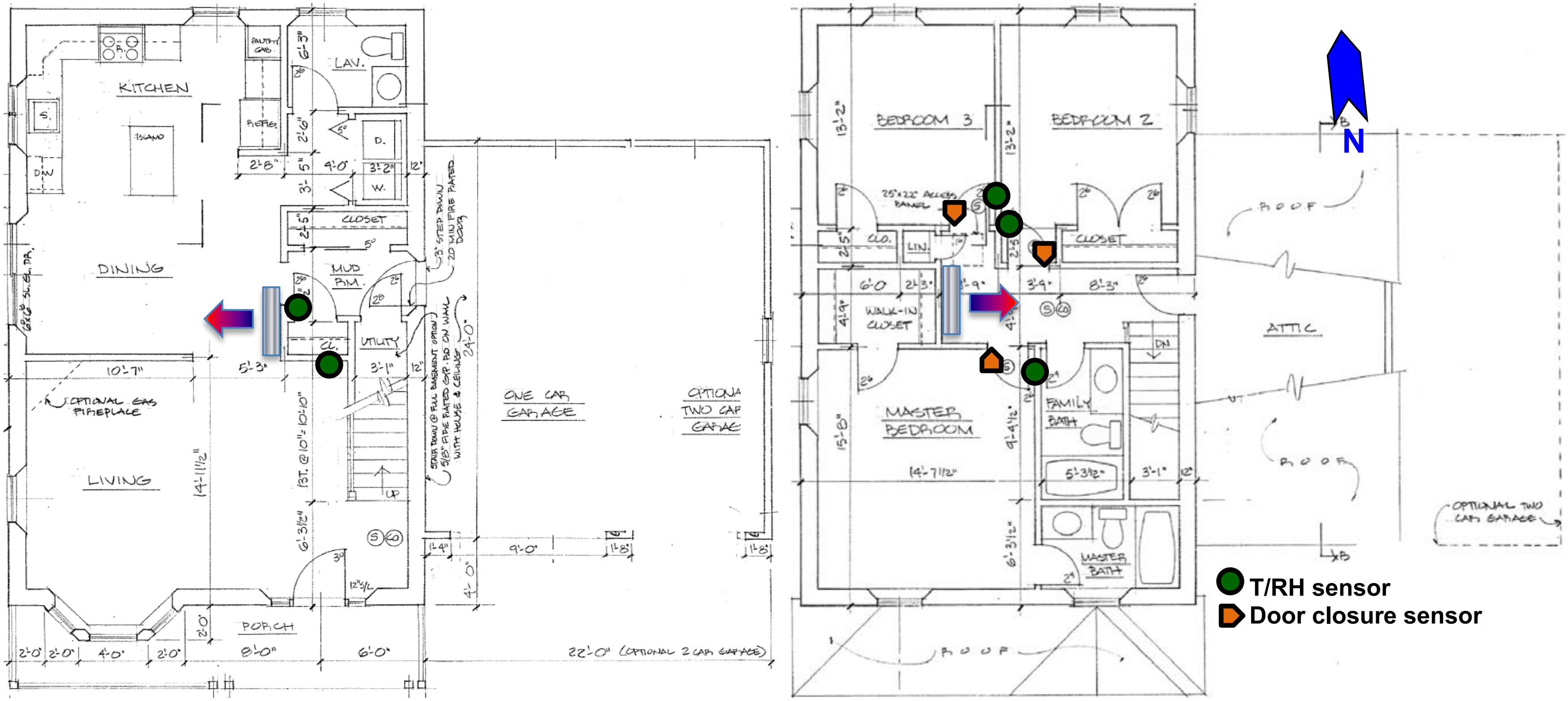

Figure 107. Devens Lot 4 floor plans, MSHP locations, monitoring locations

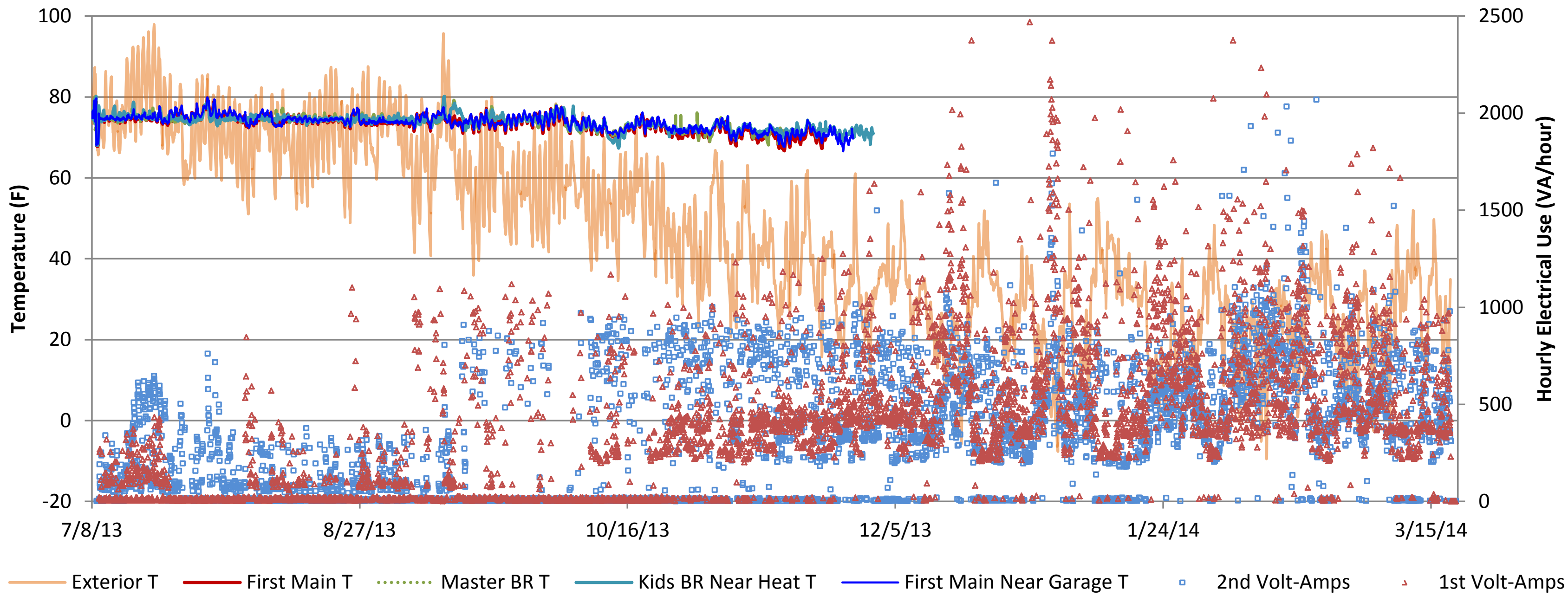

Figure 108. Devens Lot 4 interior and exterior temperatures, with MSHP hourly electricity use

Devens Lot 7 (Custom Saltbox)

Figure 109. Devens Lot 7 front and side views

This was one of three houses that were monitored from July 2013 through March 2014. Unfortunately, the interior temperature/RH loggers malfunctioned in November/December 2013; therefore, no temperature data were available for winter conditions. The MSHPs were logged with amperage measurements of one power leg.

This house has three MSHPs (two downstairs, one upstairs).

Table 29. Characteristics of Devens Lot 7

Characteristic	Value
Stories	2
Foundation Type	Basement
Square Footage (w/o bonus room)	1952 + 1256 basement
Bedrooms	3
Occupants	2 adults, 2 children
Bonus Room Status	n/a

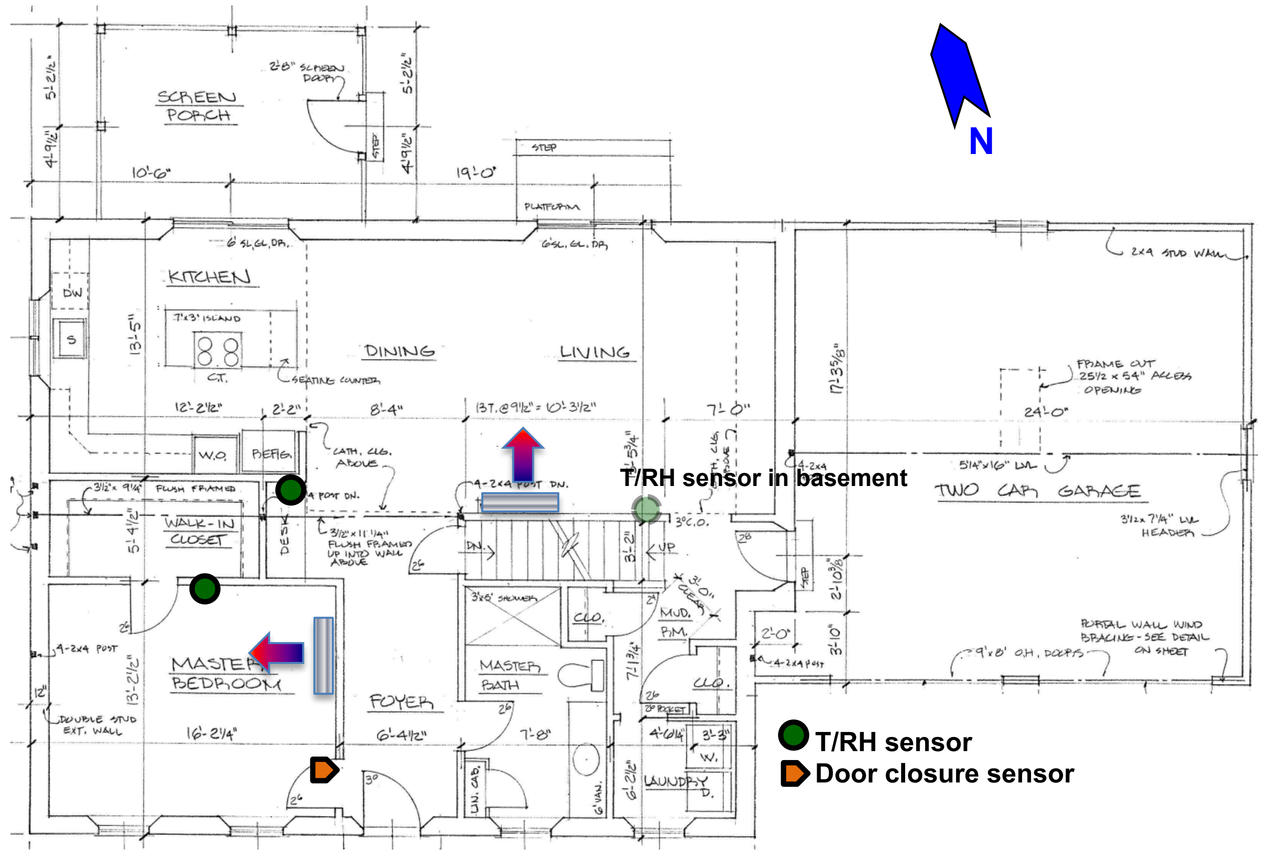

Figure 110. Devens Lot 7 floor plans, MSHP locations, monitoring locations

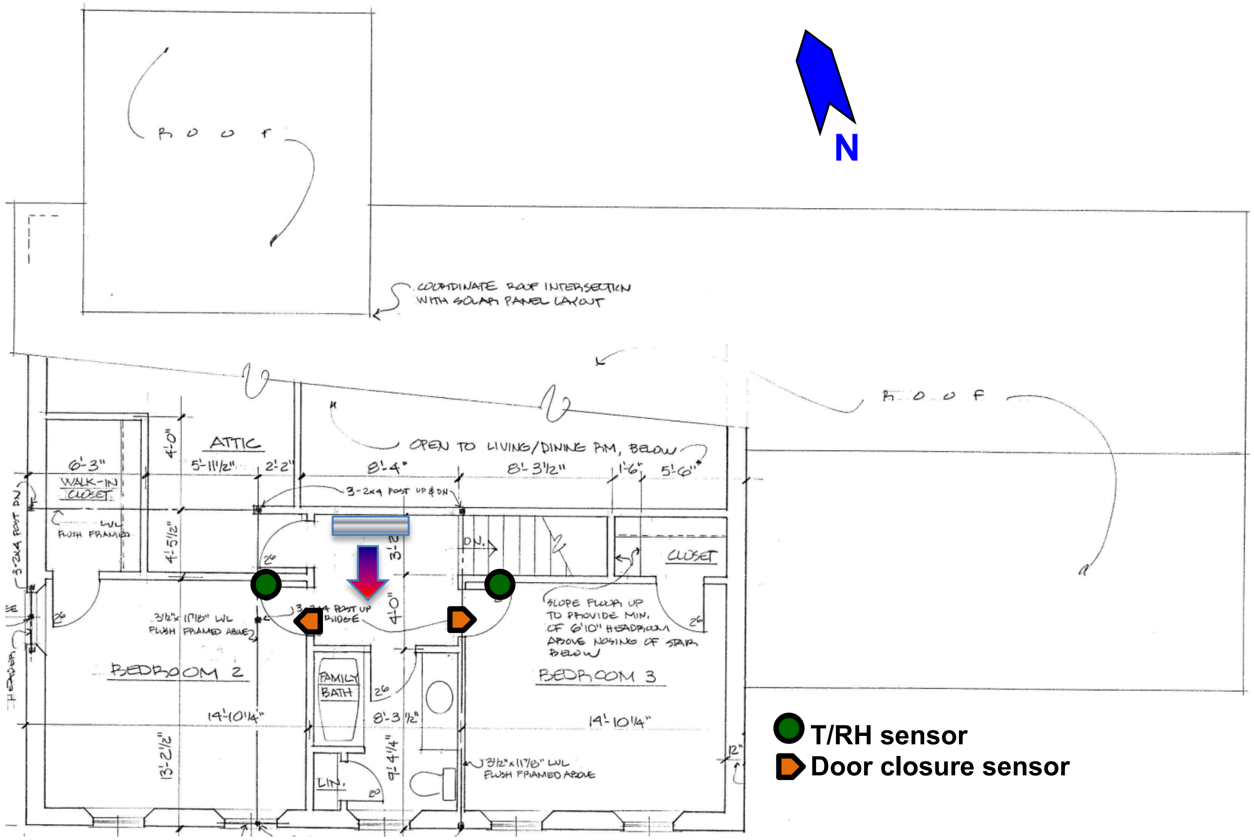

Figure 111. Devens Lot 7 floor plans, MSHP locations, monitoring locations

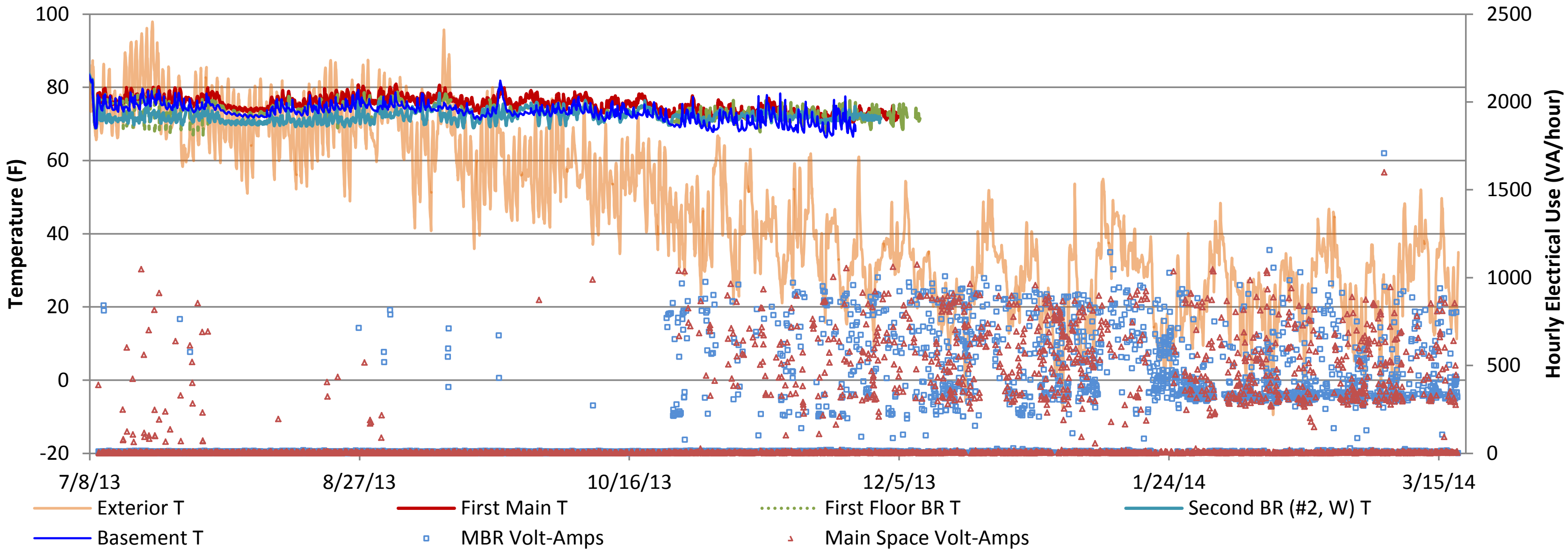

Figure 112. Devens Lot 7 interior and exterior temperatures, with MSHP hourly electricity use (downstairs units only)

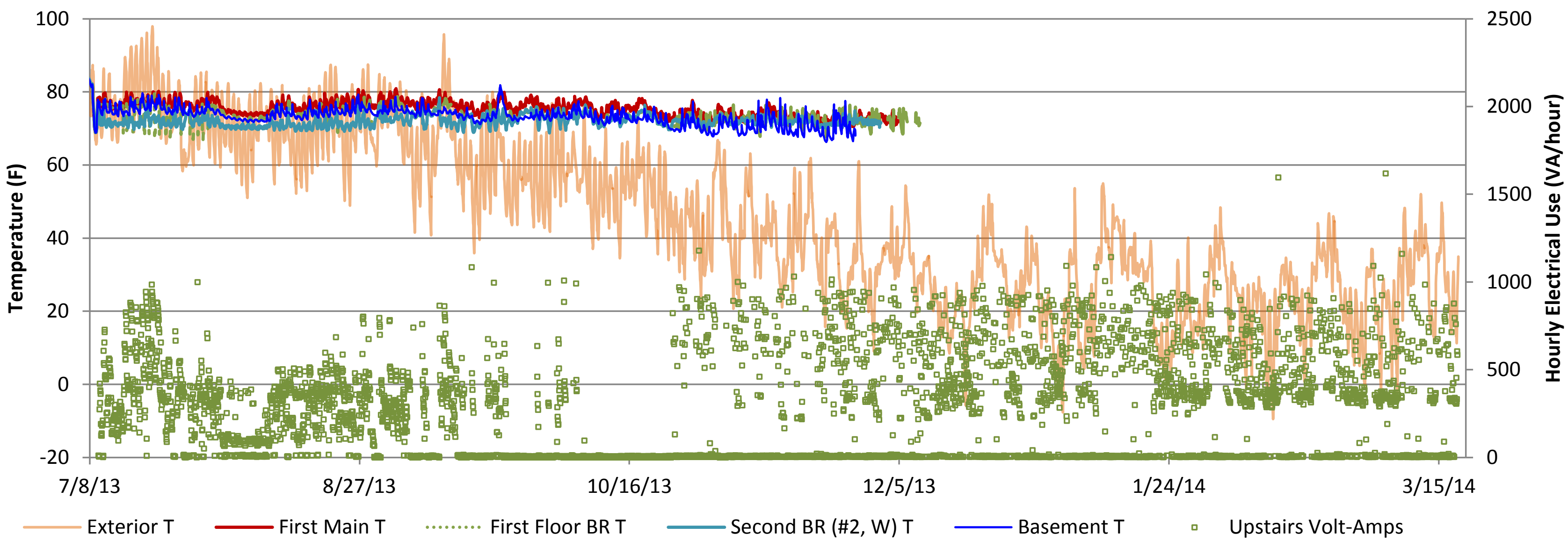

Figure 113. Devens Lot 7 interior and exterior temperatures, with MSHP hourly electricity use (upstairs unit only)

Devens Lot 8 (Ranch)

Figure 114. Devens Lot 8 front and side views

This was one of three houses that were monitored from July 2013 through March 2014. Unfortunately, the interior T/RH loggers malfunctioned in November/December 2013; therefore, no temperature data were available for winter conditions. The MSHPs were logged with amperage measurements of one power leg.

This house is the only one-story house monitored in this work.

Table 30. Characteristics of Devens Lot 8

Characteristic	Value
Stories	1
Foundation Type	Basement
Square Footage	1524 + 1524 basement
Bedrooms	2
Occupants	2 adults
Bonus Room Status	n/a

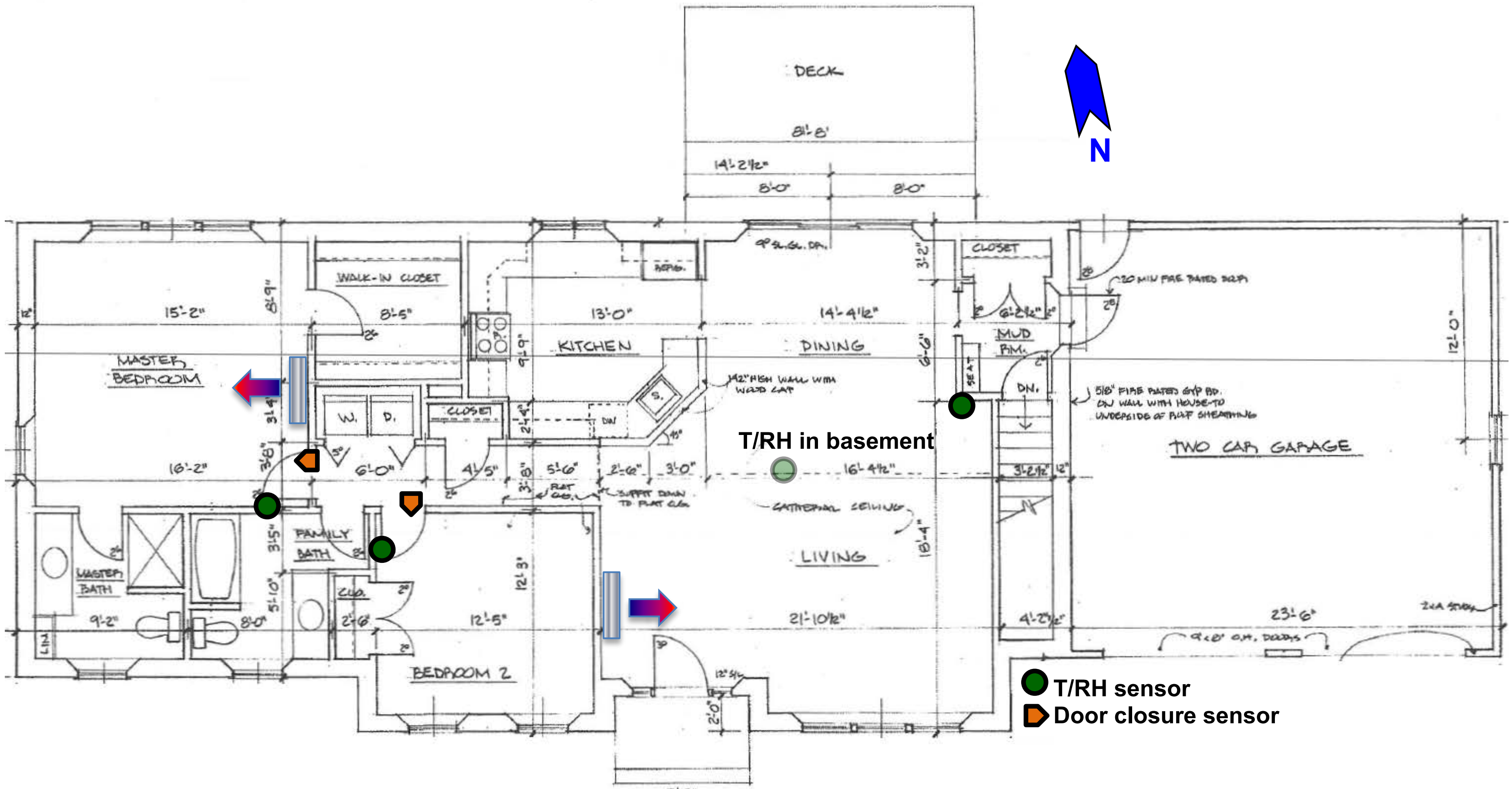

Figure 115. Devens Lot 8 floor plans, MSHP locations, monitoring locations

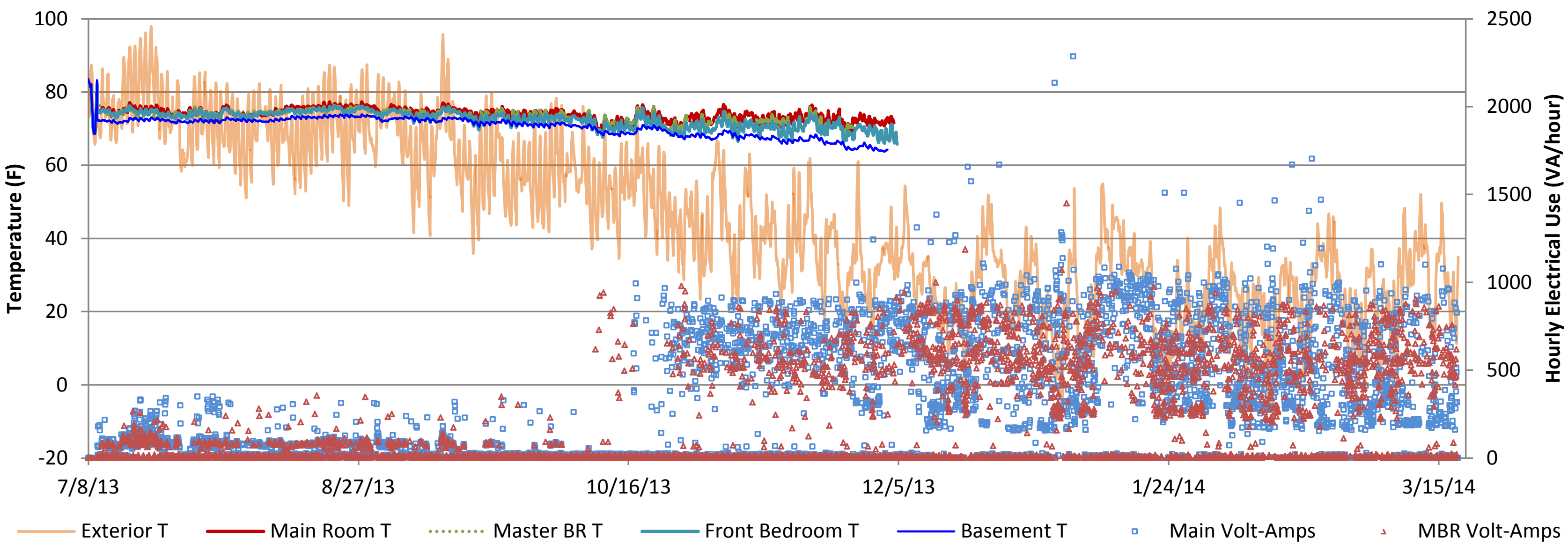

Figure 116. Devens Lot 8 interior and exterior temperatures, with MSHP hourly electricity use

Easthampton Lot 13 (Farmhouse) Former Model

Figure 117. Easthampton Lot 13 front and side views

This house was originally the model for this subdivision, but was sold in November 2013 to a family of four.

This house was equipped with a 120 CFM transfer fan, which draws air from the second-floor common space, and supplies it to the bedrooms. It was an inline fan, located in the attic; it also had an outdoor air hood to supply blended outside air to the bedrooms. However, it was not run in service, due to noise issues, even after being retrofitted with an inline duct noise muffler.

After this experience, the builder transitioned to low-sone ceiling-mounted exhaust fans for general dilution ventilation.

The master bedroom T/RH data are missing from October 2013–March 2014; the logger was missing during retrieval of instrumentation.

Table 31. Characteristics of Easthampton Lot 13

Characteristic	Value
Stories	2
Foundation Type	Slab
Square Footage (w/o bonus room)	1728
Bedrooms	3
Occupants	2 adults, 2 children
Bonus Room Status	Renovated by homeowner into office/professional space

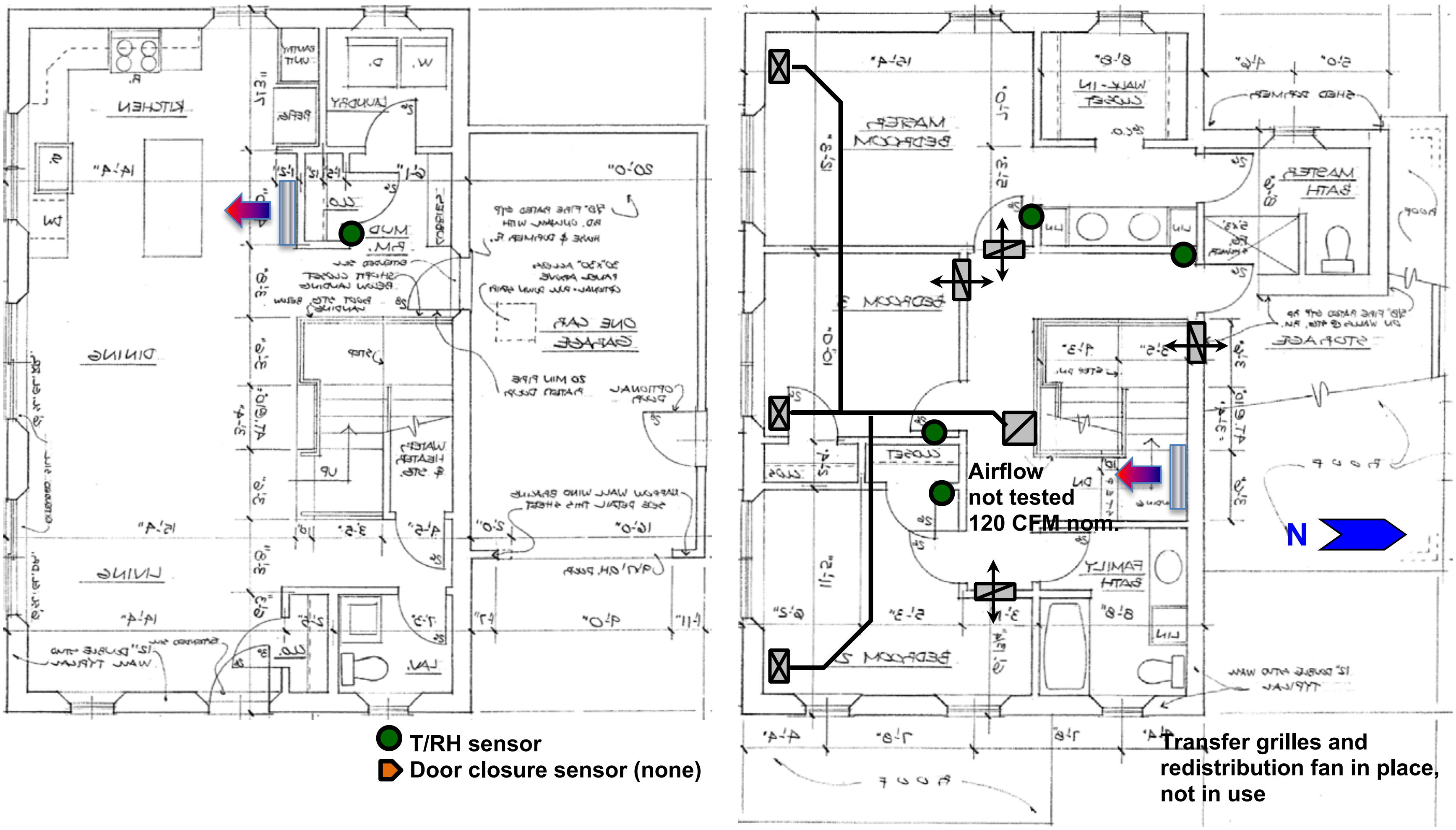

Figure 118. Easthampton Lot 13 floor plans, MSHP locations, monitoring locations

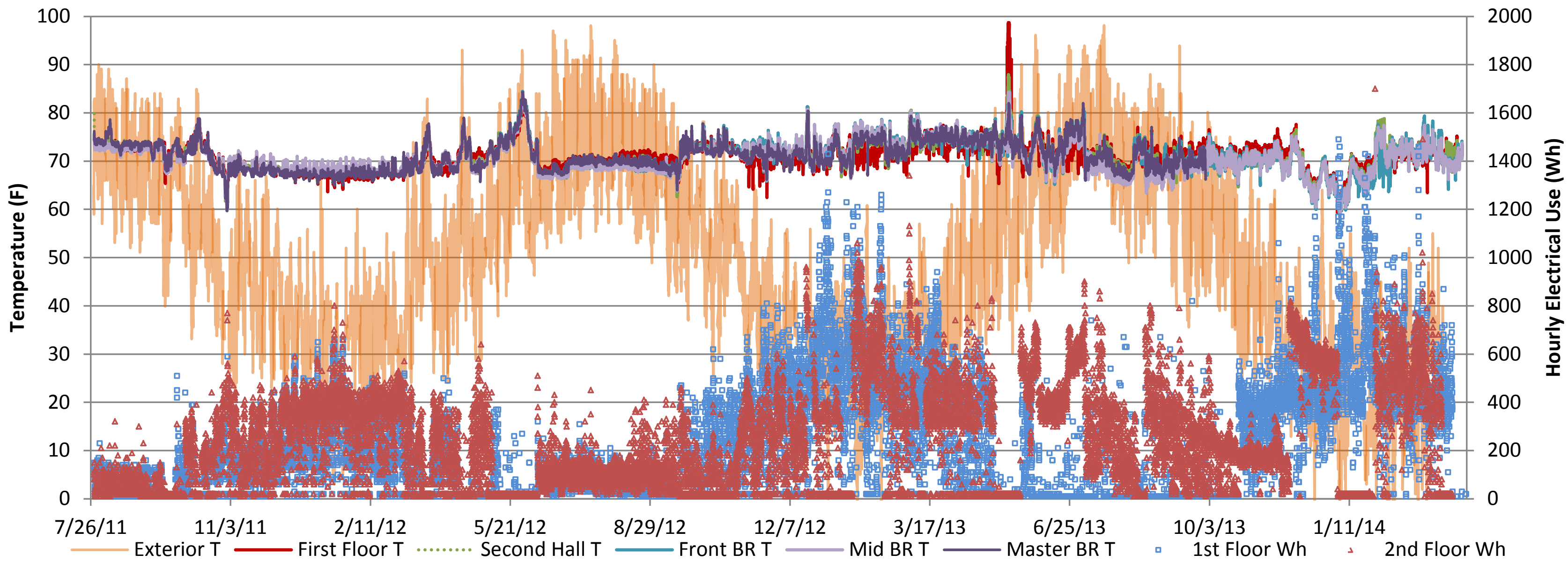

Figure 119. Easthampton Lot 13 interior and exterior temperatures, with MSHP hourly electricity use

Easthampton Lot 17 (Small Saltbox)

Figure 120. Easthampton Lot 17 front and side views

This was one of two houses that were retrofitted with a second MSHP head due to cooling season problems. This retrofit occurred in August 2012; it was installed in the upstairs Bedroom 2. The master bedroom (first floor) was used mostly as an office for most of the monitoring period, but was recently configured as a bedroom shortly before the conclusion of monitoring.

There is a 40 CFM ceiling-mounted exhaust fan used for temperature redistribution; it draws from the first-floor main space, and supplies to the three bedrooms. Flows were measured during site visits. During the first summer (prior to the second MSHP retrofit), the fan was configured to try to direct as much air as possible to the second floor, but it did not reach set point.

Table 32. Characteristics of Easthampton Lot 17

Characteristic	Value
Stories	2
Foundation Type	Slab
Square Footage (w/o bonus room)	1239
Bedrooms	3
Occupants	2 adults, 2 children
Bonus Room Status	n/a

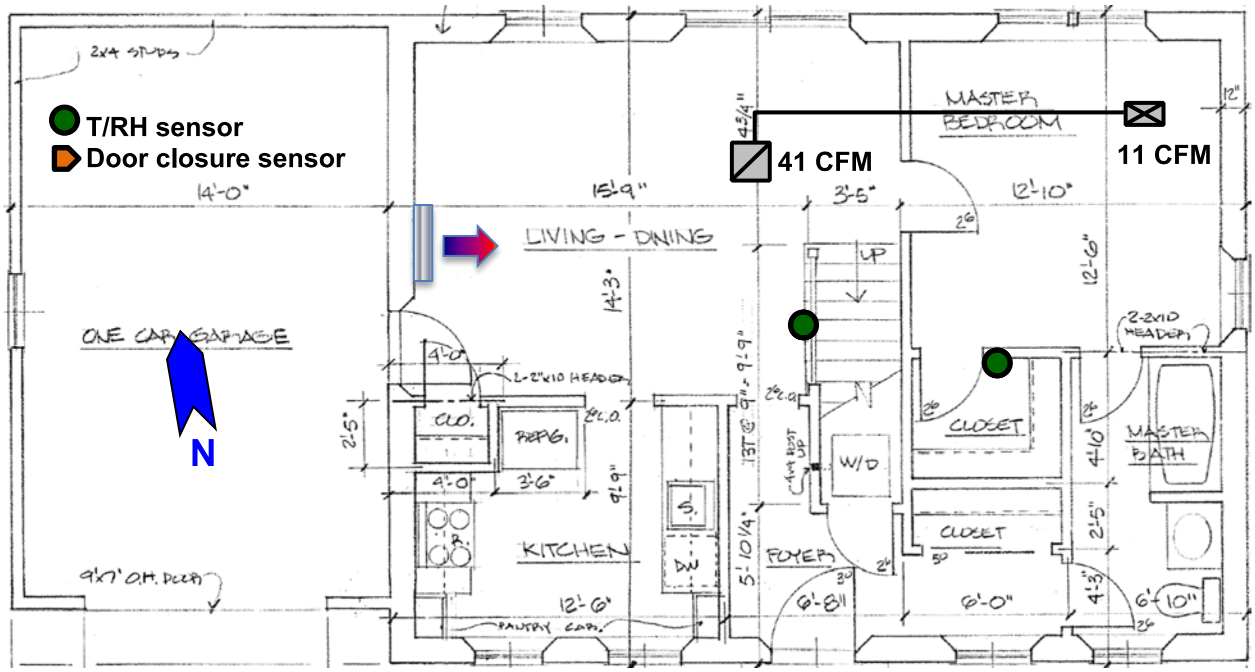

Figure 121. Easthampton Lot 17 first-floor plan, MSHP locations, monitoring locations

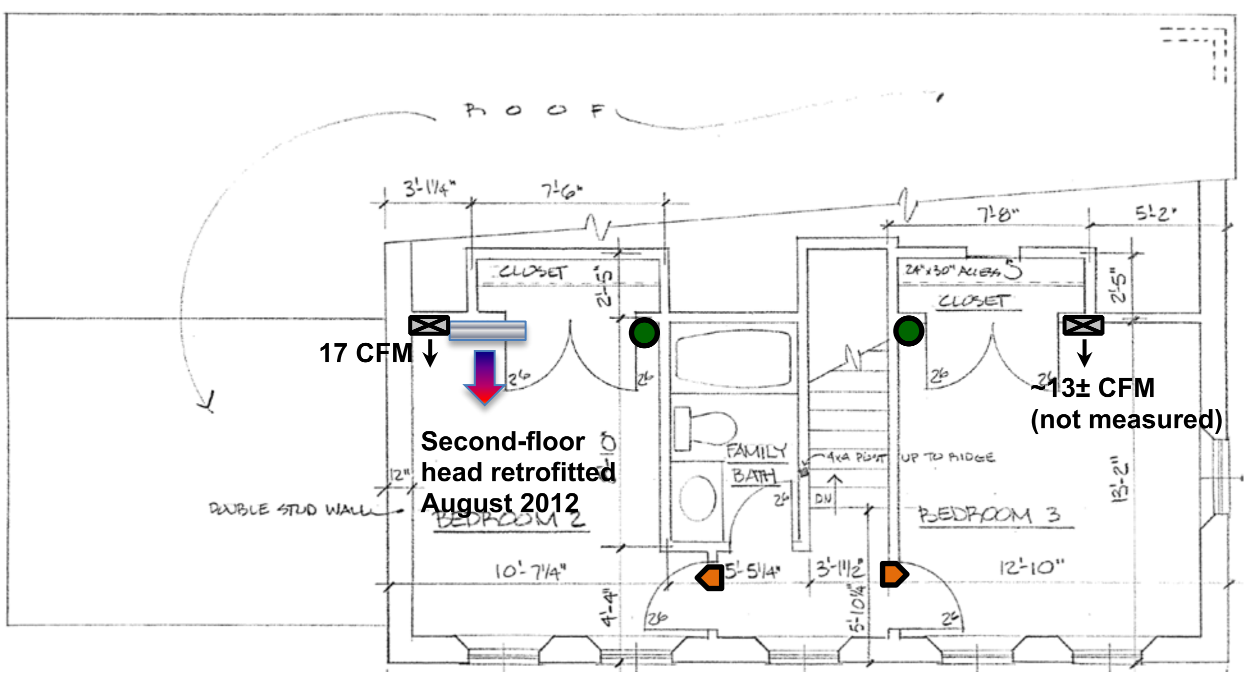

Figure 122. Easthampton Lot 17 second-floor plan, MSHP locations, monitoring locations

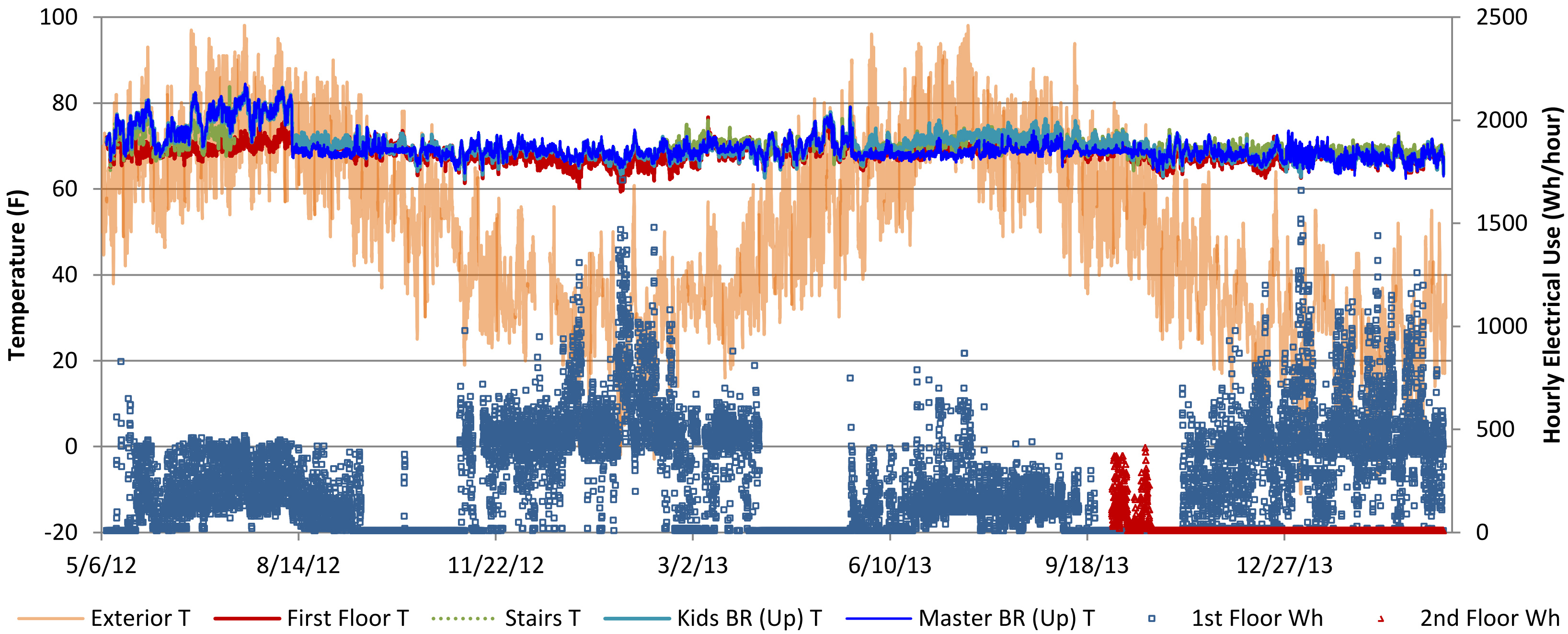

Figure 123. Easthampton Lot 17 interior and exterior temperatures, with MSHP hourly electricity use

Easthampton Lot 23 (Cottage)

Figure 124. Easthampton Lot 23 front and side views

This was one of two houses that were retrofitted with a second MSHP head due to cooling season problems. This retrofit occurred in August 2012; it was installed in the upstairs master bedroom.

This is the house that showed monitored evidence of deep setbacks or on/off operation of the MSHPs. This operation was confirmed during a site visit.

There is a 38 CFM ceiling-mounted exhaust fan used for temperature redistribution; it draws from the first-floor main space, and supplies to the two bedrooms. Flows were measured during site visits.

During the decommissioning visit (March 2014), the damper to the second-floor bedroom was closed by the research team, given that there was no longer a need to distribute heat from the first-floor unit to the second floor.

The bedroom 1 door sensor was not logging correctly until September 30, 2012.

Table 33. Characteristics of Easthampton Lot 23

Characteristic	Value
Stories	2
Foundation Type	Slab
Square Footage (w/o bonus room)	1132
Bedrooms	2
Occupants	2 adults
Bonus Room Status	n/a

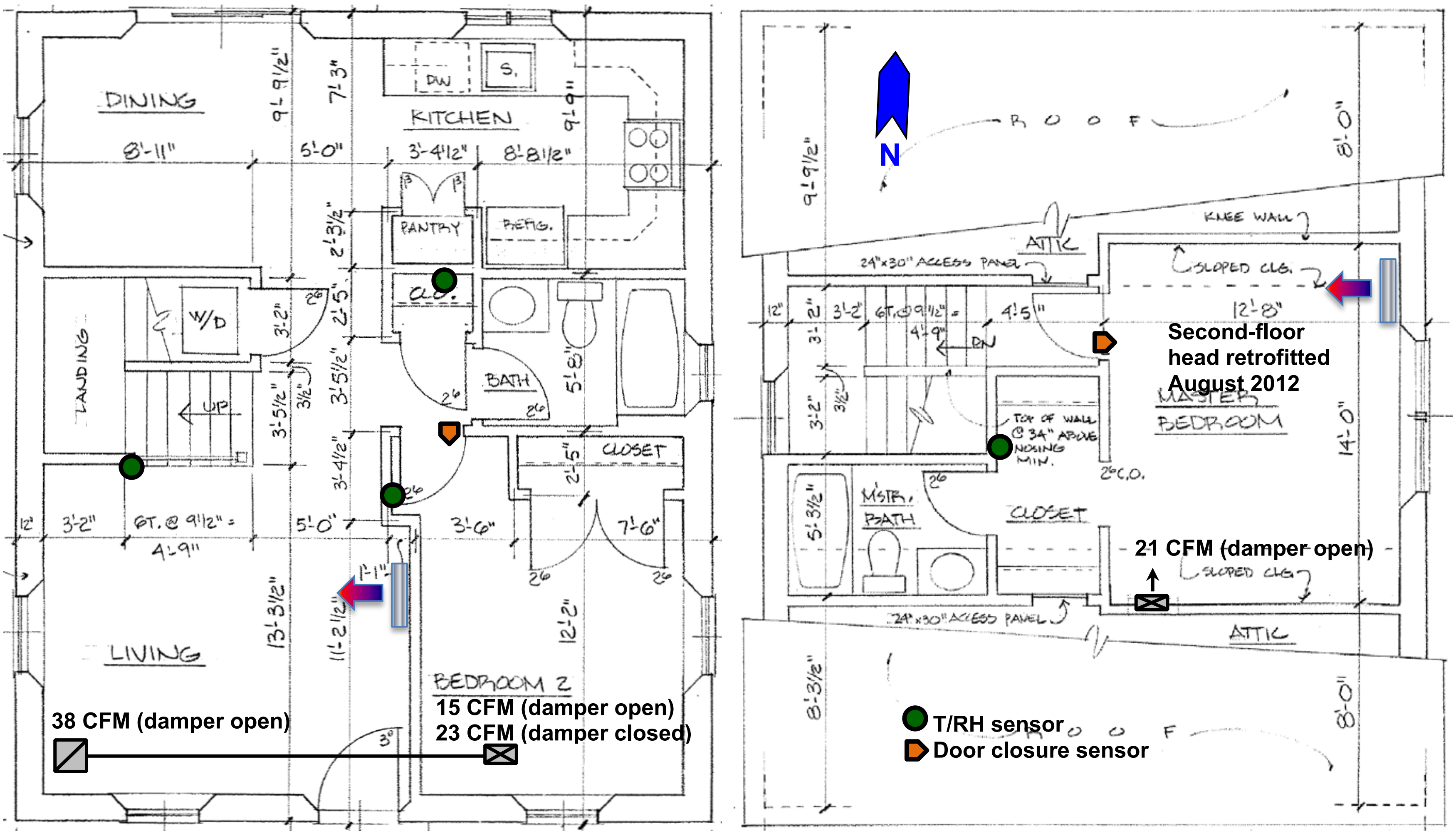

Figure 125. Easthampton Lot 23 floor plans, MSHP locations, monitoring locations

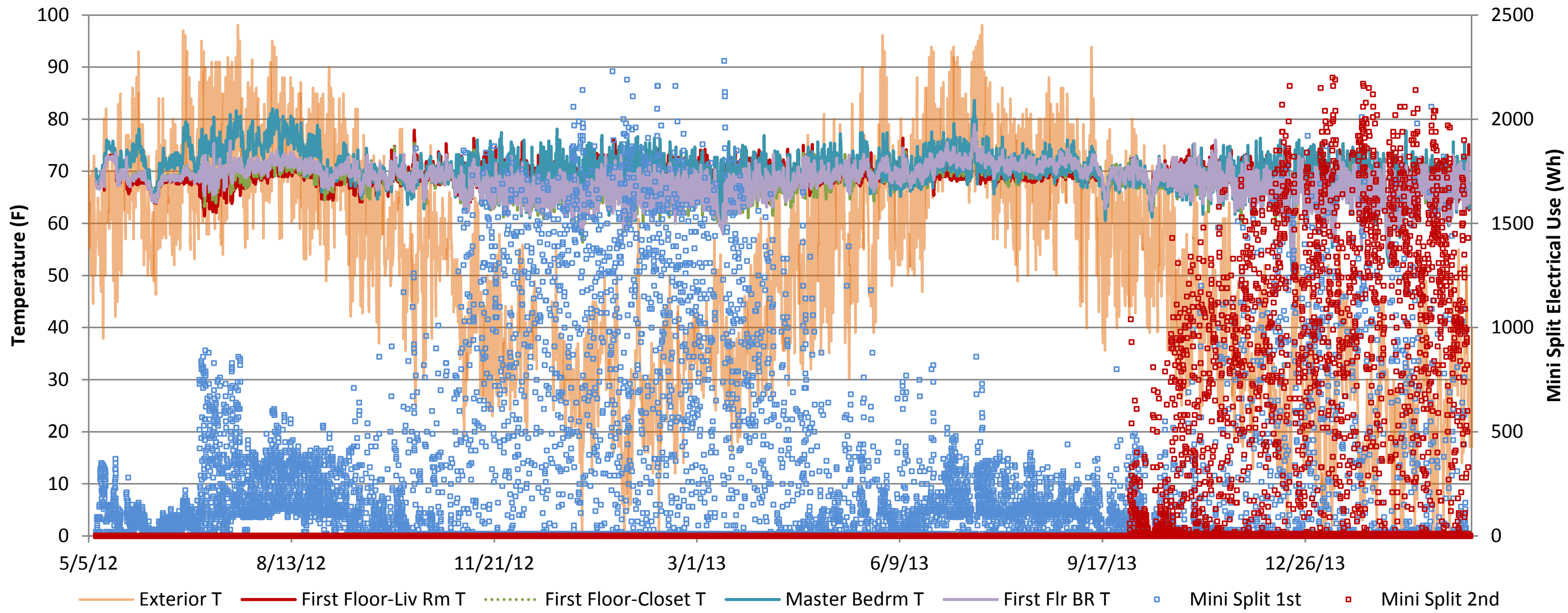

Figure 126. Easthampton Lot 23 interior and exterior temperatures, with MSHP hourly electricity use

Easthampton Lot 30 (Custom Home, Comfort Complaint)

 

Figure 127. Easthampton Lot 30 front and side views

This was the house that had comfort complaints, due to cold conditions in the bonus room and master bedroom (rear) suite. A 3:1 (three indoor heads; one outdoor unit) MXZ series MSHP was retrofitted after the complaint, with one head in each bedroom. No complaints have been reported since this retrofit.

No MSHP electricity use instrumentation was installed at this site.

Table 34. Characteristics of Easthampton Lot 30

Characteristic	Value
Stories	2
Foundation Type	Basement
Square Footage (includes bonus room)	2266 + 979 basement
Bedrooms	3
Occupants	2 adults, 1 child
Bonus Room Status	Part of finished plan

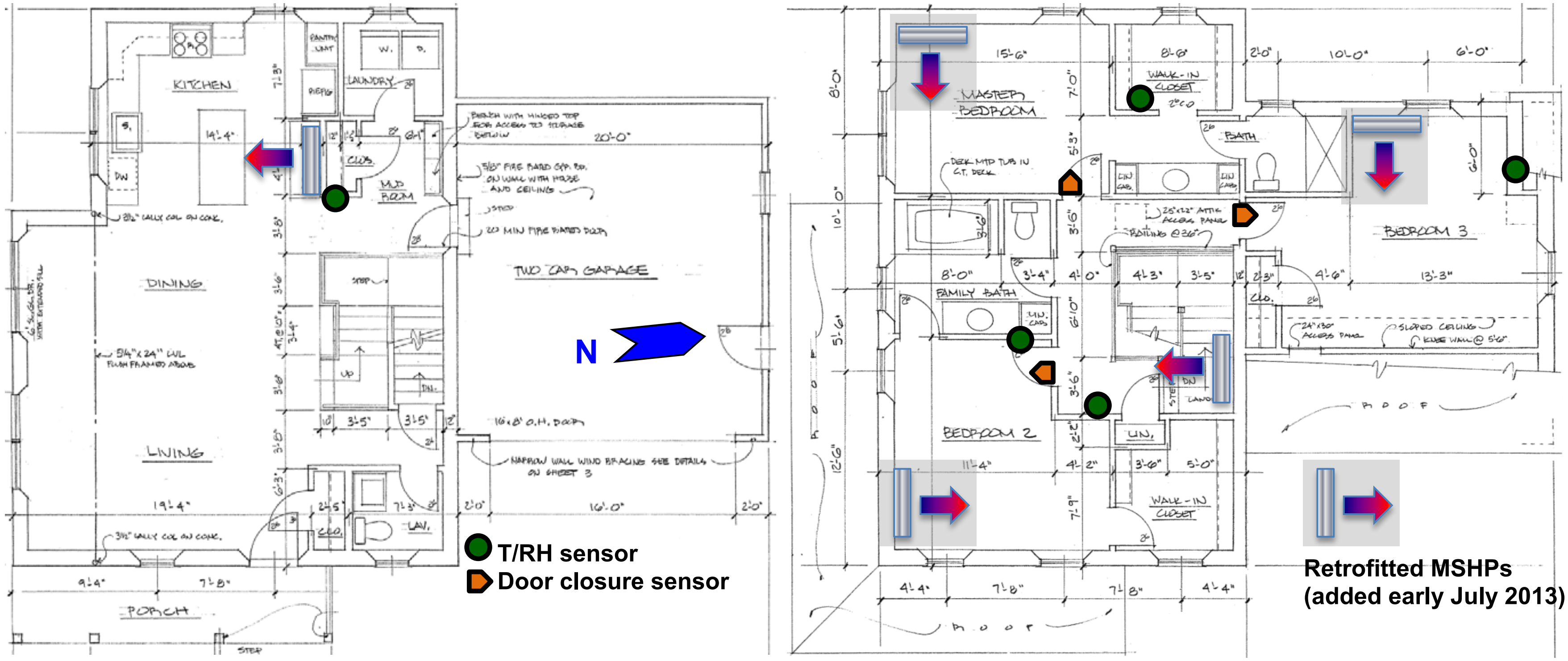

Figure 128. Easthampton Lot 30 floor plans, MSHP locations, monitoring locations

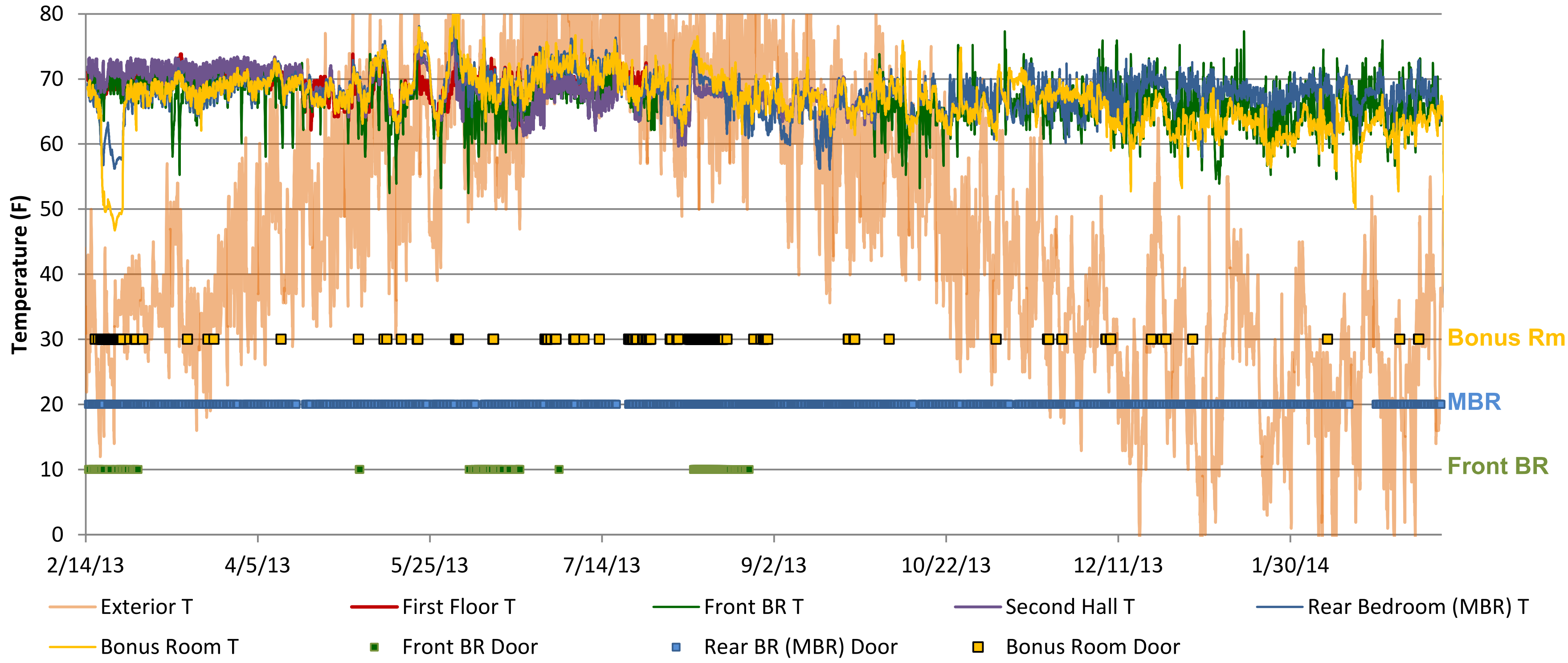

Figure 129. Easthampton Lot 30 interior and exterior temperatures, with door closure status (over 50% closed hours)

Appendix D: House Design Loads and Equipment Capacity

The design temperatures for the development locations were as follows:

- Easthampton (Greenfield, Massachusetts weather station: winter –2°F/summer 85°F)
- Devens (Worcester, Massachusetts weather station: winter 4°F/summer 84°F).

Design heating and cooling loads for the houses are shown inTable 35.

Table 35. Heating and Cooling Design Loads for Devens and Easthampton Houses

Location	Lot	Model	REM/Rate Square Feet	Design Loads Heating kBtu/h	Design Loads Cooling kBtu/h
Devens	3	Victorian	1728	16.8	9.6
Devens	4	Farmhouse	1728	16.3	9.7
Devens	7	Custom Saltbox	1952	18.2	10.6
Devens	8	Ranch	1524	13.0	6.7
Easthampton	13	Farmhouse	1728	12.1	8.7
Easthampton	17	Small Saltbox	1239	11.0	7.3
Easthampton	23	Cottage	1132	10.0	7.0
Easthampton	30	Custom Home	2266	18.1	11.3

The installed equipment capacity is compared to the design loads in Table 36 in terms of a percent oversizing factor. Several houses had new equipment installed after construction; both triple head (see Builder Mini-Split Heat Pump Experience), and adding second-floor head; retrofitted equipment capacity is noted in [brackets].

Table 36. Heating Design Loads and Equipment Sizing for Devens and Easthampton Houses

Location	Lot	Square Feet	Heating Design Load kBtu/h	Installed Equipment Capacity kBtu/h	Oversizing Factor
Devens	3	1728	16.8	25.0	149%
Devens	4	1728	16.3	25.0	153%
Devens	7	1952	18.2	37.5[a]	206%
Devens	8	1524	13.0	25.0	192%
Easthampton	13	1728	12.1	22.0	182%
Easthampton	17	1239	11.0	11.0 [22.0][b]	100% [200%]
Easthampton	23	1132	10.0	11.0 [22.0][b]	110% [220%]
Easthampton	30	2266	18.1	22.0 [33.7][c]	121% [186%]

Original installed capacity [Retrofitted Equipment Capacity]
[a] 3x 12,000 heads installed at Devens Lot 7
[b] Second MSHP head added on second floor after cooling season issues
[c] Second-floor switch from MSHP to 3:1 multisplit (MXZ, not low-temperature capacity)

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