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BUILDING TECHNOLOGIES PROGRAM

High Performance New Construction in Climate Zones 2 – 4

M. L. Sweet, Ph.D., A. Francisco, and S. G. Roberts, Ph.D.

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High Performance New Construction in Climate Zones 2-4

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Prepared by:

M. L. Sweet, A. Francisco, and S. G. Roberts
Southface Energy Institute

As a part of the Home Innovations Research Lab's
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400 Prince George's Boulevard

Upper Marlboro, Maryland 20774

NREL Technical Monitor: Stacey Rothgeb

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Definitions

ACH_{50}	Air changes per hour at 50 Pascals, infiltration measurement
AFUE	Annual Fuel Utilization Efficiency
Btu	British thermal unit, unit of energy
CFA	Conditioned floor area
CFIS	Central fan integrated supply, ventilation method
CFL	Compact fluorescent lamp
CFM_{25}	Air flow (CFM) at 25 Pascals, duct leakage measurement
CFM_{50}	Air flow (CFM) at 50 Pascals, infiltration measurement
CMU	Concrete masonry unit
CO	Carbon monoxide
COP	Coefficient of performance
CZ	Climate Zone
EF	Efficiency Factor (domestic hot water efficiency)
ERSWH	Electric Resistance Storage Water Heater
EPACT	Energy Policy Act of 2005
GSHP	Ground Source Heat Pump
HSPF	Heating seasonal performance factor, heating efficiency
HVAC	Heating, ventilation, and air conditioning
kWh	Kilowatt hour, power measurement
LFL	Linear fluorescent lamps
NCTH	New construction test house
SEER	Seasonal energy efficiency ratio, cooling efficiency
SHGC	Solar Heat Gain Coefficient
SLA	Specific leakage area, infiltration measurement
SPF	Spray polyurethane foam
Sq.ft	Square Footage (Area)
TND	Traditional Neighborhood Development
ZERH	Zero Energy Ready Home

Executive Summary

Southface Energy Institute (Southface) partnered with owners and/or builders with various market constraints and ultimate goals for three projects in different climate zones (CZ): Savannah Gardens in Savannah, GA (CZ 2), JMC Patrick Square in Clemson, SC (CZ 3), and LaFayette in LaFayette, GA (CZ 4). This report documents the design process, computational energy modeling, construction, envelope performance metrics, long term monitoring results, and successes and failures of the design and execution of these high performance homes.

The three bedroom/two bathroom test home in Savannah Gardens is approximately 1,200 ft^2 on an elevated slab foundation and has a semi-conditioned, encapsulated attic. A neighboring home built to their standard EarthCraft specifications was also monitored as a control for certain measures, namely exterior foam insulation and a heat pump water heater (HPWH). Analysis predicted a net positive annual cash flow for the owner of $45.

The JMC Patrick Square project is a single floor with, 1,828 ft^2 of conditioned living space, three bedrooms, two bathrooms, and an attached two car garage. This small-scale production builder wanted to increase their level of energy efficiency beyond their current green building practices, including bringing ducts into conditioned space. Through a combination of upgrade measures the team met this goal and achieved many Zero Energy Ready Home requirements.

LaFayette Housing Authority partnered with Lord, Aeck & Sarget architects and Southface to design and construct a development of 30 affordable rental housing units in 15 duplexes in LaFayette, GA. Because they would be long-term owners, their priorities were low utiilty bills for the residents and durable, maintainable buildings. The team employeed BEopt to optimize buidling envelope and systems choices, including 2x6 advanced framed walls, insulated slab, and heat pump water heater in a utility closet which was ducted to/from an encapsulated attic.

Monitoring of four ducted HPWHs in LaFayette and one in Savannah revealed that HPWH exhaust air only impacts attic air during HPWH run time, and attic conditions return to previous levels shortly after the HPWH turns off. The HPWH did not appear to impact the loads on the heating and cooling systems, which were also located in the attic. HPWHs should not be considered dehumidifiers if one is needed in an attic or basement/crawlspace.

Ducting the HPWHs did not negatively impact performance compared to other published data of field performace. Additionally, changing duct configurations also did not alter COP. HPWHs in efficiency mode (heat pump only) were capable of satisfying hot water demand for most residents. This mode maximizes energy efficiency.

Adding ½ inch of insulated sheathing using the Huber Zip Syster R Sheathing reduced peak summer and increased minimum winter temperatures inside the wall assemblies compared to the neighbor home. The neighbor home experiences signifcantly more risk of condensation and failed ASHRAE Standard 160-2009: Criteria for Moisture-Control Design Analysis in Buildings. Dispite the fact that energy modeling only predicted a 2% annual savings from the insulated sheathing, preliminary data indicates reduced HVAC run times and energy consumption attributed to this measure. Additonal research is necessary.

1 Introduction

1.1 Problem Statement

The purpose of this report is to document the design process, computational energy modeling, construction, envelope performance metrics, and long term monitoring results of three high performance homes in three different Southeastern Climate Zones (CZ). The three projects in this report are referred to accordingly: Savannah Gardens located in Savannah, GA (CZ 2), JMC Patrick Square in Clemson, SC (CZ 3), and LaFayette in LaFayette, GA (CZ 4). Southface Energy Institute (Southface) partnered with owners and/or builders with different market constraints and ultimate goals for each project. Southface's partnerships in Savannah Gardens and LaFayette were with the local municipality's housing authority, while the partnership for JMC Patrick Square was with a small-scale production builder. The housing authorities' key driver was to provide comfortable housing with low utility bills to people who qualified for affordable housing, however one project was rental and the other owner-occupied. The production builder's key driver was to maximize market value with efficiency improvements that fit within their existing construction practices. Heating and cooling degree days for each location are listed in Table 1.

Table 1. Heating and cooling degree days (base 65°F) of the three project sites. Degrees day calculations are the average of the last 5 years. Historical data obtained from nearest data collection site archived in the National Climatic Data Center database.

Location	CZ	Heating Degree Days	Cooling Degree Days
Savannah, GA	2	1,985	2,644
Clemson, SC	3	2,770	2,193
LaFayette, GA	4	3,415	2,042

1.2 Project Overview

1.2.1 *Savannah Gardens*

Southface partnered with the Savannah Housing Department (SHD) to specify and construct a single family new construction test home (NCTH) in Savannah, Georgia (CZ 2) (Figure 2). SHD's goal was to redevelop a poverty stricken community with sustainable homes at affordable prices for income-qualified buyers. The home is located in the Savannah Gardens community, a 44 acre site redeveloped to meet the standards of the EarthCraft Communities[1] program (Community Housing Services Agency Inc., 2012). The Savannah Gardens community is part of a large neighborhood redevelopment effort and will include over 500 housing units (120 single family) upon completion. The site's master plan includes five acres of green space, and all homes are required to earn EarthCraft Certification. The three bedroom/two bathroom test home is approximately 1,200 square feet of conditioned floor space on an elevated slab foundation and has a semi-conditioned, encapsulated attic. Like all homes in the community, this home is all electric, and no natural gas service is available. While Southface partnered with SHD and Chatham Home Builders on the construction of Lot 207, a neighboring home built to their standard EarthCraft specifications was also monitored as a control for comparison of certain measures, namely exterior foam insulation and a heat pump water heater (HPWH). Construction was completed in 2013.

[1] http://earthcraft.org/communities

Figure 1. Savannah Gardens Lot 207.

1.2.2 *JMC Patrick Square*

A small-scale production builder partnered with Southface on the design and construction of a NCTH in Clemson, SC in the mixed humid climate (CZ 3) (Figure 2). As a homebuilder also participating in Southface's regional high-performance/green building program, EarthCraft Communities, the builder sought a cost-effective approach to reaching even higher levels of energy savings and homebuyer value. In addition, the team set a goal to achieve DOE Challenge Home / Zero Energy Ready Home certification and the Energy Policy Act of 2005 (EPAct) tax credit. The plan chosen for the prototype home includes a single floor with, 1,828 ft^2 of conditioned living space, three bedrooms, two bathrooms, and an attached two car garage. The team restricted their options to measures that could be replicable to future construction beyond this test home, including various plan layouts and foundation types. The perceived ability to sell the improvement cost to homebuyers was a key driver in selecting the final measure package. Foundation and attic construction were chosen in order to move HVAC air handler unit and ducts into conditioned space and achieve cost-effective elevations and storm water control on this lot. The builder chose a semi-conditioned encapsulated attic and elevated slab foundation. Construction was completed in January 2015.

Figure 2. JMC – Patrick Square Test Home.

1.2.3 *LaFayette Housing Authority*

Southface partnered with the LaFayette Housing Authority (LHA) and architecture firm Lord Aeck & Sargent (LAS) to design, construct, and test 30 sustainable, affordable housing units in 15 duplexes (Figure 4). Each one-story duplex is comprised of a two bedroom and three bedroom unit. Lafayette, GA is situated in the northwest corner of the state, approximately 30 miles due south of Chattanooga, TN (CZ 4). Client goals were to minimize occupant utility bills and increase property durability and maintainability. This project, which is seeking LEED for Homes Gold certification, was intended to serve as replicable example for rural housing authorities following the design-bid-build procurement process, which is typical of public housing initiatives.

Figure 3. Typical Lafayette 2BR/3BR Duplex.

1.3 Research Questions

The research goals for all test homes included developing replicable energy efficiency solution packages that meet Building America savings goals. Each project had individual additional marketing, construction, maintenance, or technology goals and questions.

1.3.1 *Savannah Gardens*

The Lot 207 test home was constructed with Huber's ZIP System® R-Sheathing (½" of rigid foam) in the vertical walls of the building envelope and equipped with an A.O. Smith Voltex® heat pump water heater (HPWH) located in an open cell spray polyurethane foam (SPF) sealed attic. Southface's long term research interests in this project were to analyze the performance of these two unique features over the course of a year and expand the knowledge of actual field performance of these emerging technologies. Temperature, humidity, and wood moisture content (WMC) inside the wall assemblies and attic temperatures and humidities were monitored in the test home and a similarly built neighboring home. The neighboring home provided a baseline as it has approximately the same dimensions, but has an electric resistance storage water heater in the attic and is clad with traditional ZIP System® sheathing without the rigid foam. The data will also provide a reference point for future computational models. The following questions are to be answered:

- What is the average daily coefficient of performance (COP) of the HPWH as a function of daily hot water use, and real-world variations in use patterns?
- The ability of the HPWH to keep up with hot water demand, and if occupants change the operating mode or temperature set point to ensure they have enough hot water. Determine the amount and any patterns of auxiliary electric heat supplied.
- The effect HPWH exhaust air has on temperature and relative humidity conditions in the attic space and any effect on HVAC system performance which is also located in the encapsulated attic.
- Impact of HPWH ducting on water heater COP.
- How much does the insulated sheathing effect cavity temperature and moisture content of exterior walls?
- Describe behavioral difference of both wall systems under extreme weather conditions to explore issues of resilience.

1.3.2 *JMC Patrick Square*

The research goals for the JMC test home included developing a market-ready, energy efficiency solution package that meets Building America savings goals, assessing cost/performance tradeoffs that improve overall system performance and value while minimizing increased cost, and including consideration of occupant comfort, health and safety. Because this builder was already building homes within a high-performance/green building program, particular attention was given to identification of gaps or improvements necessary to meet DOE Challenge Home / Zero Energy Ready Home program requirements.

Evaluation of success includes calculation of estimated energy savings, evaluation of overall costs, identification of systems integration opportunities, and identification QA/QC lessons learned. No long term monitoring was conducted at this site.

1.3.3 *LaFayette Housing Authority*

The research focus for the LaFayette project will be the performance of the HPWH installed with different ducting configurations. It will also clarify the potential space conditioning impacts of a HPWH drawing air from and exhausting air to an SPF encapsulated attic. Four HPWH units were monitored. Southface monitored HPWH power consumption, temperature and relative humidity conditions in the attic and mechanical closet, inlet and exit water temperatures, and domestic hot water (DHW) flow rates. Additionally, Southface and LHA administered a resident survey. The following questions are addressed:

- What is the average daily COP as a function of daily hot water use, and real-world variations in use patterns?
- The ability of the HPWH to keep up with hot water demand, and if occupants report challenges in meeting hot water demand.
- The effect water heater exhaust air has on temperature and relative humidity conditions in the attic space and mechanical closet.
- Resident acceptance of this emerging technology, as installed.
- Perceived resident comfort and energy conservation measures.

This research also provides real-world hot water draw profiles associated with low flow fixtures.

2 Test Home Specifications

2.1 Overview

Southface worked with each team of builder and designer/architects to specify energy efficiency solution packages which achieved Building America and builder/owner's energy efficiency goals, as well as constructability and marketing goals. The as-built specifications are listed in Table 2, below.

Table 2. Test Home Specifications.

Measure	Savannah	JMC	LaFayette
Foundation	Elevated Slab	Elevated Slab	Slab on grade
Foundation Insulation	Uninsulated	Uninsulated	R-5 perimeter
Wall Construction	2x4, 16 in o.c., advanced framing	2x4, 16 in o.c.	2x6, 24 in. o.c., advanced framing
Wall Insulation	R-13 Fiberglass Batts, Grade I; R-3.6 Insulated exterior sheathing	Grade I, R-13 Cellulose	Grade I, R-22 Blown-in Fiberglass
Ceiling Construction	Encapsulated Attic	Encapsulated Attic	Encapsulated Attic
Ceiling Insulation	R-20 open-cell spray foam	R-20 open-cell spray foam	R-20 open-cell spray foam
Window Ratings	U-0.34, SHGC-0.26	U-0.33, SHGC-0.24	U-0.35, SHGC-0.31
Infiltration	1.88 ACH_{50}	2.5 ACH_{50}	2.1 ACH_{50}*

Heating Efficiency	3.7 COP	Gas 92.5% AFUE	8 HSPF
Cooling Efficiency	18.6 EER	16 SEER; 1 stage compressor	14 SEER
Supply Duct Location	Encapsulated Attic	Encapsulated Attic	Encapsulated Attic
Return Duct Location	Encapsulated Attic	Encapsulated Attic	Encapsulated Attic
Duct Leakage	R-8 Flex Insulation, 0% to outside	R-10 Insulation, 0% to outside	R-6 Flex Insulation, 0% to outside
Ventilation	Balanced	Supply only	Supply only
Hot Water Efficiency	HPWH, 2.33 EF, R-2 Trunk Branch PEX	ENERGY STAR tankless; 0.82 EF gas, R-2 Trunk Branch PEX	HPWH, 2.33 EF, R-2 Trunk Branch PEX
Lighting	90% CFL, 10% LFL	90% incandescent; 10% CFL	80% Fluorescent
Appliances	ENERGY STAR	Gas range; ENERGY STAR dishwasher 260 kWh	ENERGY STAR

*Average of four homes

2.2 Savannah Gardens

The Savannah Garden NCTH was built within a community utilizing a pre-approved set of construction plans. The team, therefore, worked within the chosen plan to upgrade specifications on the given lot in order to meet project goals (Figure 4). The two significant upgrades were to include Huber's ZIP System® R-Sheathing (½" of rigid foam) and an A.O. Smith Voltex (PHPT-60) HPWH in the attic.

2.3 JMC Patrick Square

JMC chose the York Cottage for the prototype home on a prominent, corner lot. This plan includes a single floor with elevated slab foundation, 1,828 ft^2 of conditioned living space, three bedrooms, two bathrooms, an unfinished attic, and an attached, two car garage. Figure 5, below, represents JMC's York Cottage base model. The NCTH was upgraded with a sunroom and a tankless gas water heater replacing the tank shown in the garage.

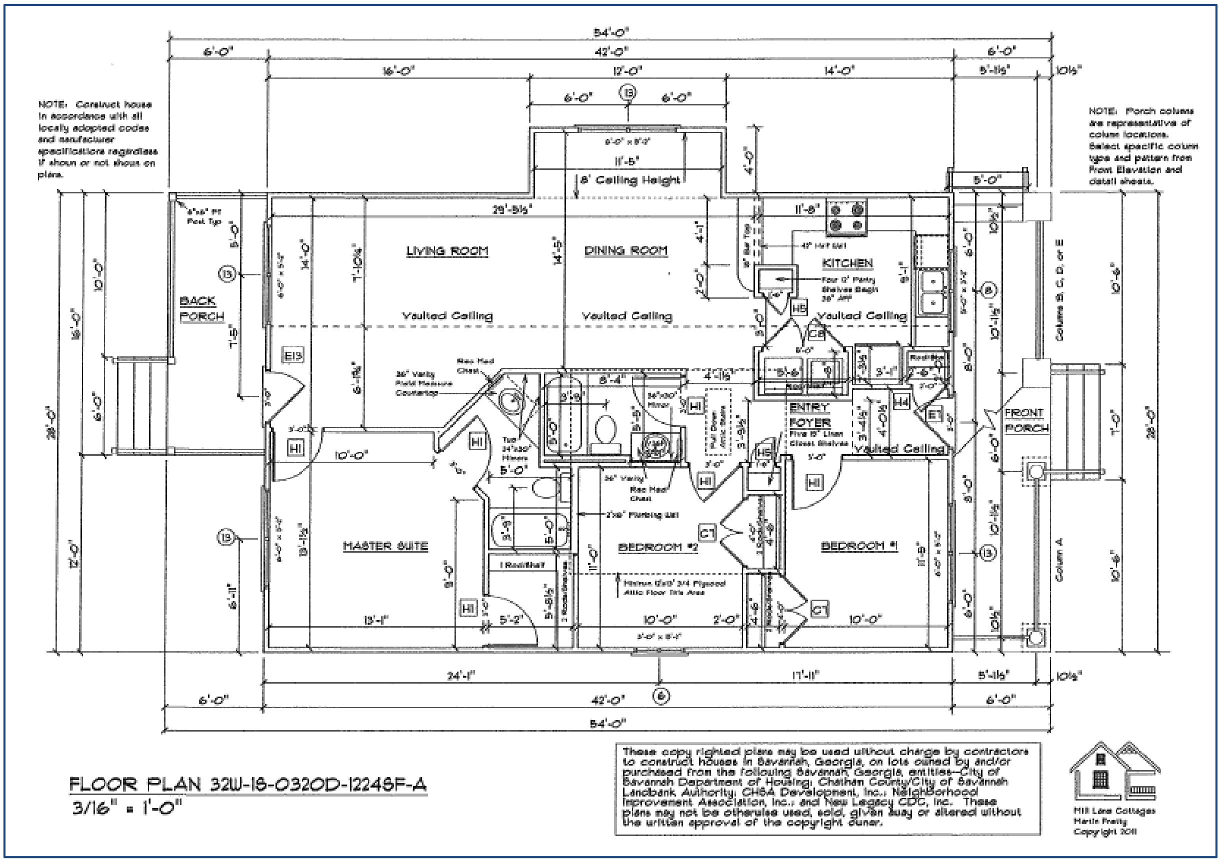

Figure 4. Savannah Test Home Floor Plan.

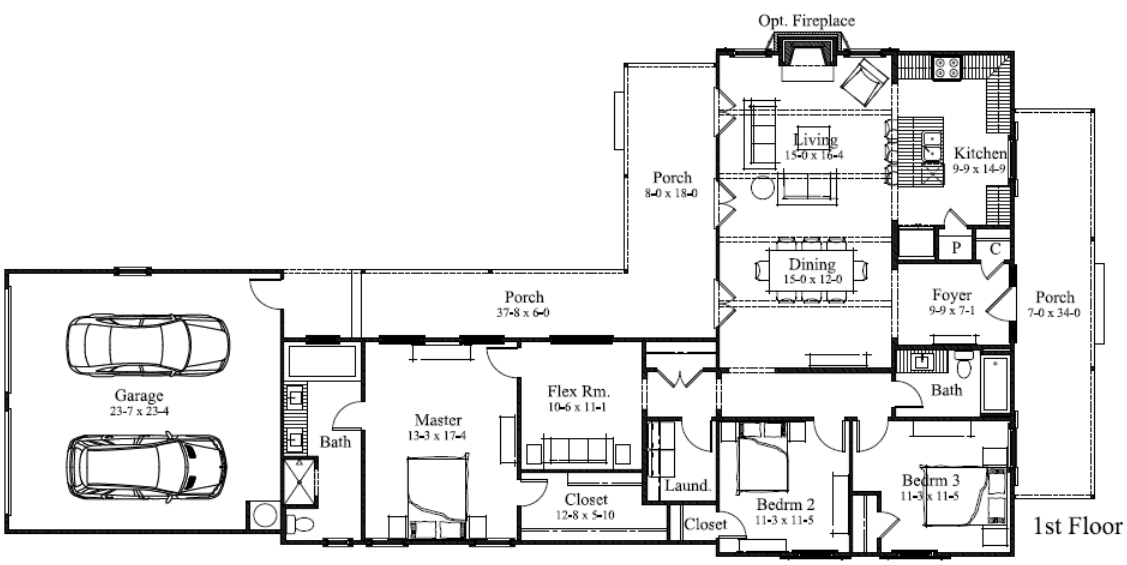

Figure 5. JMC Test Home Floor Plan (8x18 Porch was upgraded to a sunroom in As-Built)

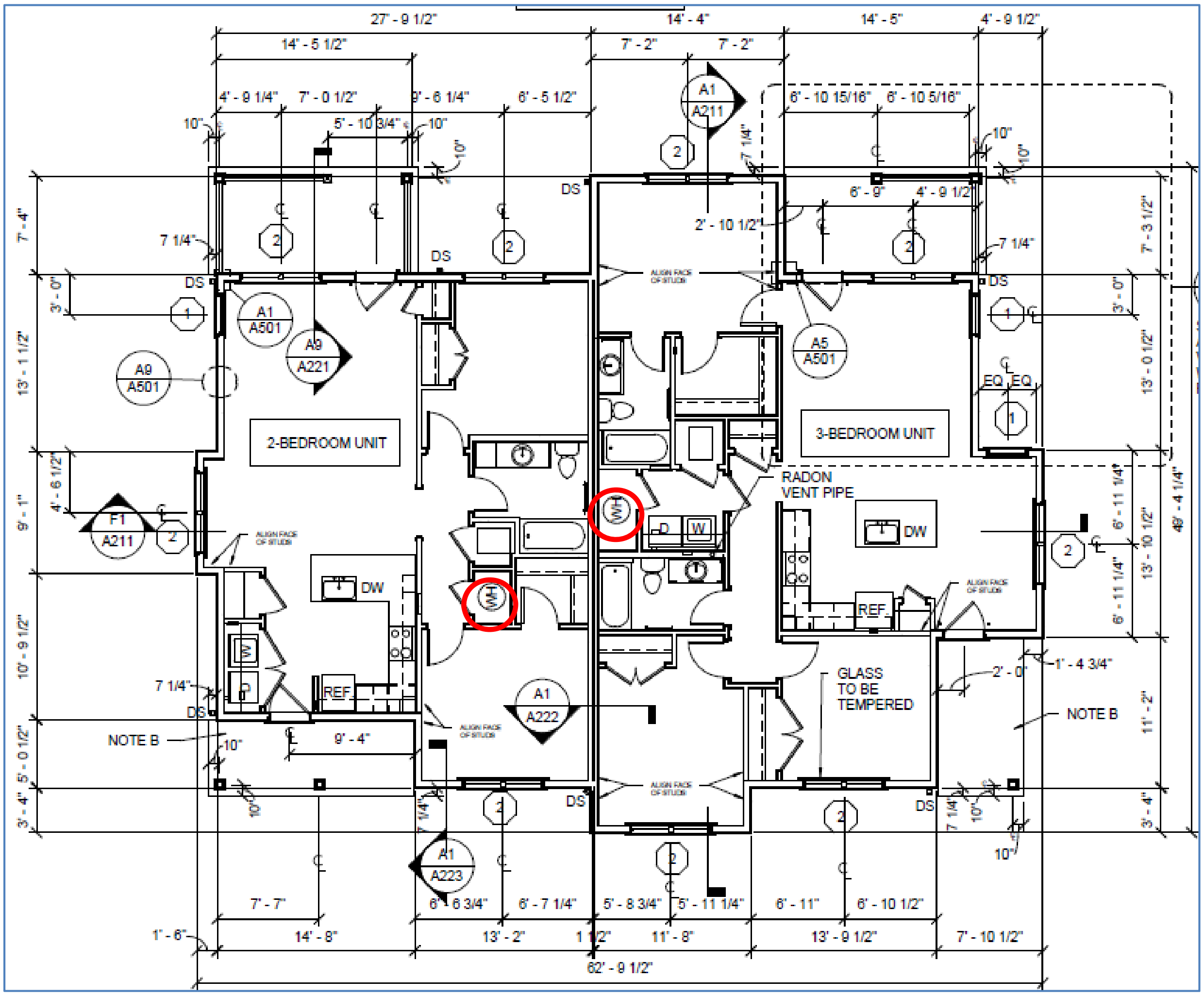

Figure 6. Typical LaFayette 3BR/2BR duplex floor plan with red circles indicating HPWH locations.

2.4 LaFayette Housing Authority

LAS designed 29 identical duplexes and 1 ADA-compliant duplex that were built on two sites (Figure 6). Each duplex consists of a two-bedroom and a three-bedroom unit. Note the location of the ducted heat pump water heaters in each unit inside utility closets with solid doors.

3 Energy Model Analysis

Energy simulation and optimization analysis was utilized at various stages during all three projects for decision making and performance evaluation. Various versions BEoptE+ were utilized during project development, depending on project timing, but the final results presented are from BEoptE+2.3. The B10 benchmark is consistent with the 2009 International Energy Conservation Code (IECC), federal appliance standards in effect as of January 1, 2010, and 2010 estimates of average lighting and miscellaneous electric loads. Where appropriate, electric appliances were chosen for heating and water heating benchmarks due to lack of available gas utility at the site.

3.1 Improvements to Standard Home in Savannah Gardens

BEopt modeling (Figure 7, next page) indicated the most significant savings would be achieved from the HPWH by reducing total consumption by 1,017 kWh/yr (12%) compared to an electric resistance storage water heater (ERSWH). The modeled savings from adding a ½" of rigid foam (ZipR) to the exterior sheathing was 118 kWh/yr (2%). Due to CZ 2 being cooling dominant, adding R-5 slab edge insulation (inSlab) increased energy consumption by 9 kWh/yr because it reduced the heating load and increased the cooling and HVAC fan loads by decoupling the slab from the relatively cool ground. Miscellaneous savings compared to the B10 Benchmark, 1058 kWh (8.5%), were achieved from removal of gas fueld fireplace, grill, and lighting; pool/hot tub/spa equipment; and extra freezers and refrigerators.

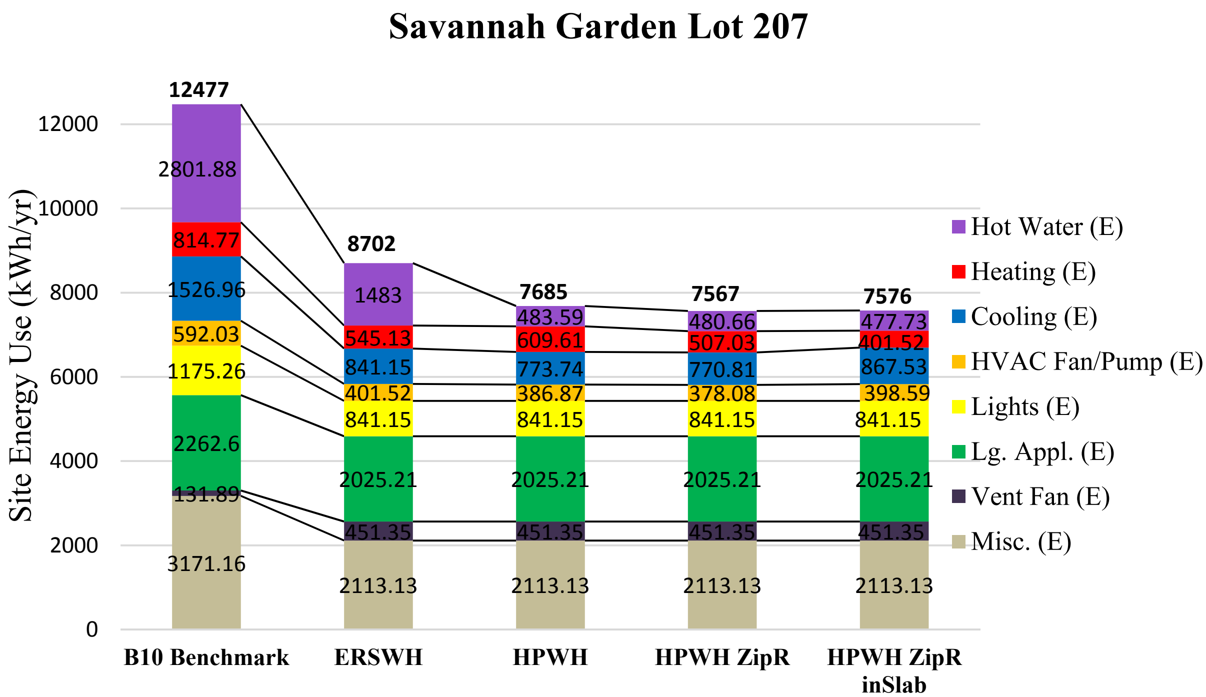

Figure 7. 39% predicted site energy savings of as-built (HPWH ZipR) Savannah Gardens Lot 207 compared to the B10 Benchmark (BEopt+2.3).

3.1.1 *Savannah Gardens REM/Rate™ Site Energy Analysis*

ENERGY STAR v3 compliance is a prerequisite for DOE Challenge Home / Zero Energy Ready certificaiton. There are two paths, prescriptive or performance, which can be followed in order to achieve certification under ENERGY STAR v3. If the home meets the Benchmark Home Size, the builder can follow the Prescriptive Path to achieve qualification. Alternatively, the performance path utilizes energy modeling, in this case REM/Rate™, to determine an ENERGY STAR HERS Index Target which is most commonly used by builders as it allows for substitutions in the prescriptive requirements and UA tradeoffs. The performance path incentivizes the design of smaller homes by including a favoring size adjustment factor, but it also offers optional performance measures which can be traded off as appropriate to achieve the ENERGY STAR HERS Index Target. In this case, the house met the Benchmark Home Size;

therefore its adjustment factor is 1. The ENERGY STAR v3 HERS Index Target is 79, and the test home exceeded this with a final HERS Index of 54.

In addition to assessing a HERS rating, REM/Rate^{TM} simulation was completed to confirm Challenge Home qualification and Energy Policy Act of 2005 (EPAct) tax credit ($2,000) eligibility. Through the model, Challenge Home specifications passed; however, the home did not qualify for the EPAct tax credit. The home is required to use 50% less site energy in heating and cooling loads than the benchmark home (based on the 2006 IECC); additionally 10% of the total reduction must come from the envelope loads. Envelope improvements reduced heating and cooling loads by more than the minimum 10%; however the end-use loads are 19.2 MMBtu/yr (47.5%) less than the 2006 IECC, narrowly missing the 50% minimum reduction target of 18.3 MMBtu/yr (Figure 8). The cooling end-use loads are greater than the 50% target site energy.

Normalized, Modified End-Use Loads (MMBtu/yr)

	2006 IECC 50% Target	As Designed
Heating	7.1	6.7
Cooling	11.3	12.5
Total	18.3	19.2

Envelope Loads (MMBtu/yr)

	2006 IECC 90% Target	As Designed
Heating	12.7	8.8
Cooling	20.3	18.6
Total	33.0	27.3

Figure 8. EPAct tax credit eligibility report generated by REM/Rate^{TM}.

The impact of an insulated slab on energy consumption was investigated. REM/Rate indicated insulating the exterior of the slab to R-5 would decrease the total cooling and heating load by 1.2 MMBtu/yr (352 kWh/yr) meeting the EPAct tax credit (Figure 9). The designed cooling loads remained unchanged, but the heating loads were reduced 20% from the current design.

Normalized, Modified End-Use Loads (MMBtu/yr)

	2006 IECC 50% Target	As Designed
Heating	7.1	4.7
Cooling	11.3	12.4
Total	18.3	17.1

Envelope Loads (MMBtu/yr)

	2006 IECC 90% Target	As Designed
Heating	12.7	5.8
Cooling	20.3	18.4
Total	33.0	24.2

Figure 9. EPAct tax credit eligibility report generated by REM/Rate^{TM} with exterior slab insulation.

3.1.2 *Savannah Gardens REM/Rate^{TM} Total Cost of Ownership Analysis*

Because a HERS Index is required for EarthCraft certification, Southface analyzed concurrent submissions for homes built by Chatham Home Builders in Savannah Gardens. For 13 homes built in 2013, the average HERS Index was 63. This is also the HERS Index of the neighboring home monitored in this study. Predicted utility costs were compared for the test home and the neighbor home resulting in a $174 annual saving compared to builder standard practice. Using an incremental upgrade cost of $2130 and mortgage rate of 4.5%, the resulting annual cash flow is $45 positive.

3.2 JMC Patrick Square Builder Base Package Optimization

Southface analyzed BEopt models (Figure 10) for analysis of the JMC home including the builder base package and an exploration of options for moving the ductwork from the vented attic to inside conditioned space. The builder base package, earning EarthCraft certification, was 9.5% more efficient than the B10 benchmark. Southface modeled the home with a sealed and insulated crawlspace, with ducts in a furred-down chase below the attic ceiling, and several options for encapsulating ducts in the attic. In consultation with the builder and his estimator, the team decided that the most replicable solution which also met all ENERGY STAR v3 requirements would be to encapsulate the roofline with open cell spray polyurethane foam.

Full gutters are not standard for this builder, and community design guidelines require half-round gutters if they are installed. Because gutters can be omitted for slab foundations under ENERGY STAR v3 requirements, the builder felt that it was preferable to build a slab and place the HVAC in the encapsulated attic than to build a sealed crawlspace and add gutters.

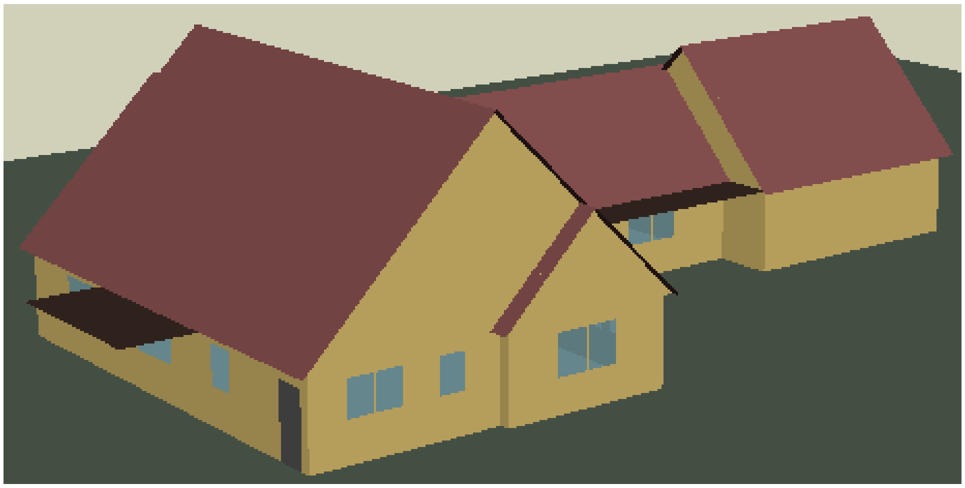

Figure 10. JMC BEopt model of the test home, View 1.

In order to find improvements over the builder base model and meet Zero Energy Ready Home, Southface proposed upgrades to all major systems and specifications, as reported in Table 3.

Table 3. JMC Patrick Square proposed base package upgrades and the as-built specifications

Measure	B10 Benchmark	Base Spec	Proposed Package	As Built
Foundation	Elevated Slab-On grade	Elevated Slab-On grade	Elevated Slab-On grade	Elevated Slab-On grade
Foundation Insulation	Uninsulated	Uninsulated	Exterior R-5 XPS	Uninsulated
Wall Construction	2x4, 16 in o.c.	2x4, 16 in o.c.	2x4, 16 in o.c.	2x4, 16 in o.c.
Wall Insulation	R-13 fiberglass batts	Grade I, R-13 Cellulose	Grade I, R-13, R-5 Exterior sheathing	Grade I, R-13 Cellulose

Ceiling Construction	Vented Attic	Vented Attic	Sealed Attic	Sealed Attic
Ceiling Insulation	R-30	R-38 cellulose	R-20 open-cell spray foam	R-20 open-cell spray foam
Window Ratings	U-0.37, SHGC-0.30	U-0.35, SHGC-0.28	U-0.33, SHGC-0.24	U-0.33, SHGC-0.24
Infiltration	7 ACH_{50}, 0.5 shelter coefficient	7 ACH_{50}	2.5 ACH_{50}	2.5 ACH_{50}
Heating Efficiency	Gas 78% AFUE	Gas 92.5% AFUE	Gas 92.5% AFUE	Gas 92.5% AFUE
Cooling Efficiency	13 SEER	13 SEER	15 SEER	16 SEER; 1 stage compressor
Supply Duct Location	Vented Attic	Vented Attic	Sealed Attic	Sealed Attic
Return Duct Location	Vented Attic	Vented Attic	Sealed Attic	Sealed Attic
Duct Leakage	R-8 Insulation; 15% total	R-8 Insulation, 5% to outside	R-10 Insulation, 0% to outside	R-10 Insulation, 0% to outside
Ventilation	Exhaust 2010 ASHRAE 62.2	Supply 2010 ASHRAE 62.2	Supply 2010 ASHRAE 62.2	Supply 2010 ASHRAE 62.2
Hot Water Efficiency	0.59 EF, gas	0.61 EF, gas storage; R-0, Trunk Branch Copper	0.67 EF, gas storage; R-0, Trunk Branch Copper	ENERGY STAR tankless; 0.82 EF gas
Lighting	34% CFL	90% incandescent; 10% CFL	80% ENERGY STAR qualified	90% incandescent; 10% CFL
Appliances	Benchmark Standards	Gas range; ESTAR dishwasher 260 kWh	Gas range; ESTAR dishwasher 260 kWh	Gas range; ESTAR dishwasher 260 kWh

The proposed package would meet the project goals of achieving ENERGY STAR certification, and result in total source energy consumption savings of 33 MMBtu/yr (22%) relative to the B10 Benchmark (Figure 11). This would be a 12% improvement over the builder's base package, saving 19.2 MMBtu/yr. Additional costs required to meet mandatory requirements for Zero Energy Ready Home, including further window and plumbing upgrades, were not viewed as cost effective by the builder. The As-Built package was only a modest improvement over base specifications by saving 4.9 MMBtu/yr (3%).

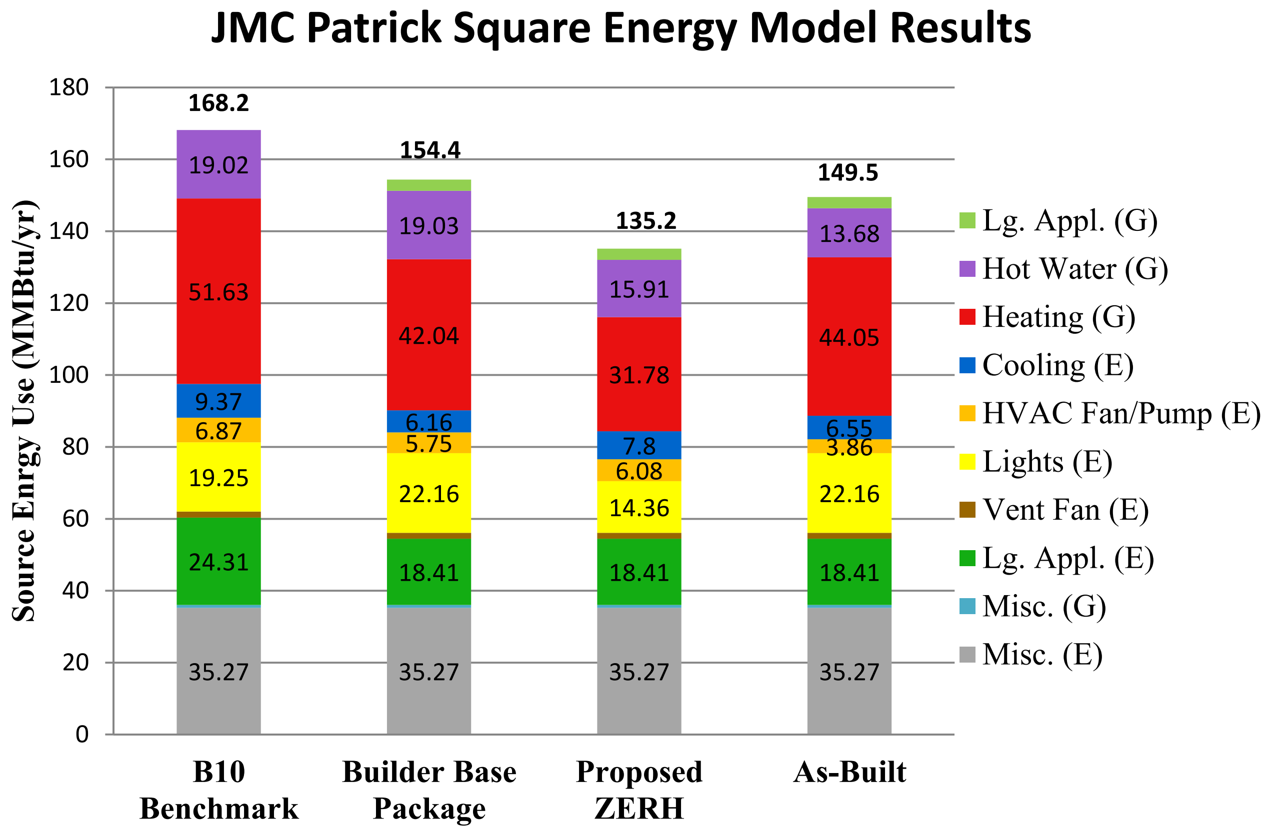

Figure 11. JMC Builder Package, Proposed, and As Built BEopt comparison

Note that the heating source energy of the as-built home is increased from the builder base package. Several changes to the building specifications which have positive impacts on other components of energy consumption, indoor air quality, buyer appeal, and durability combine to produce this result. For instance, the choice to bring the HVAC system and ducts into conditioned space by encapsulating the roofline with R-20 SPF resulted in a significant increase in total u-value times surface area along the insulated top surface of the house. Even though this strategy reduced duct leakage and enclosure leakage and enclosed the system in a semi-conditioned space, the combined effect of this change alone was a net increase of nearly 4 MMBtu/yr.

3.3 LaFayette DHW Analysis

Parametric energy model analyses of LaFayette 2BR and 3BR units were conducted using BEopt v1.1 - 2.3 throughout the design and specification process, but all results presented are products of BEoptE+2.3. The home geometric features and builder base specifications were entered and compared to the B10 benchmark (Figure 12). The as-built specifications achieved 31% source energy savings over the B10 benchmark for both units.

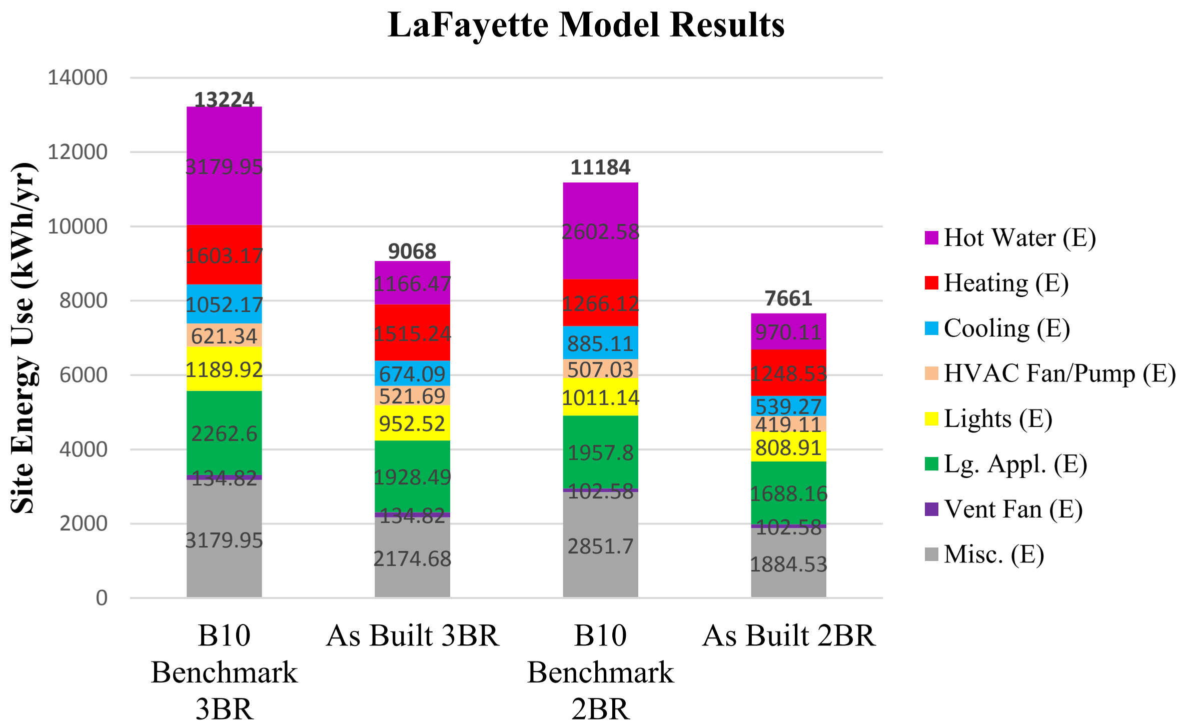

Figure 12. BEoptE+2.3 energy model comparisons of as-built to B10 Benchmark for the 2 bedroom and 3 bedroom LaFayette unit types predicts 31% source energy savings for both.

The original design of the duplex was to include solar thermal hot water heating for each unit, as seen in Figure 13. Southface modeled two different sized solar thermal arrays (40 ft^2 and 64 ft^2), electric tankless, and a HPWH to analyze potential savings of different DHW technologies compared to a standard ERSWH. Results are in Table 4 and Figure 14. For the 3BR unit, the solar thermal water heaters produced the greatest total energy savings (30% for 40 ft^2 and 36% for 64 ft^2) followed by HPWH (27%). The electric tankless water heater produced very little energy savings (2%). An analysis of simple payback was performed using standard installed costs for all water heater types and an average electicity price[2] of $0.11/kWh. For the HPWH, the cost included the necessary ducting. Because the installed cost of a solar thermal system is over three times as expensive as the HPWH, the simple paybacks for the systems were quite different. The simple payback for the HPWH is 10 years, within the expected usful life of the appliance. The simple payback for the 64 ft^2 solar thermal system is 33 years, beyond the age at which the appliance would be expected to require repair or replacement. The LHA decided to install ducted HPWH based on this analysis.

[2] U.S. Energy Information Administration (EIA) 2015 year to date residential electricity cost data for the state of Georgia.

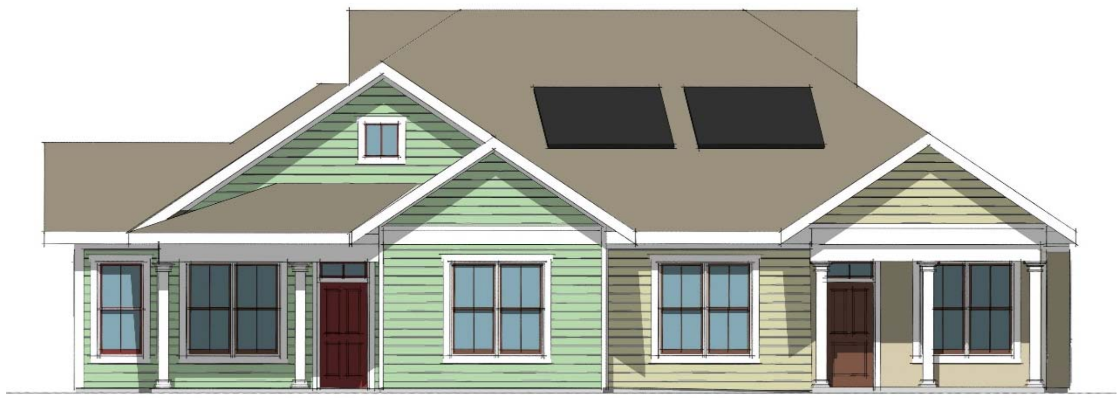

Figure 13. Front elevation of LaFayette duplex with the original plan to include a south facing solar thermal DHW system.

Table 4. LaFayette water heating analysis revealed HPWH provided the best value.

Water Heater	Installed Cost	Energy Savings (per year)	Simple Payback* (years)
ERSWH	$500	-	-
Tankless	$700	126 kWh (2%)	50
HPWH	$2,100	1,437 (27%)	10
Solar Thermal 40 ft^2	$7,500	1,630 kWh (30%)	42
Solar Thermal 64 ft^2	$7,500	1,920 kWh (36%)	33

*Simple payback is calculated using incremental cost to install (i.e. installed cost less $500 cost for ERSWH)

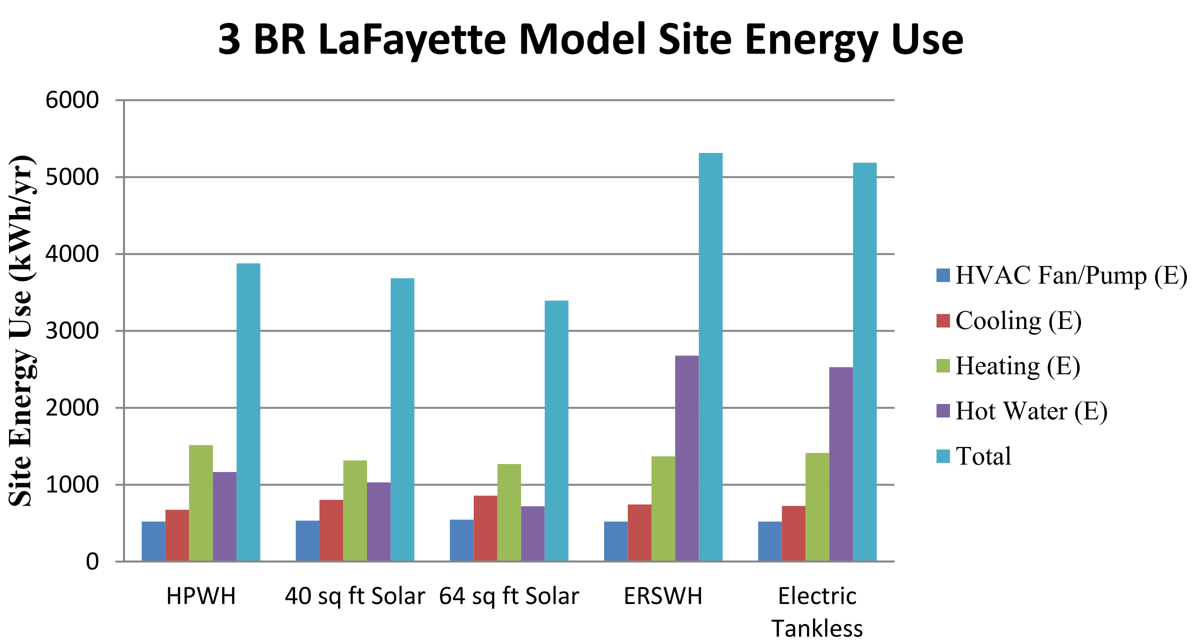

Figure 14. Modeling results of different DHW technologies.

4 Construction and Quality Management Systems

4.1 Wall Assemblies

Three different wall assemblies were constructed at the different NCTHs (Table 5). Savannah Gardens and JMC Patrick Square both used 2x4 framing with R-13 cavity insulation, but Savannah added Huber Zip-R insulated sheathing system boasting a ½" of continuous exterior foam, R-3.6 (Figure 15). LaFayette used advanced framing with 2x6 studs and Johns Manville Spider® as cavity insulation.

Table 5. Test Home Wall Assemblies

Test Home	Framing	Cavity Insulation	Exterior Insulation
Savannah Gardens	2x4	R-13 Fiberglass Batts	½ inch Huber Zip R
JMC – Patrick Square	2x4	R-13 Cellulous	none
Lafayette	2x6 24" o.c. Advanced Framing	R-22 JM Spider Fiberglass	none

Figure 15. Zip System R-Sheathing cross-section

4.1.1 *Advanced Framing Details*

Several advanced framing details were included in LaFayette's construction drawings, including two-stud corners, ladder tees at partition walls, and a header design which left 3 ½ inches of cavity above all windows and doors for insulation (Figure 16 and Figure 17). The drawings also showed a single top plate, but after a discussion about hardware needed to strap intersecting walls together and the framer's process of standing and racking the walls to get them plumb and square, this was abandoned for a conventional double top plate. The framer had implemented some of these details on a previous EarthCraft certified project and was comfortable with using them on this project.

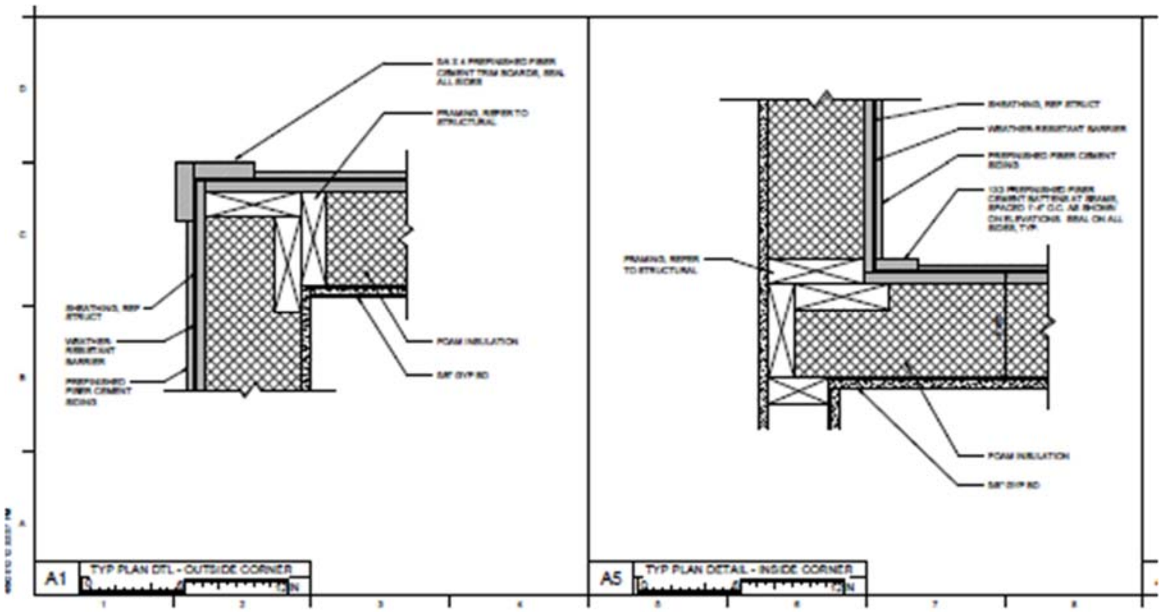

Figure 16. Framing details from LaFayette construction drawings

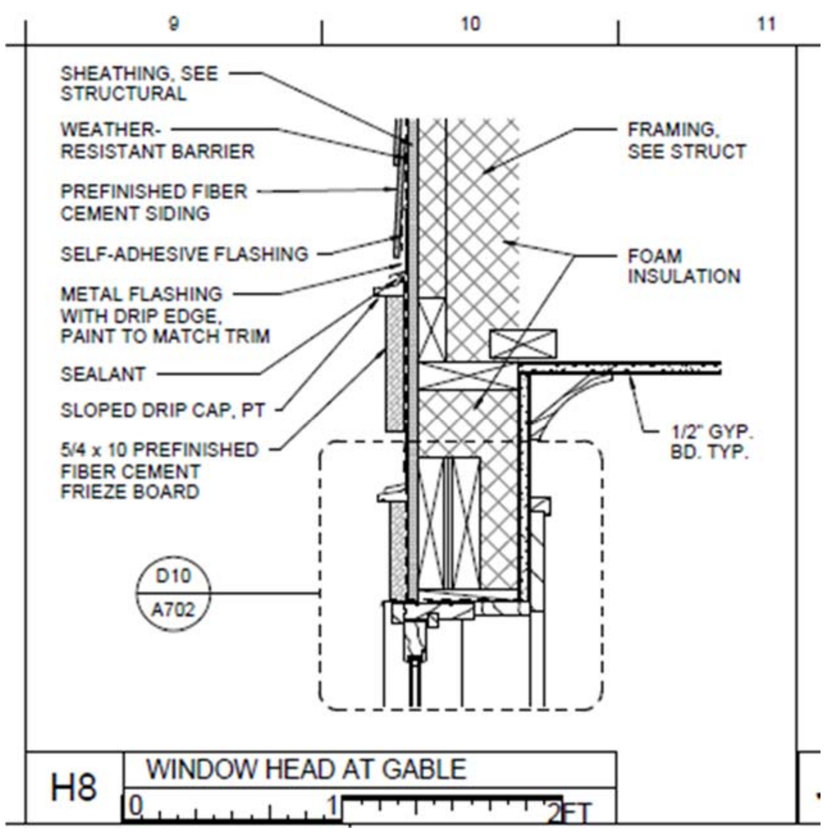

Figure 17. Window head at gable details from construction drawings

4.1.2 *Spider Spray Installation*

Johns Manville (JM) provided additional technical support by flying two product engineers out to the jobsite to witness the first day of Spider installation. This proved to be extremely beneficial to the project as it was discovered that the installation crew was using a hose head and spray nozzles for spray applied cellulose, not the specified head and nozzles for Spider. The improper nozzles were delivering a stream of adhesive instead of a mist and the air pressure on the hose was causing too much fiberglass to be put into the cavity. Instead of cleanly adhering and filling the cavity in a few passes, the cavity filled quickly and overflowed onto the floor requiring additional vacuuming of the product. Despite being trained on-site by two JM Spider technical representatives, installation was tedious and required vacuuming of excess blown fiberglass off the ground (Figure 18).

Figure 18. Installation of Johns Manville Spider insulation

It was also discovered that the rotating head used to shave the insulation flush to the studs was for cellulose, not fiberglass. This left a rough finish on the insulation (Figure 19). The JM rep provided a calibrated plunger to test the density of the installation and measure its installed R-value. Tests of this initial installation consistently yielded R-values of R-21, two less than specified, however BEopt modeling predicted this to have an insignificant effect.

Samples were taken in several locations throughout each building during subsequent pre-drywall inspections. Results were consistently between R-22 and R-21. Another issue that was prevalent across the project was that at ladder-tees the shaving device would gouge out the insulation because it was not supported on both ends by studs and easily tilted into the cavity.

During insulation installation on the fifth building at the first site, the spray rig failed. To stay on schedule the crew installed netting and dense packed the cavities with dry product (Figure 20). From this, the installer discovered that the time spent installing the netting was much cheaper and faster than the application of adhesive, shaving, and vacuuming required for the spray applied application, and used this method for the remainder of the project. Unfortunately the density tester is only calibrated for spray applied product and could not be used to measure the R-value of netted installations.

Figure 19. Spray applied Spider insulation.

Figure 20. Netted Spider insulation.

4.2 Sealed Attics

At all three sites, the attics were encapsulated with approximately 6 inches of open cell spray polyurethane foam (SPF) applied to the OSB roof decking (R-20). This system created a semi-conditioned attic in which to locate the air handler, for the JMC and Savannah Gardens projects, and to run the supply and return ductwork for all three projects.

Although this strategy has the tremendous advantages of increased enclosure air tightness, decreased HVAC system leakage to outside, and enclosing the HVAC system in a tempered space, resistance to heat transfer through the attic thermal barrier is decreased compared to code values. Ceiling R-value requirements of the 2009 IECC are R-30 (CZ 2 and 3) and R-38 (CZ 4). Builders who choose either the UA alternative or simulated performance pathways for meeting code requirements can demonstrate compliance with energy code by either increasing insulation values elsewhere in the home and/or increase other energy efficiency features beyond code minimums.

4.3 Foundations – Slab Edge Insulation

JMC Patrick Square and LaFayette both had 1” of rigid foam insulation installed around their elevated slabs (Table 6). The Savannah Gardens home was built on an uninsulated slab on grade because energy models predicted insulation would increase annual energy consumption by decoupling the slab from the cool ground in a cooling dominant climate.

Table 6. Test Home Slab-edge Insulation

Test Home	Slab Type	Slab Edge Insulation Type	R-value
Savannah Gardens	On Grade	none	n/a
JMC – Patrick Square	Elevated	interior	5
Lafayette	Elevated	exterior	5

Prior to slabs being formed in LaFayette, a meeting was held with the contractor's pre-construction manager and site superintendent, the project architect, and crew leaders from the framing, electrical and masonry contractors. The purpose was to review details contained in the drawings and to coordinate the installation of the slab edge insulation and additional details. This discussion answered the framer's questions regarding alignment of the sheathing with the insulation (Figure 21 and Figure 22). It was determined that the masons doing the brick plinths covering the slab edges would install the insulation board ahead of their brickwork. This would minimize the amount of time the insulation was exposed to the elements and better ensure its protection from construction damage. The concrete crew would install the insulation board where it occurs between the building slab and the porch, and would place it just before the porch pour. Here the insulation also functions as an expansion joint to allow differential movement between the two slabs.

No such kick-off meeting occurred during construction at JMC Patrick Square and issues arose regarding installation of the slab insulation. An elevated slab foundation with concrete masonry unit (CMU) stem walls was constructed. This is a typical construction technique in the Southeast, used to raise the floor level of the home for both storm water management and architectural aesthetics. Instead of constructing a 'floating slab' by leaving the CMUs unaltered, the builder notched the CMUs in order to support the poured slab. Thus, the proposed slab insulation solution was to insulate the slab exterior with 1-inch (R-5) of XPS foam board.

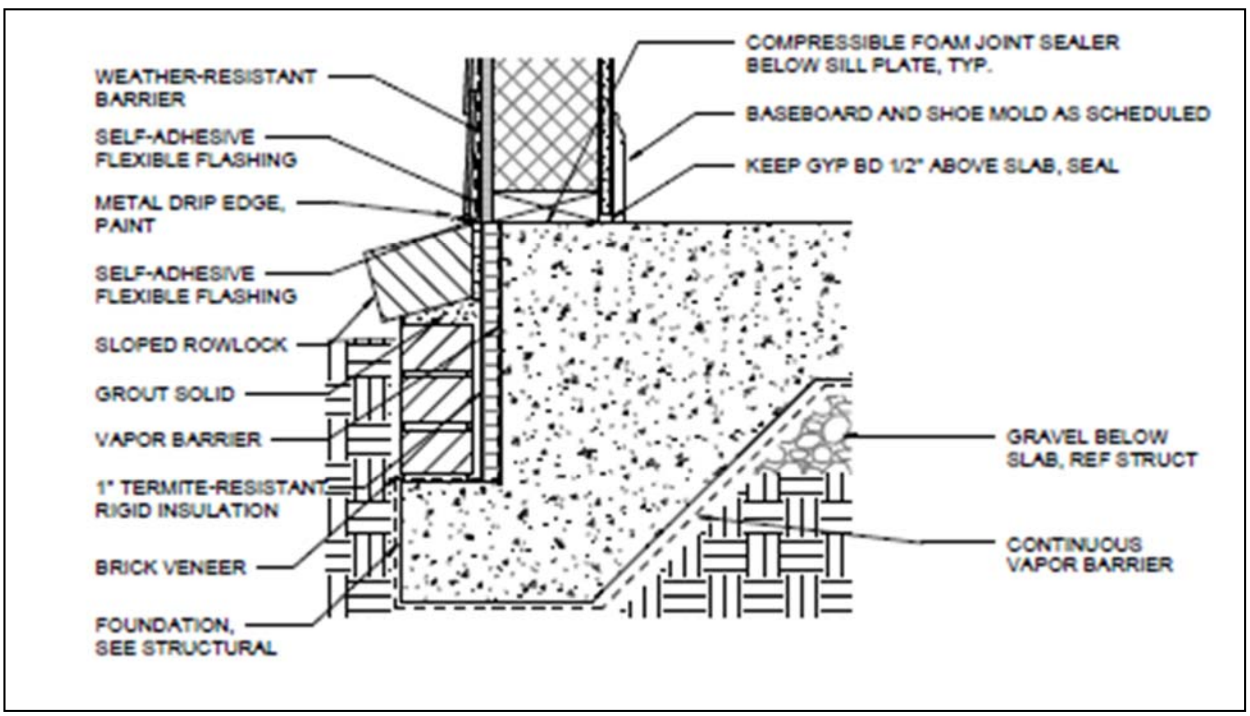

Figure 21. Lafayette Slab edge insulation detail.

Figure 22. Lafayette slab edge insulation installed before the porch pour.

The builder chose instead to attempt an interior and gap insulation solution (Figure 23) to eliminate the need to provide a protective covering for the exterior foam. The lower portion of the slab is insulated while the top half of the slab filling in the CMU notches is exposed to the stem wall creating a thermal bridge. The cost of the slab insulation was $1,645.

Figure 23. JMC elevated slab construction in progress showing gap insulation and stem wall.

The thermal bridge was evident during infrared thermography investigations conducted on a cool morning at the junction of the slab and exterior wall (Figure 24). The coldest temperatures are on the floor at the exterior wall junction. The image also depicts insulation defects and thermal bridging through the wood studs.

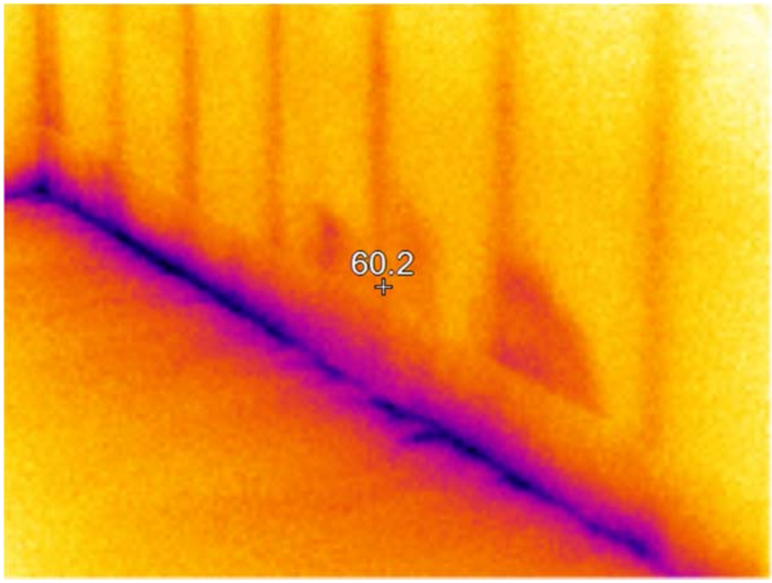

Figure 24. JMC thermal image facing exterior wall showing heat transfer through the slab.

4.4 Domestic Hot Water

Table 7 documents the DHW technology installed in each of the test homes. The test homes in Savannah Gardens and LaFayette had only electric energy service, so HPWHs were chosen for being the most efficient and cost effective solution for DHW. JMC Patrick Square had a natural gas line to serve the kitchen range/oven, furnace, and DHW. We recommended an ENERGY STAR gas storage water heater (EF 0.67) upgrade from their base gas storage tank (EF 0.61), but the builder chose a gas tankless unit because it was an upgrade option of their existing package.

Table 7. Test Home Water Heater

Test Home	Water Heater	Location	EF/COP
Savannah Gardens	Heat Pump	Encapsulated attic	3.1*
JMC – Patrick Square	Tankless Gas	Garage	0.82
LaFayette	Heat Pump	Closet – ducted to encapsulated attic	3.1*

*Manufacturer's rating in Efficiency mode (A.O. Smith, 2014)

The HPWHs in LaFayette are located in the mechanical closets with sealed doorways. The doorways were sealed to reduce noise and air transfer to the living space. Noise reduction was the primary reason to duct the HPWHs to the attic and not use a louvered door, as previous studies have reported noise as the major complaint from tenants living with a HPWH (Chasar & Martin, 2013). Figure 25 is a schematic of the ducted HPWH installation in the mechanical closet. There is a transfer duct in the ceiling of the mechanical closet to the encapsulated attic to provide intake air (Figure 26, left), while the HPWH's exhaust is directly ducted to the attic (Figure 26, right). The distance between the ducts' terminals is to be a minimum of 5 feet, and the different orientations of the ducts are to prevent cool exhaust air from recirculating into the intake duct.

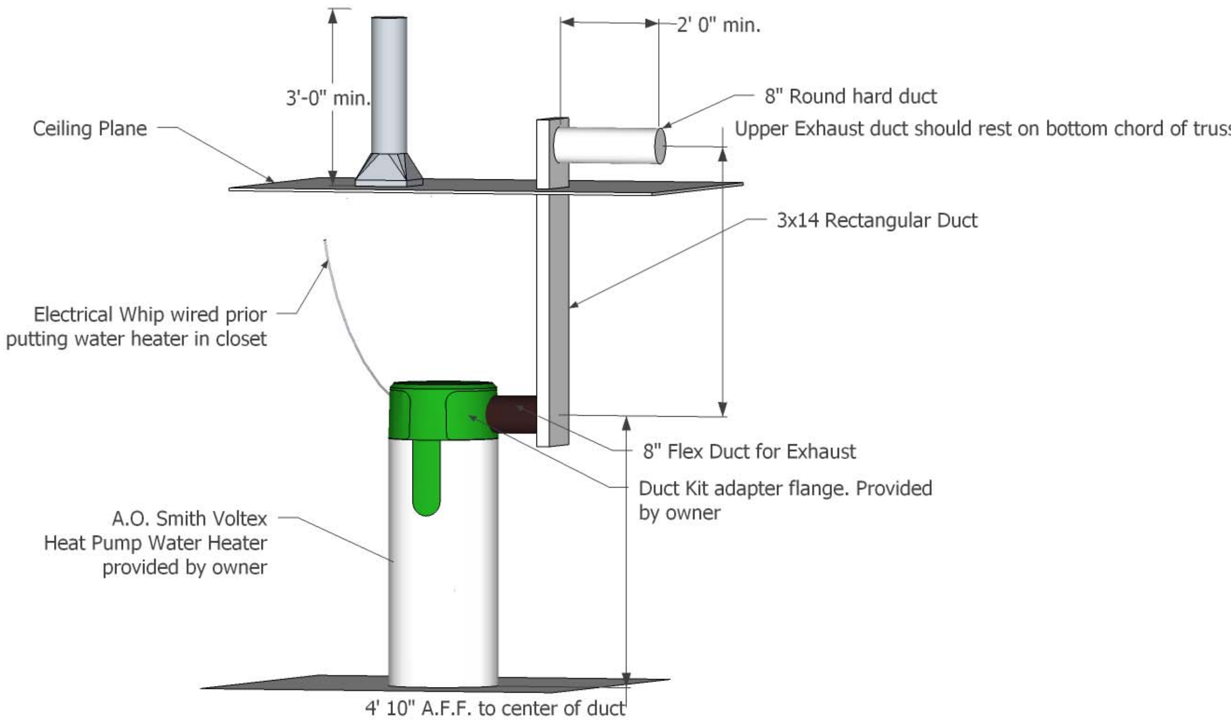

Figure 25. Rendering of Lafayette HPWH critical dimensions.

Figure 26. (Left) Vertical intake transfer duct leads to a vent in the mechanical closet's ceiling; (Right) Horizontal exhaust duct connected to 3" x 14" rectangular duct inside the wall cavity leading to the HPWH in closet.

The test home in Savannah Gardens had a HPWH installed directly in the SPF encapsulated attic (~1508 ft^3) with a 10 foot duct terminating therein (Figure 27). The house adjacent to the test home is of similar size, dimension, and construction with an electric 50 gallon A.O. Smith water heater (ECRT-52) in its encapsulated attic. The temperature and relative humidity in the attic of the neighboring home was also monitored.

Figure 27. Savannah Gardens Lot 207 HPWH located in the encapsulated attic; Prior to installation of exhaust duct (Left) and after installation of exhaust duct (Right)

4.5 Performance Testing Results

An envelope leakage (blower door) test was performed on each building and duct leakage tests were performed at Savannah Gardens and JMC Patrick Square and the results are reported in Table 8.

Table 8. Test Home Performance Testing Results

Test Home	Air Tightness (ACH_{50})	Total Duct Leakage (CFM_{25})	Duct Leakage to Outside (CFM_{25})
Savannah Gardens	1.9	65 (5.4%)	0
JMC – Patrick Square	2.5	87 (4.8%)	0
LaFayette	2.1	n/a	0

Concerns at LaFayette with the impact on envelope air leakage of using Spider instead of spray foam in the wall cavities proved unfounded. Blower door testing done as the homes were nearing completion showed that nearly every apartment was below our target of 3.3 ACH_{50}, with a few units below 2 ACH_{50}. Figure 28 shows the variation of building envelope leakage of all units by number of bedrooms. The two 2 bedroom units in the Uniform Federal Accessibility Standards (UFAS) building are the outliers in the data. All the other buildings' layouts were 2BR/3BR duplexes. The front facing bedrooms in the outlying duplex have dormers which were not specifically detailed for air sealing and insulation, and some sort of sealing was clearly omitted from these two 2BR units. While they still easily exceeded 2009 IECC infiltration rates (7 ACH_{50}), one unit narrowly missed ENERGY STAR v3 infiltration levels (5 ACH_{50}). All of the 3 BR units met the 2012 IECC requirements (3 ACH_{50}). LaFayette also had guarded blower door tests performed on two duplex buildings to distinguish envelope leakage to the outside from that to the adjacent unit. It was found that approximately 35% of the total leakage was to the adjacent unit.

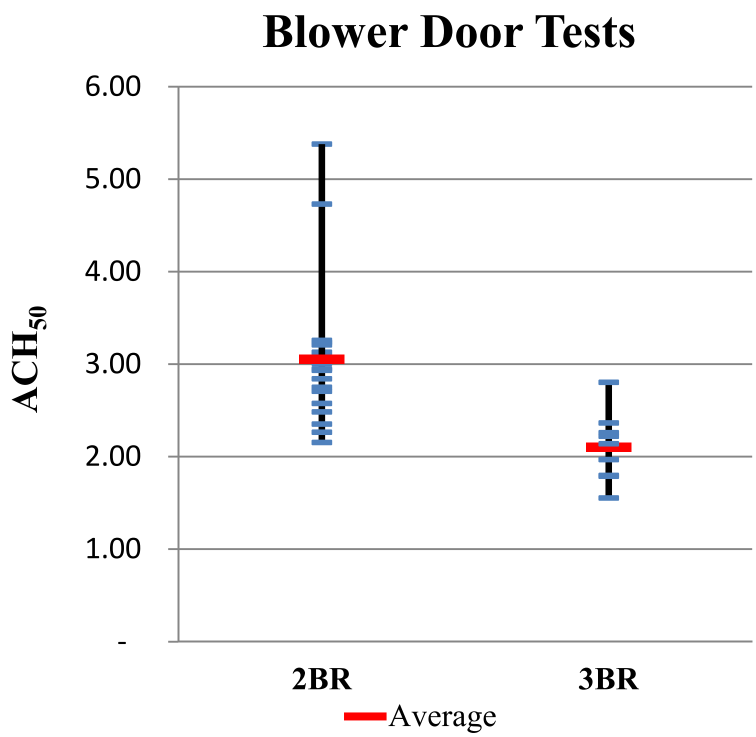

Figure 28. LaFayette air tightness values (Data Courtesy of SKCollaborative[3])

JMC Patrick Square had the greatest envelope leakage of all three homes, and an infrared camera was used to identify major air leakage pathways. Large sources of air leakage were identified in the attic where the SPF did not make an airtight seal between the bases of the trusses and the wall top plates (Figure 29) and behind the bathtub in the master suite (Figure 30).

[3] http://krugersustainabilitygroup.com/

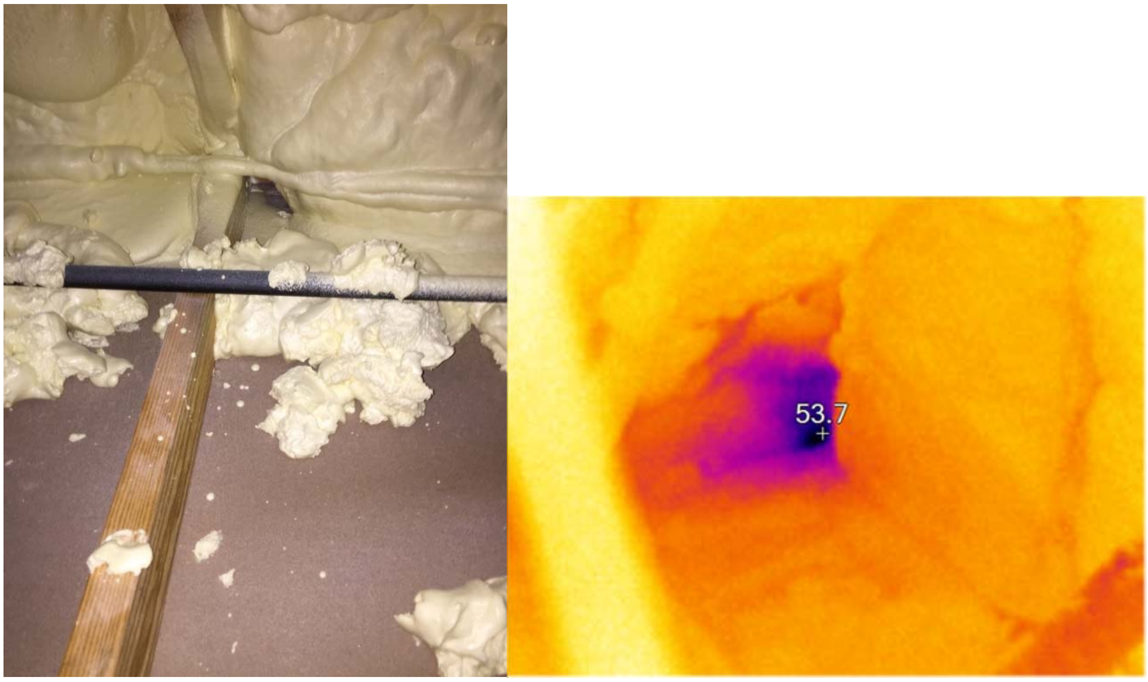

Figure 29. Attic air leakage pathways identified in SPF at truss-to-top plate intersection.

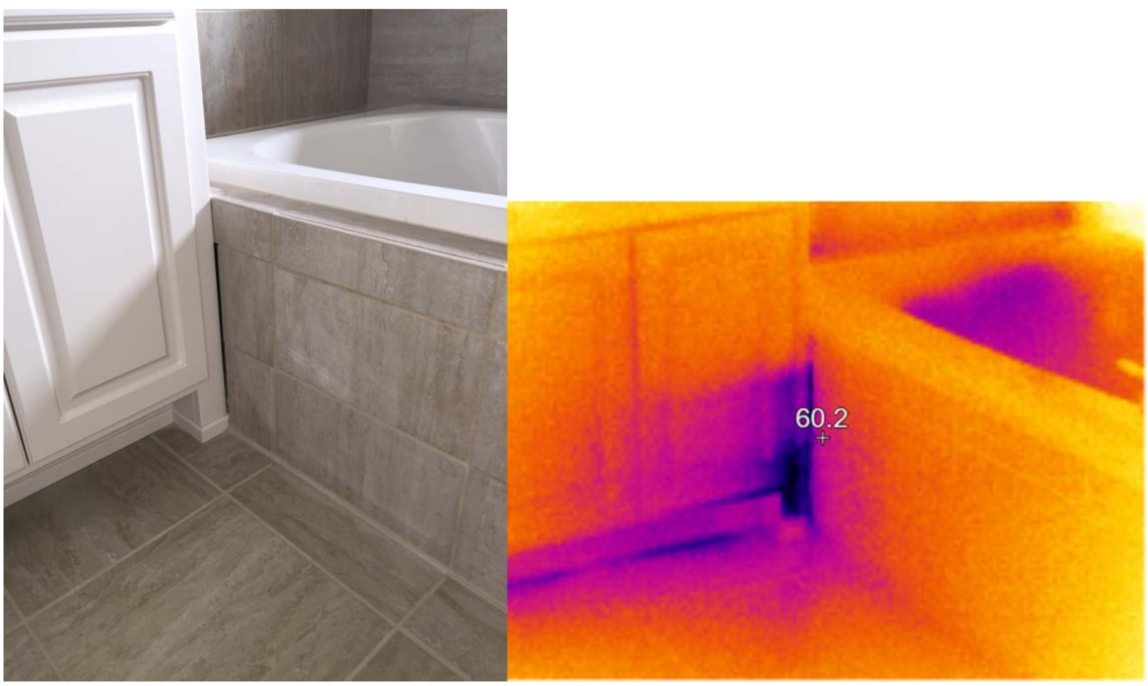

Figure 30. Attic air leakage pathways identified around master bathtub.

5 Monitoring Analyses and Results

5.1 Ducted Heat Pump Water Heaters

This study analyzed five 60 gallon A.O. Smith Voltex HPWHs (model PHPT-60), four installed at LaFayette and one at Savannah Gardens. Both test sites had open cell SPF rooflines to create encapsulated attics. The Efficiency mode (heat pump only; no electric resistance assistance) was of primary interest in this study because the affordable housing providers were motivated to minimize occupant utility expenses while ensuring hot water demand it met. The PHPT series has the ability to be ducted (maximum of 10 ft.) to another zone when the free air volume of the occupied zone is less than 750 ft^3 (A.O. Smith, 2011, 2012). Inlet and Outlet Duct Kits, which were found to be identical, are available from the manufacturer, enabling multiple ducting configurations.

A previous Building America field monitoring study was conducted on both the 60 and 80 gallon A.O. Smith Voltex HPWHs by Steven Winter Associates. They reported COP values of 2.1 for both model sizes. The 80 gallon unit did not use the electric resistance elements, while 11% of the 60 gallon unit's energy consumption was from the electric resistance elements. They also reported an efficiency reduction of 16% (COP 1.76) for installations in confined spaces (Shapiro & Puttagunta, 2013). Due to their investigation of reduced performance in confined spaces, preliminary results indicating the ducted HPWHs at both sites performed comparably to other studies (Amarnath & Bush, 2012; Ecotope Inc & Northwest Energy Efficiency Alliance, 2015; Larson & Bedney, 2011), and A.O. Smith's recommendation to not operate them unducted in the mechanical closets, we did not test any unducted HPWHs.

Southface adhered to NREL's Field Monitoring Protocol for HPWHs (Sparn et al., 2013) to collect valuable data on in-situ ducted HPWHs to add to the limited amount of field monitored data, and serve as a reference point for the refinement of HPWH computational models.

The HPWH's were installed by local plumbing tradesmen at each site whose HPWH training consisted of a 30 minute installation video provided by AO Smith. The ducts were installed by local HVAC tradesmen and commissioned by Southface for an extra cost of $250-$300/unit at the LaFayette site. The only installation issue to date specific to HPWHs was the plumber installing a condensation drain pipe to only one of the two condensation drains at the Savannah site.

5.1.1 *Monitoring equipment and Uncertainty Analysis*

The following monitoring equipment was installed (Table 9):

Table 9. Monitoring Equipment and Purpose

Parameter of Interest	Monitor Type	Purpose	Accuracy
BTUs Hot Water Delivered	Badger In-line BTU meter	Measures temperatures of cold water supply and hot water outlet lines and flow rate at the water heater.	± 0.3 °C, ± 2% of flow rates above 1.65 GPM
Power Consumption	Trendpoint Enersure	Power meter capable of reading multiple CTs to monitor total electric consumption and component level power of the HPWH.	± 1%
Duct Air Temp and Humidity	Vaisala In-duct Temperature and Humidity Probe	Measure the temperature and humidity of the air stream within the duct just before air enters and just after the air leaves the HPWH.	± 0.3 °C ± 3% RH
Attic and Room Temp and Humidity	OmniSense Wireless Temp and RH sensors	Measure changes in temperature and humidity to determine the impact of the HPWH on attic and occupied space conditions.	± 0.4 °C ± 3.5% RH

An uncertainty analysis was performed by propagating the error of each sensor measurement used for calculating COP. Sensor accuracies are listed in Table 3. First, the uncertainty of ΔT_{draws} was calculated using the following equation.

$$\delta \Delta T = \sqrt{(\delta T_{out})^2 + (\delta T_{in})^2}$$

The uncertainty of ΔT_{draws} was calculated to be $\pm\sqrt{0.18}$. Total COP uncertainty can be approximated using the following equation.

$$\frac{\delta COP}{COP} = \pm\sqrt{\left(\frac{\delta V_{draws}}{V_{draws}}\right)^2 + \left(\frac{\delta W_{input}}{W_{input}}\right)^2 + \left(\frac{\delta \Delta T_{draws}}{\Delta T_{draws}}\right)^2}$$

Total COP uncertainty was determined to be ± 3.1%. An example uncertainty for daily parameters is shown in

Table 10 below.

Table 10: Uncertainty for Example Daily Values

Metric	Daily Value	Daily Uncertainty
COP	2.4	± 0.07
Daily V_{draws} (gal)	47.8	± 1.0
Daily ΔT_{draws} (°C)	22.7	± 0.3
Daily W_{input} (kWh)	2.8	± 0.03

5.1.2 *HPWH Performance Results*

Ducted HPWH results were calculated at all LaFayette sites (A, B, C, and D). In Savannah, the HPWH was appeartently turned to Vacation mode for several days while the homeowners were still at home and using "hot" water at a normal rate. In response, the HPWH was then set to the highest setpoint available, 150 °F. The time periods with 120 °F and 150 °F setpoints were analyzed separately (E1 and E2). When averaging the daily COP calculations, equal weight was given to each daily COP value. Average daily COP values for a 120 °F tank set point at the LaFayette site ranged between 1.9 and 2.5 and was 3.1 at the Savannah site. This average gives equal weight to each day regardless of hot water consumed so the COP across the entire monitored period was calculated, and resulted in a slightly different COP values at each site. As would be expected, raising the setpoint resulted in lowering the COP in Savannah. It also resulted in a decrease in total how water draw, possibly due to a decrease requirement for hot water to achieve the same hot and cold water mix at the tap. These results and the daily average values of variables used in the COP calculation are listed in Table 11.

Table 11. Summary of all monitored HPWH daily average variables used to compute daily average COP.

Site	Water Heater Set Point (˚F)	Avg. Daily DHW Use (gal)	Avg. Cold Water Temp (˚F)	Avg. Hot Water Temp (˚F)	Avg. Daily HPWH Electric Use (kWh)	Avg. Daily COP	Average COP*
A	120	76.5	68.3	111.0	3.1	2.5	2.6
B	120	27.1	71.5	110.2	1.4	1.9	2.0
C	120	55.1	71.1	111.5	2.4	2.2	2.4
D	120	41.6	70.7	109.2	1.9	2.0	2.2
E1	120	76.6	77.7	113.5	2.2	3.1	3.0
E2	150	55.5	75.2	128.8	3.7	2.0	1.9

*Average COP was calculated across the entire time period.

Because both intake and exhaust ducting is available, the researchers varied ducting configurations in order to determine whether or not there is an impact on HPWH performance. To compare HPWH performance under different ducting configurations, variables were analyzed for equivalent time durations directly before and after the duct configuration changes. Table 12 below documents the date ranges of different HPWH duct configurations and the corresponding average daily COP values. All units began with the standard exhaust duct strategy during Time

1; during Time 2, Units A and B were subjected to variations. The COP values remained the same for both Units A and B with intake ducting as well as for Unit C whose duct configuration remained unchanged.

Table 12. Date ranges of each site and the duct configuration applied. 'X' indicates the location was ducted if the intake or exhaust was ducted.

Site	Location	Time 1 8/26 - 9/16	Time 1 Avg. Daily DHW Use (gal)	Time 1 Avg. Daily COP	Time 2 9/18 - 10/19	Time 2 Avg. Daily DHW Use (gal)	Time 2 Avg. Daily COP
A	Intake		82.7	2.5	X	86.9	2.5
	Exhaust	X			X		
B	Intake		27.4	1.8	X	29.8	1.8
	Exhaust	X					
C	Intake		64.7	2.3		52.5	2.3
	Exhaust	X			X		

Figure 31 displays the trend between daily hot water consumption and average daily COP. The COP increases sharply before reaching the knee of the curve between 20 – 40 gal/day before leveling. This is the same trend reported by Shapiro and Puttagunta in their HPWH field monitoring report. They reported an average COP value of 2.1 for the unducted A.O. Smith Voltex models (Shapiro & Puttagunta, 2013), while the average of daily averages for all units in this study is 2.3 (excluding E2).

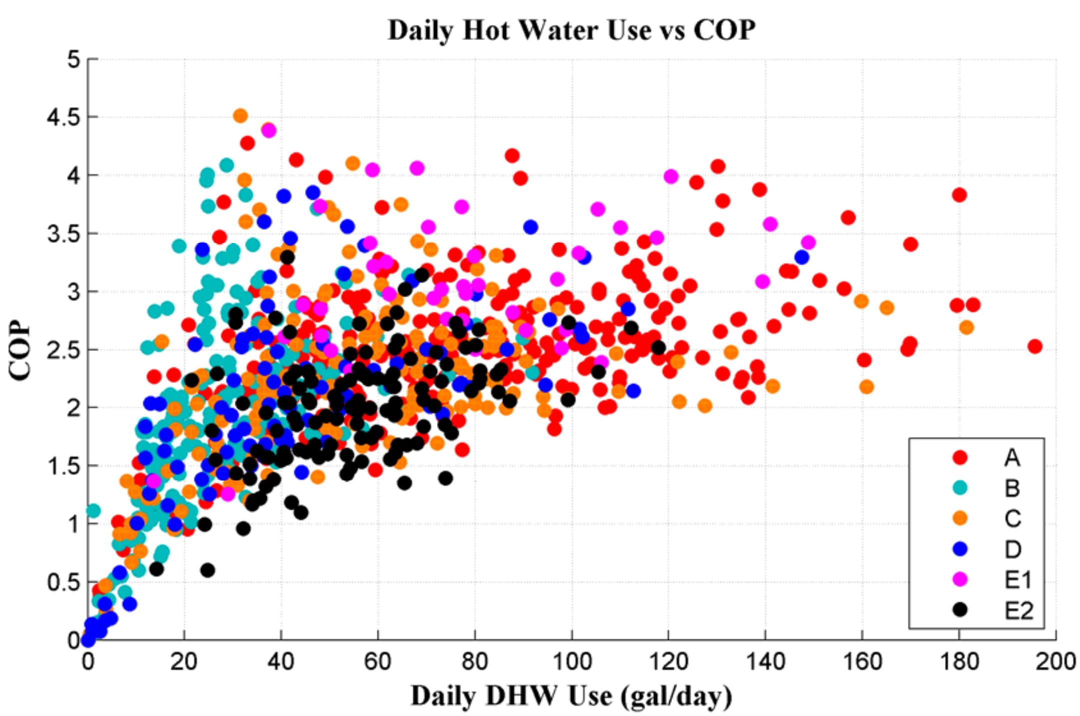

Figure 31. Scatter plot of Daily Hot Water Use vs COP for all 5 units.

5.1.3 *Impact on Encapsulated Attic Air Temperature and Humidity*

One of the primary research questions was what impact the exhaust air of the HPWH has on the HVAC loads of living space. Temperature and humidity sensors placed in the attics of all five test homes plus the neighboring home in Savannah provide a good basis for comparison. Large diurnal swings in absolute and relative humidity were observed in the attics of all six monitored homes. The fluctuations of the absolute humidity levels in the attics are believed to be highly influenced by the "sponge" effect of open cell foamed rooflines which is due to moisture loads driven in/out of the foam by solar heating and night cooling (Boudreaux, Pallin, & Jackson, 2014). The moisture levels in the sealed attics at all six sites show similar daily moisture levels throughout the year. Under the current regime of operation the HPWH does not appear to remove enough moisture on a daily basis to make significant reductions in daily peak moisture loads compared to the adjacent house with a standard electric water heater (Figure 32). Further monitoring and research is needed to better understand this effect and to develop strategies that are effective at reducing moisture levels in sealed attics of low-load homes. One potential HPWH operating regime would be to introduce more complex control strategies such as increased morning set points or "learning" logic.

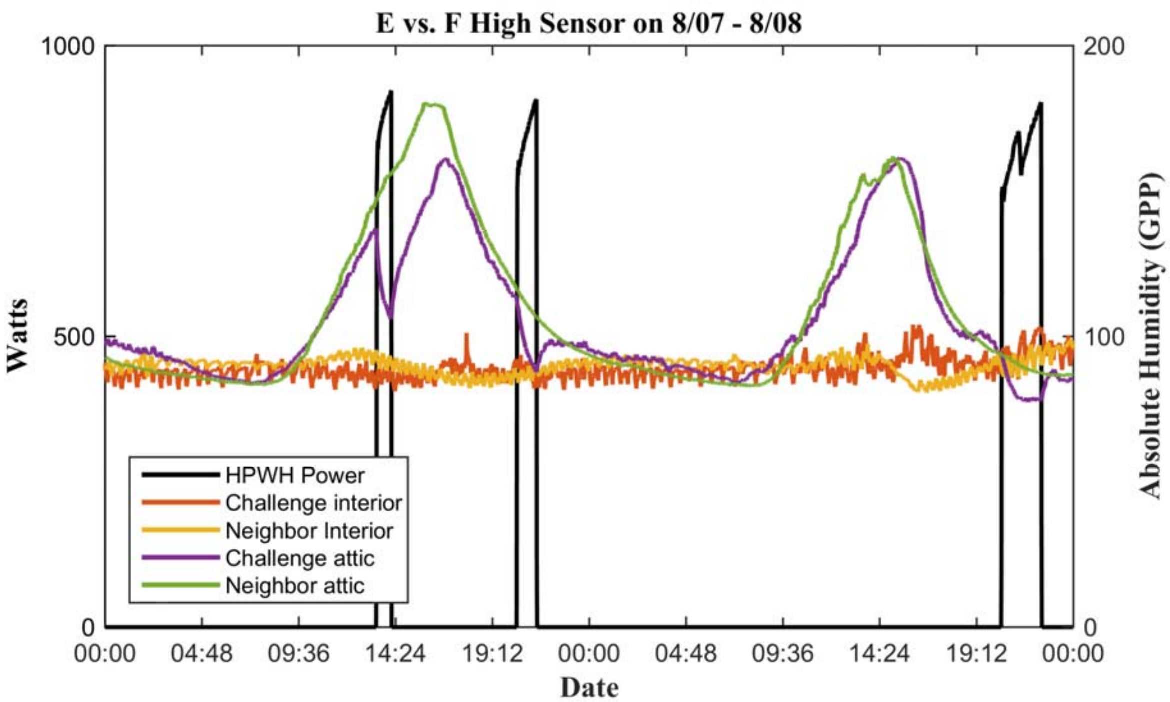

Figure 32. Savannah Unit E and F absolute humidities at the high center location of the attic and of the living space.

Attic temperatures were monitored in four different locations (north, south, and east sides of the house and high center of the attic about 6 feet from the attic floor) (Figure 33). The temperatures decreased when the HPWH operated during the end of the day, but it is difficult to distinguish the cause between HPWH operation and the sun setting. During the first half of the day attic temperatures rose due to the sun rising. In one instance, the HPWH operated during the first half of the day and the east side, where the duct pointed, decreased by less than 2 °F. The north and south sensor readings decreased by less than 0.4 °F. The sensor at the high center of the attic continued to increase while the HPWH operated. Figure 34 shows a zoomed in image of the temperatures during this time. Since the HPWH was only able to reduce the attic temperature in one area of the attic and not the rest of the attic, it is unlikely that the HPWH had any impact on the temperature in the living zone or the energy consumed by the HVAC equipment.

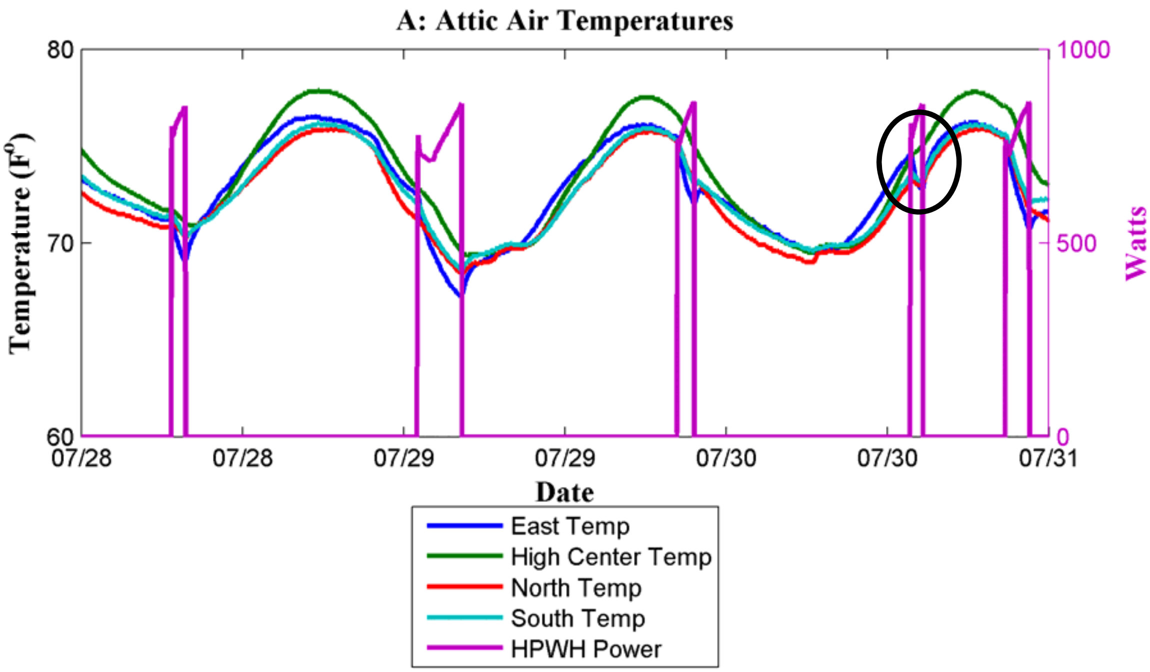

Figure 33. Attic temperatures at five locations around the attic during the summer at LaFayette Site A. The circled area can be seen in zoom in Figure 34.

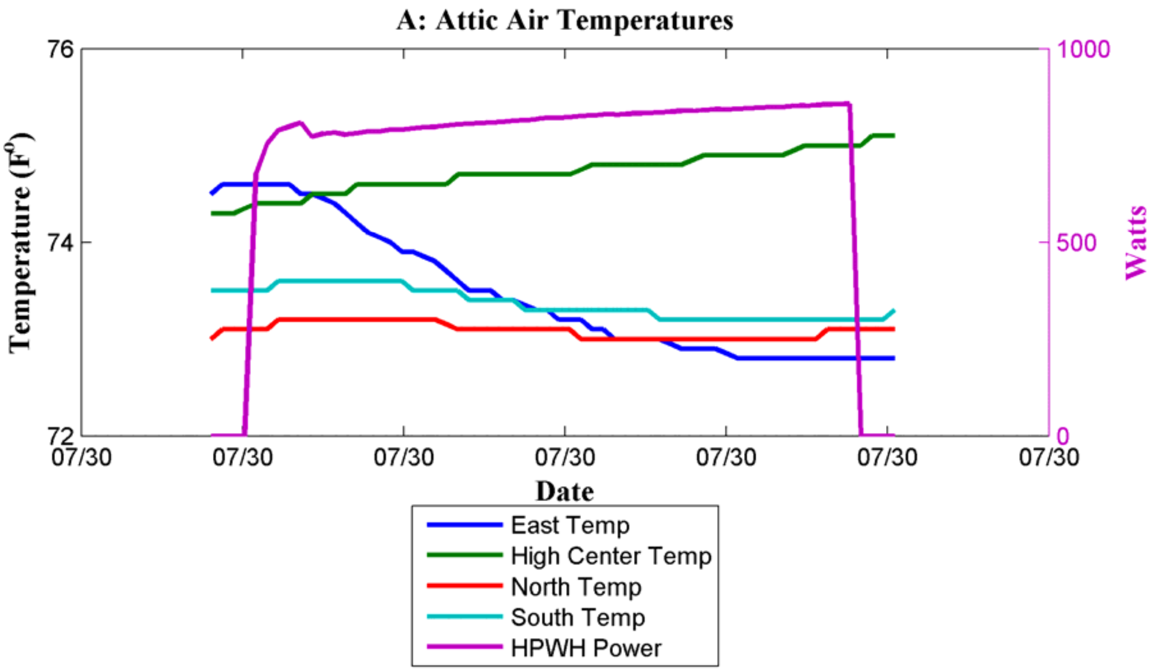

Figure 34. Zoomed section of Figure 33 showing attic temperature changes during HPWH operation.

5.2 Huber Zip System® Sheathing Performance

In-situ field measurements of wall temperature, relative humidity, and wood moisture content data were analyzed to compare the Zip System® R-Sheathing (ZipR) wall assembly performance of the Savannah Gardens test home to the neighboring home with traditional uninsulated Zip System® Sheathing (Zip). All measurements were recorded with Omnisense sensors (see specifications in Table 9).

5.2.1 *Wall Monitoring Plan*

A total of seventeen sensors were installed inside the Zip and ZipR wall assemblies, and an additional sensor was installed in each home near the thermostat. The sensors inside the walls were placed in three different positions: (A) flush mount to OSB, (B) legs through Zip Foam to OSB and (C) stud side near the drywall. The locations of the sensors are depicted in Figure 35, images of the sensors in the wall assemblies shown in Figure 36, and a vertical cross section schematic in Figure 37.

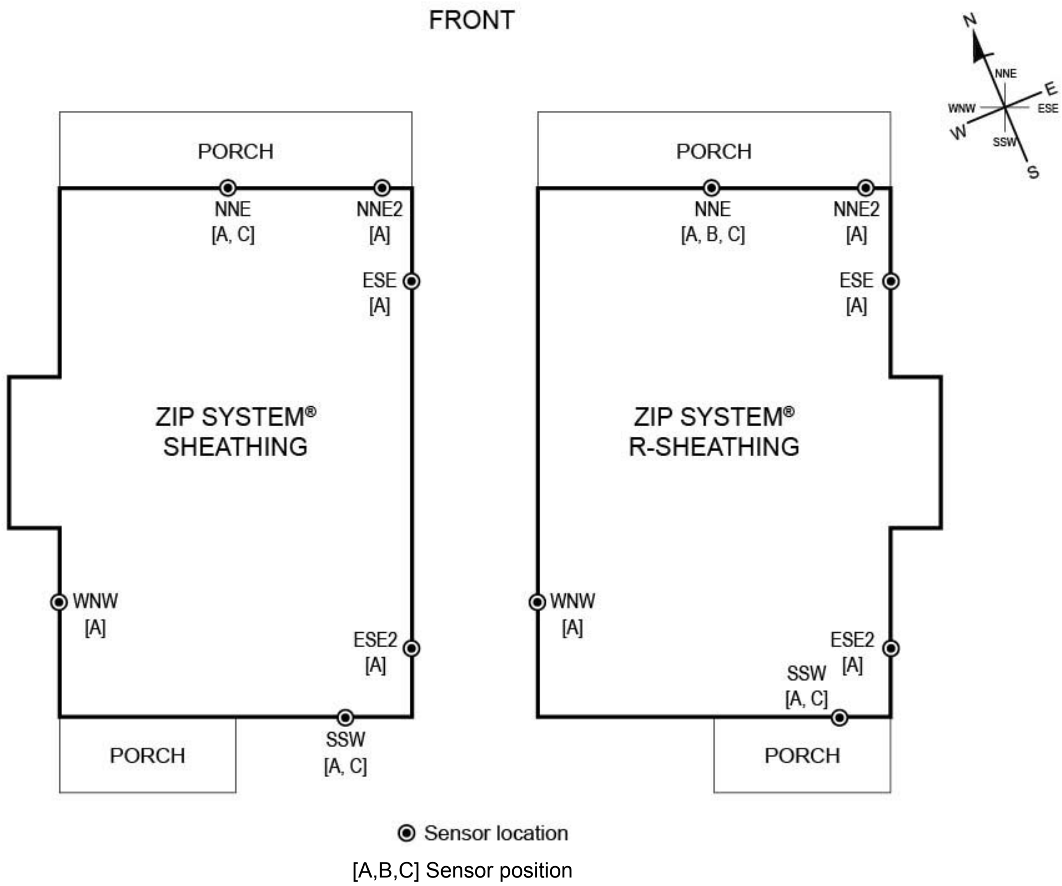

Figure 35: OmniSense sensor locations and positions in Zip and ZipR test homes.

Figure 36: OmniSense sensor position A in ZipR home (Left) and Zip home (Right).

Figure 37: OmniSense sensor position C (Left) and position B (Right).

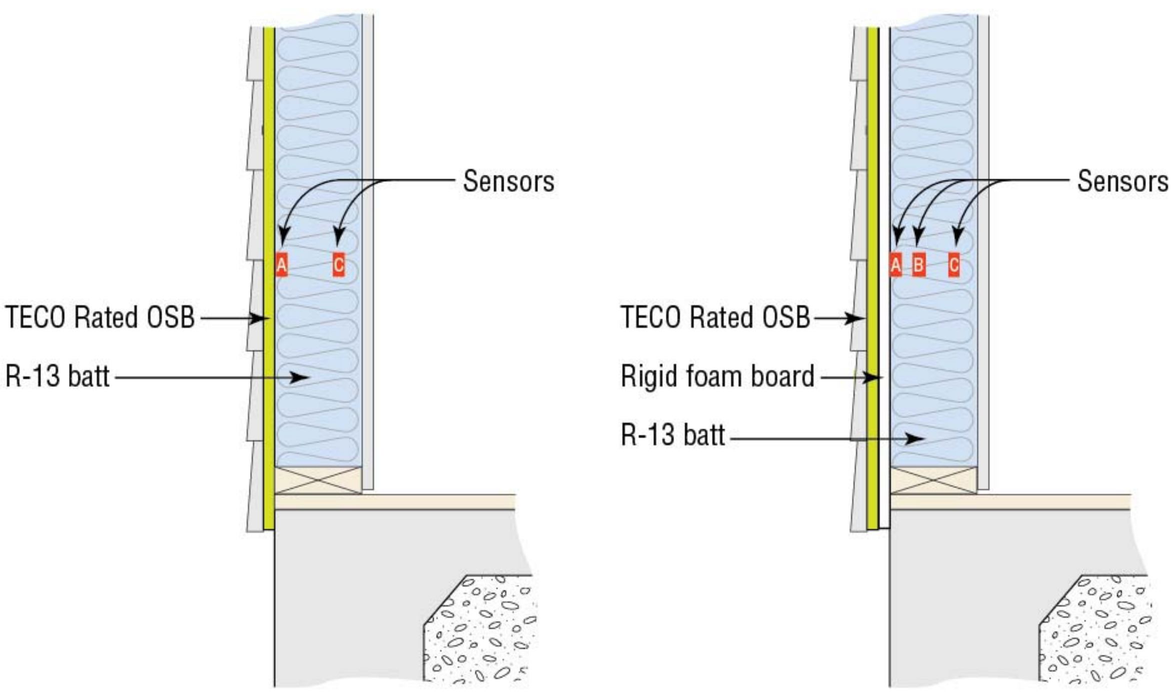

Figure 38: OmniSense sensor location and position in Zip (Left) and ZipR (Right) walls.

5.2.2 *Wall Thermal Performance*

The amount of incident solar radiation depended on the wall orientation and level of shading. As seen in Figure 35, the front of both homes face the NNE orientation. The sensors in the middle of the NNE wall were fully covered by the front porch, and received minimal solar exposure throughout the year. Due to the close proximity of the homes, they provided shade for each other during certain time periods. The sun's low angle in the winter months limited the solar exposure of the Zip home's ESE wall due to shading from the ZipR home's WNW wall. Solar exposure varied dramatically with the SSW sensors due to back porch shading on the ZipR home.

Sensors on the WNW wall received similar solar exposure, and trends comparing a cloudy and sunny day were analyzed. Figure 39 shows the temperature of the Zip and ZipR homes' WNW wall sheathing (position A) on September 2nd (a cloudy day) and September 3rd (a sunny day). The peak temperatures for 9/2/14 and 9/3/14 were 92°F and 89°F, respectively. The impact of incident solar radiation on the wall is evident on the second day by the drastic temperature increase. The Zip wall's peak temperature was 2.9°F greater than the ZipR's on the cloudy day, and 7.8°F greater on the sunny day. This trend was observed throughout the summer months, and exposure to solar radiation magnified the difference in peak temperatures between the two different wall assemblies. The ZipR WNW average daily peak was 3.4°F lower than the traditional Zip wall's daily peak temperature. The ZipR home's interior temperature was 2.2°F warmer than the Zip.

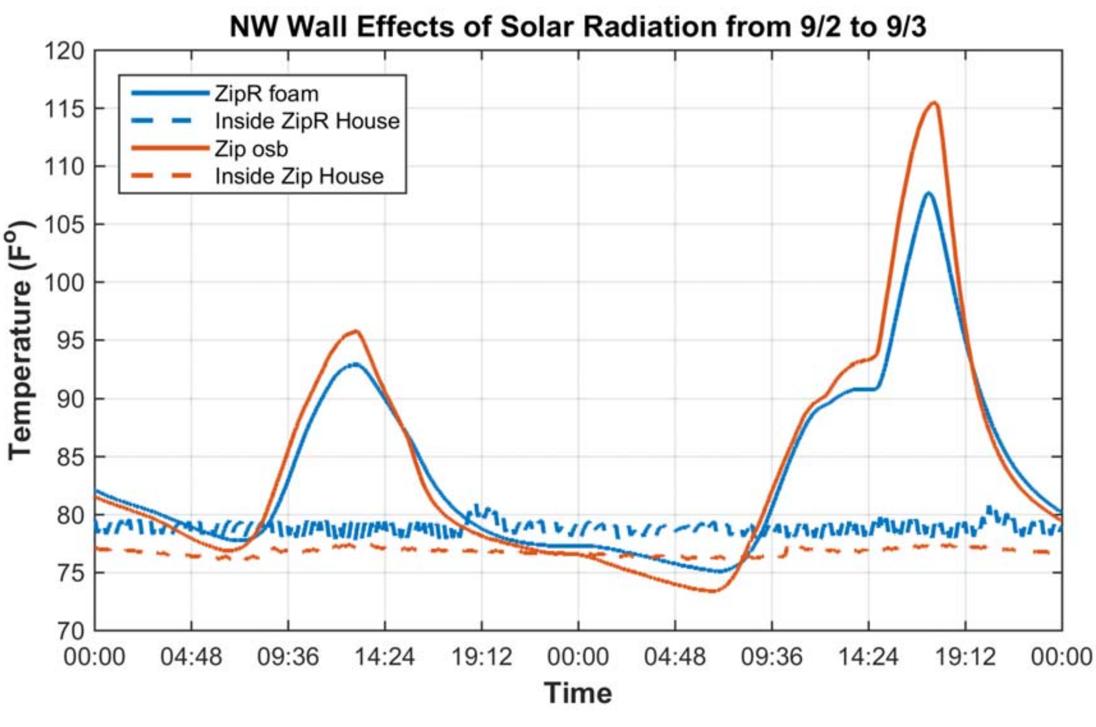

Figure 39: WNW Wall Temperatures on a Cloudy (9/2/14) and Sunny (9/3/14) Day.

Table 13 contains the WNW wall sheathing (position A) temperature summary for the summer and winter. During the summer, the difference between the Zip and ZipR maximum temperatures was calculated on a daily basis and averaged across the period. The same calculation was performed during the winter for the daily minimum temperatures at each wall. The average interior temperature refers to the daily average temperature of the sensor inside the living space of the home. The temperature swing represents the average difference between daily maximum and minimum temperatures in the walls. The average ZipR WNW wall sheathing was 6.4 °F warmer in the winter and 3.4 °F cooler in the summer when compared to the Zip WNW wall sheathing. In addition, the ZipR wall experienced less severe daily temperature fluctuations, as exhibited by its lower daily temperature swing.

Table 13: ZipR and Zip WNW wall sheathing (Position A) temperature summary.

Average Daily Difference (ZipR – Zip)	Heating[4]	Cooling[5]
Minimum Wall Temperature	6.4^{0}F	-
Maximum Wall Temperature	-	-3.4^{0}F
Average Interior Temperature	-0.4^{0}F	2.2^{0}F
Temperature Swing	-2.7^{0}F	-3.4^{0}F

The NNE wall temperature profile was also analyzed, as both homes' NNE wall received little solar exposure due to shading from the front porch. REM/Rate™ was used to calculate the clear-wall R-value for the walls with Zip and ZipR sheathing. Clear-wall R-value is the R-value of an assembly containing only insulation and minimum necessary framing materials at a clear section with no windows, corners, columns, architectural details, or interfaces with roofs, foundations or other walls[6]. ZipR sheathing increased the clear-wall R-value by 23% compared to the home with traditional Zip sheathing panels (assuming a 24% framing factor)[7].

Table 14: Clear-Wall R-value comparison for Zip and ZipR homes

	ZipR Sheathing		Zip Sheathing	
Enclosure Component	R-Value, Cavity (ft2 ^{0}F hr/BTU)	R-Value, Stud (ft2 ^{0}F hr/BTU)	R-Value, Cavity (ft2 ^{0}F hr/BTU)	R-Value, Stud (ft2 ^{0}F hr/BTU)
Outside Air Film	0.28	0.28	0.28	0.28
7/16" OSB	0.60	0.60	0.60	0.60
0.5" Rigid Insulation	3.00	3.00	0.00	0.00
2x4 Wood Stud	n/a	4.38	n/a	4.38
3.5" Fiberglass Batt	13.00	n/a	13.00	n/a
1/2" Dry Wall	0.45	0.45	0.45	0.45

[4] December, January, February
[5] July, August, September
[6] http://www.buildingscience.com/glossary/clearwallrvalue
[7] http://web.ornl.gov/sci/roofs+walls/research/detailed_papers/thermal_frame/

Interior Air Film	0.82	0.82	0.82	0.82
Total Assembly Clear-Wall R-Value (23% Framing Factor)	16.08		13.08	

Similar to the calculations above, the difference in daily maximum and minimum temperatures experienced by the NNE walls were calculated. Three boxplots below illustrate the results (Figure 40). The first box plot shows the daily minimum temperature in the ZipR's NNE wall was on average 5.1°F warmer than the Zip's minimum temperature during the winter. During the summer, the NNE wall's daily maximum temperature was on average 0.4°F cooler in the ZipR home. The daily temperature range experienced by the NNE wall was greater in the Zip home 294 days of the 300 days of measured data.

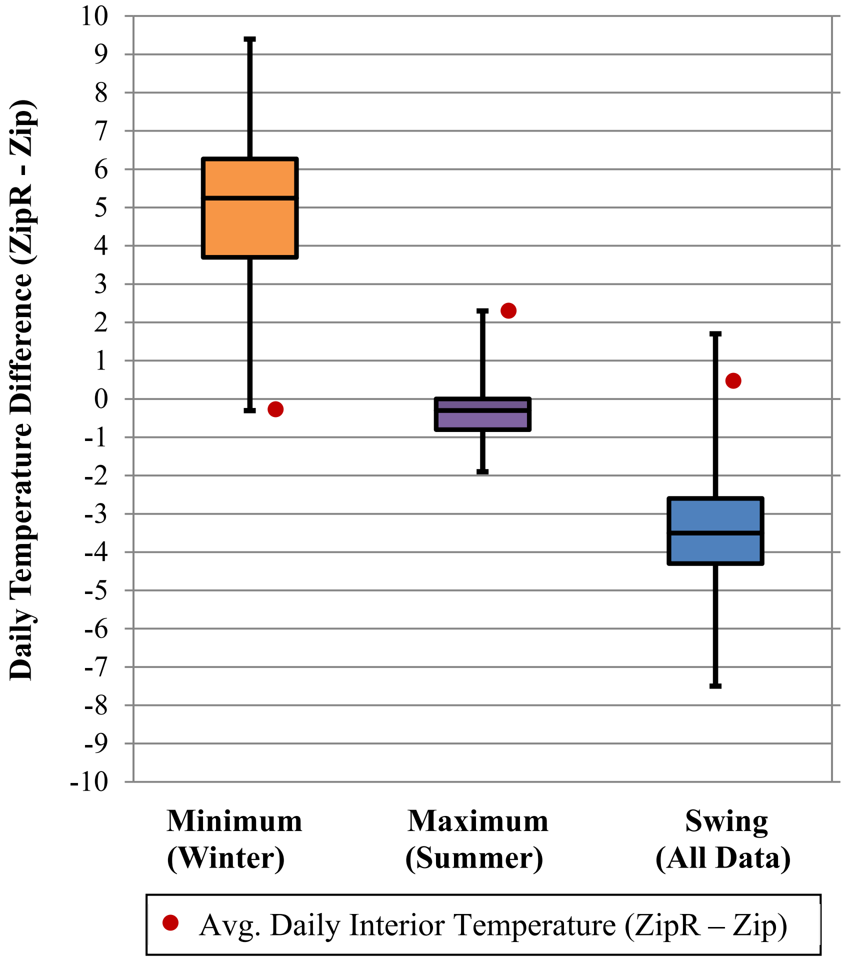

Figure 40: ZipR and Zip NNE wall daily temperature profile.

Heating and cooling energy consumption was examined to determine the impact of the ZipR wall's ability to maintain warmer temperatures in the winter and cooler temperatures in the summer. Both homes' heating and cooling is provided by a ground source heat pump (GSHP). Both GSHPs are identical, and were installed by the same contractor. The GSHP run times were analyzed during a time when the indoor set points of both homes were similar. On November 28th from 3:42am to 8:51am, the average living zone temperature of both homes averaged 69.7°F, and interior temperature difference varied by less than 0.2°F. The duration of time the GSHPs were on and off is reported in Table 15. Shorter GSHP run times are associated with the ZipR home. In addition, the average amount of time the GSHP is turned off between cycles is reduced by a third in the Zip home. During this six hour period, the Zip home's GSHP consumed 36% more energy.

Table 15: Zip and ZipR GSHP run times.

	Zip Sheathing	ZipR Sheathing
Number of GSHP Runs	13	10
Average Duration of GSHP ON (minutes)	10.2	9.7
Average Duration of GSHP OFF (minutes)	13.3	19.7
Total Energy Consumption (kWh)	3.10	2.28

From 11/21/2014 to 1/3/2015, the ZipR home's GSHP consumed 122.3 kWh and the Zip home GSHP consumed 199.2 kWh, a 39% increase. During the same time, the sum of the absolute difference in temperatures between the inside and outside of both homes differed by less than 2%.

5.2.3 *Wall Moisture Risk*

Lower sheathing temperatures increase the risk of condensation occurring on the interior side of the sheathing. Grin and Lstiburek explored the condensation potential in several hybrid (cavity and exterior insulation) wall assemblies located in Minneapolis and New Orleans using hygrothermal modeling with WUFI software (Grin & Lstiburek, 2012). On an hourly basis, the wall insulated with 1.5 inches of exterior XPS had a 47% reduction in condensation potential over the standard wall assembly in Minneapolis. The exterior insulated wall assembly in New Orleans (CZ 2), did not exhibit a significant reduction in condensation potential due to the warmer winter temperatures.

Field data in Savannah was analyzed on a minutely basis to quantify the time there was a risk of condensation in either home. Figure 41 and Figure 42 show the dew point of the air in the living space and the interior surface temperature of the sheathing for the NNE walls in both the Zip and ZipR homes. The yellow line indicates when the sheathing temperature is less than the interior air dew point, and therefore a risk for condesation exists. The ZipR home's NNE wall was subjected to 83% less time being at risk for condensation compared to the Zip home. During an average winter day, the Zip home's NNE wall was at risk for condensation for 185 minutes. During the same time frame, the ZipR home's NNE wall is at risk for condensation for 12 minutes.

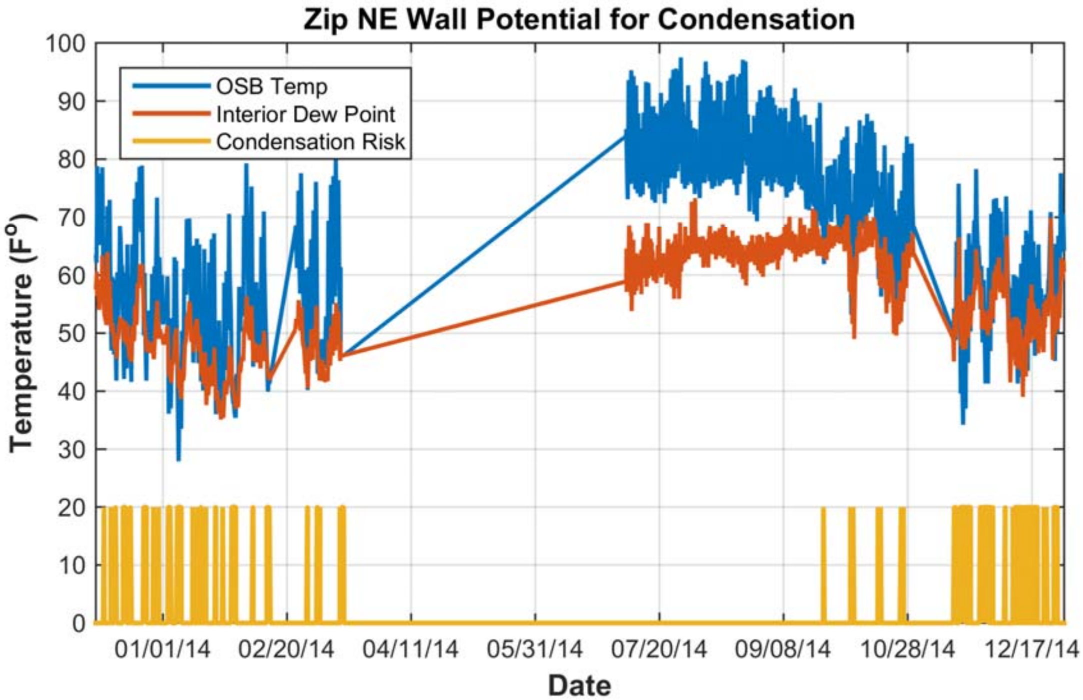

Figure 41: Minutes of potential condensation for Zip house on northeast wall.

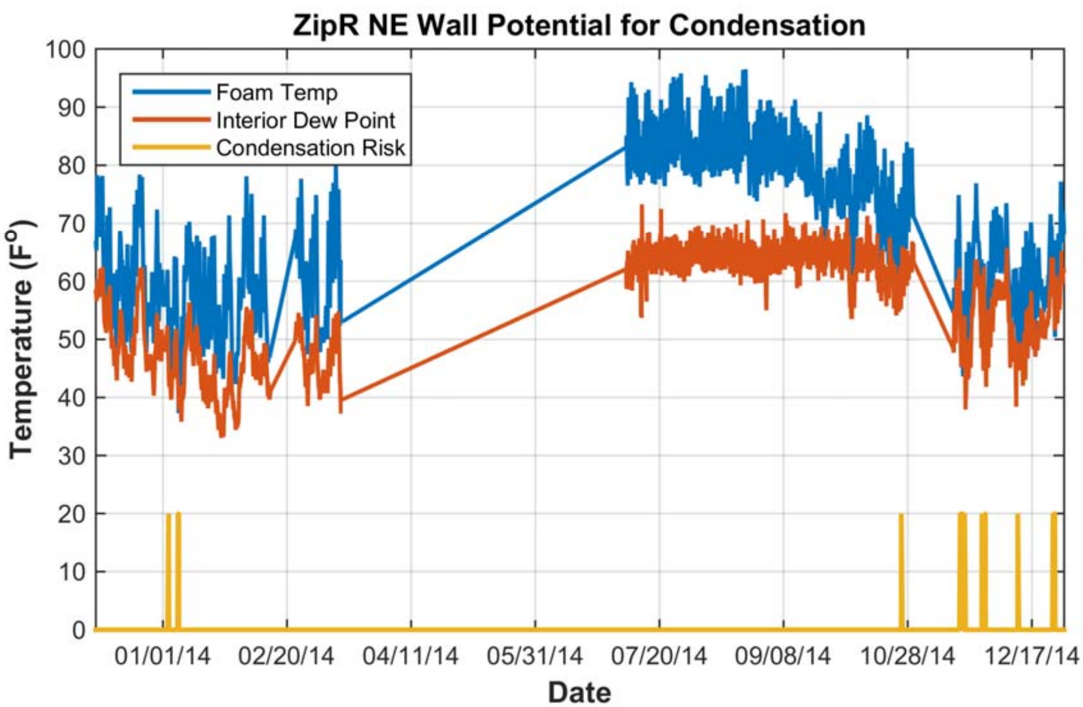

Figure 42: Minutes of potential condensation for ZipR house on northeast wall.

Condensation potential calculated at all sensor locations is detailed in Table 16. Time of condensation risk was reduced in the ZipR home for all sensor locations, from 19-96%.

Table 16. Minutes of condensation risk for all sensor locations during 300 days monitoring.

Sensor Location	Zip Minutes of Condensation Potential	ZipR Minutes of Condensation Potential	Percent Reduction in Condensation Potential
NNE	38,181	2,451	94%
NNE2	28,445	22,958	19%
ESE	55,940	15,766	72%
ESE2	67,606	4,697	93%
SSW	49,200	7,146	85%
WNW	45,575	1,973	96%

The longer the wall is continuously at risk for condensation, the higher the potential for mold growth and durability issues. The duration of time the NE walls were susceptible to condensation was explored in Table 17. Figure 43 shows the number of occurrences the NE wall was at risk for condensation and the duration of each event. The traditional Zip wall had far more risk events and a much greater average duration.

Table 17: Dispersion of Condensation Risk Events at Sheathing in NE Walls.

	Zip Condensation Risk Event	ZipR Condensation Risk Event
# of Events	153	43
Minimum (minutes)	1	1
Mean (minutes)	250	57
Maximum (minutes)	2451	823
Standard Deviation (minutes)	410	147

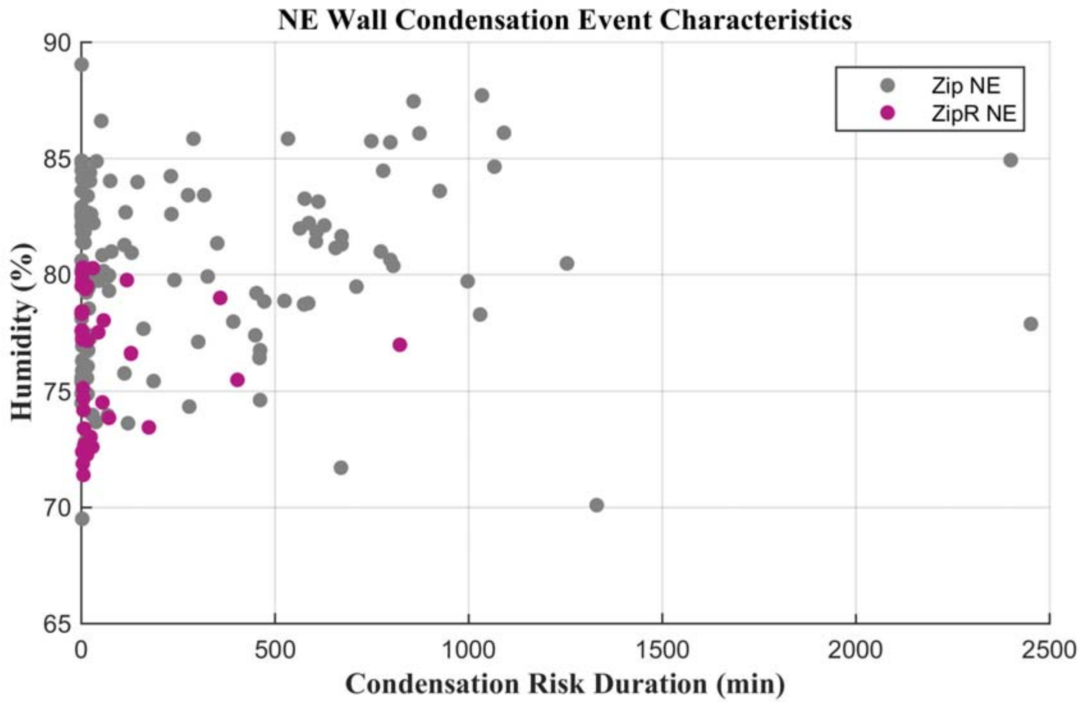

Figure 43. Plot showing the duration a wall cavity is exposed to high humidity levels when the temperature at the sheathing is less than the dew point.

ASHRAE 160

ASHRAE Standard 160-2009: Criteria for Moisture-Control Design Analysis in Buildings specifies conditions for minimizing mold growth, stating that "in order to minimize problems associated with mold growth on the surfaces of components of building envelope assemblies, the following condition shall be met: a 30-day running average surface RH<80% when the 30-day running average surface temperature is between 5°C (41°F) and 40°C (104°F)" (ASHRAE, 2009).

The 30-day temperature and humidity running averages were computed for the Zip and ZipR NNE wall, as shown in Figure 44 and Figure 45. The 30-day running average NNE wall temperatures for both homes fell between 41°F and 104°F. In the winter of 2014, both homes' NNE walls maintained 30-day running average humidities below 80%. During the winter the following year, both homes' humidities increased, however only the Zip home's 30-day running average humidity rose above 80%, causing it to fail the ASHRAE 160 standard.

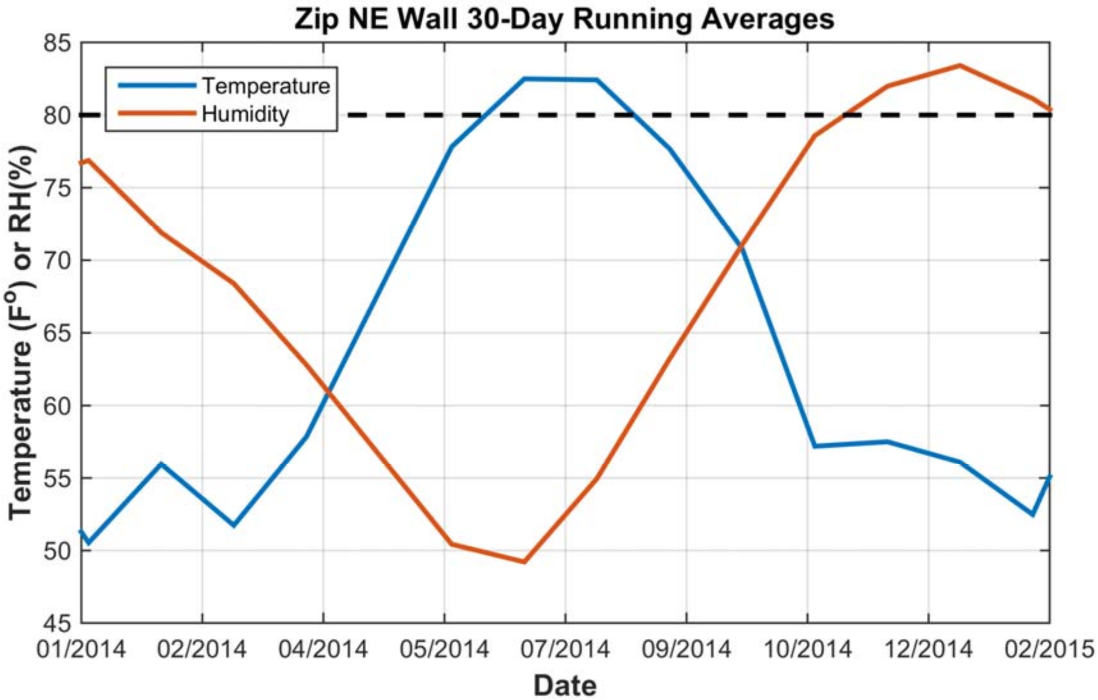

Figure 44: Zip NE Wall 30-Day Temperature and Humidity Running Averages.

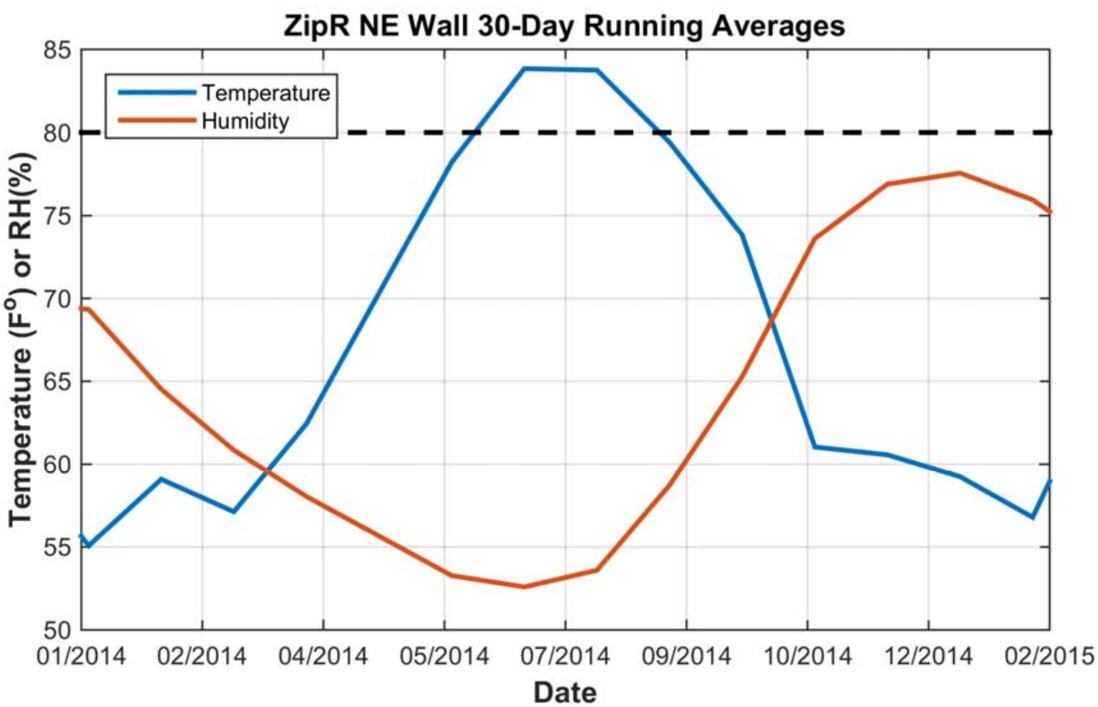

Figure 45: Zip NE Wall 30-Day Temperature and Humidity Running Averages.

Ueno studied wall moisture conditions in double-stud walls and evaluated their performance under ASHRAE 160 guidelines and an Isopleth Analysis based off of Viitanen and Ojanen's modeled nature of mold growth (Ueno, 2015; Viitanen & Ph, 2005). Ueno plotted the humidity and temperature of a north facing wall, and overlaid the isopleth curve detailing conditions optimal for mold growth. The same process was applied to the Zip and ZipR NNE facing walls, and average hourly temperature and humidity are shown in Figure 46 and Figure 47. The ZipR wall had far fewer hours in conditions susceptible to mold growth than the Zip wall.

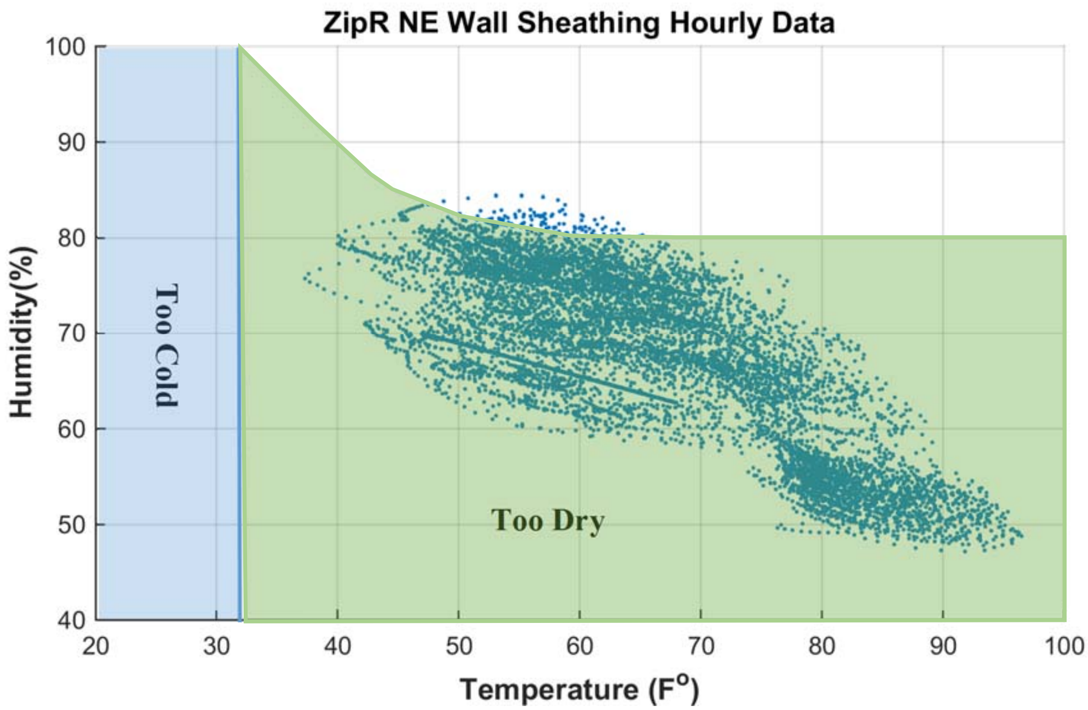

Figure 46: ZipR NNE sheathing hourly temperature and humidity.

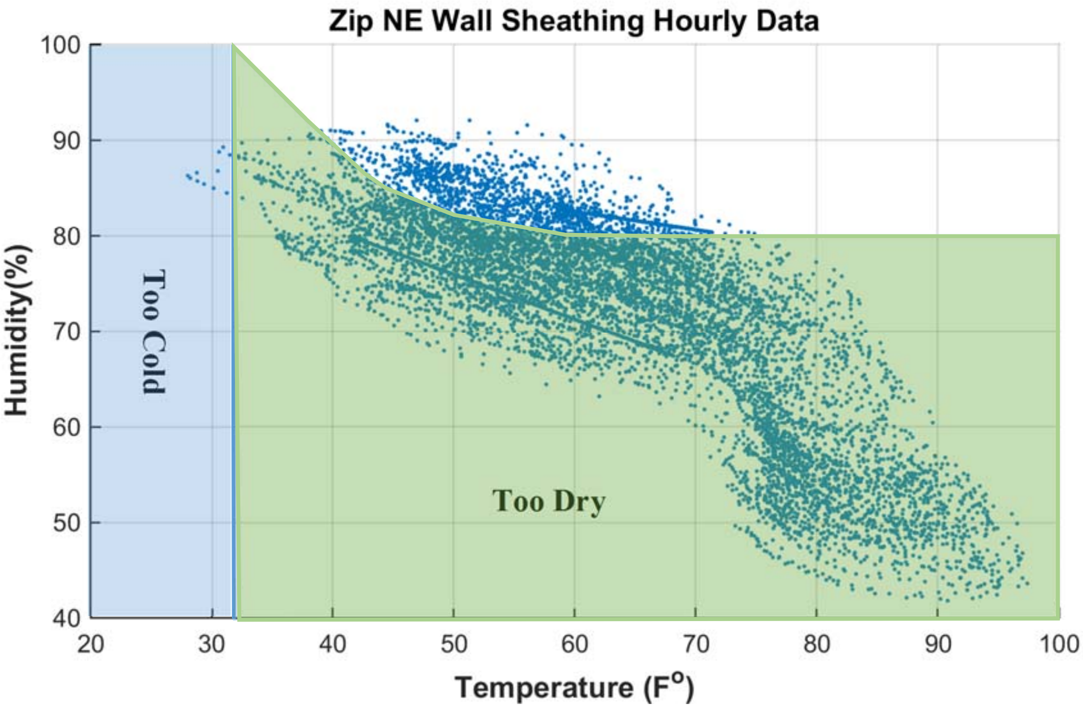

Figure 47: ZipR NNE sheathing hourly temperature and humidity.

6 Resident Experience

6.1 LaFayette Resident Survey

Resident surveys were created and analyzed by Southface and delivered and collected by the LHA. The survey was designed to determine occupants' perception of comfort and satisfaction with the various energy efficient measures incorporated into their homes. Surveys did ask which unit configuration the respondent lives in, but were otherwise anonymous. Surveys were returned for all 30 duplex units.

6.1.1 *Resident Energy Conservation Behavior*

The survey asked questions to assess the residents' behaviors that have an impact on energy usage of the domestic hot water and heating and air conditioning systems. Results of self-assessments of water usage and set points for all 30 homes are shown in the charts below. For hot water usage, most respondents reported using cold water to wash clothes (21), with successively fewer respondents using warm (8) and hot water (5). Reported typical shower durations were 6-10 minutes for the majority of households (17), with a significant number (12) taking 11-20 minute showers.

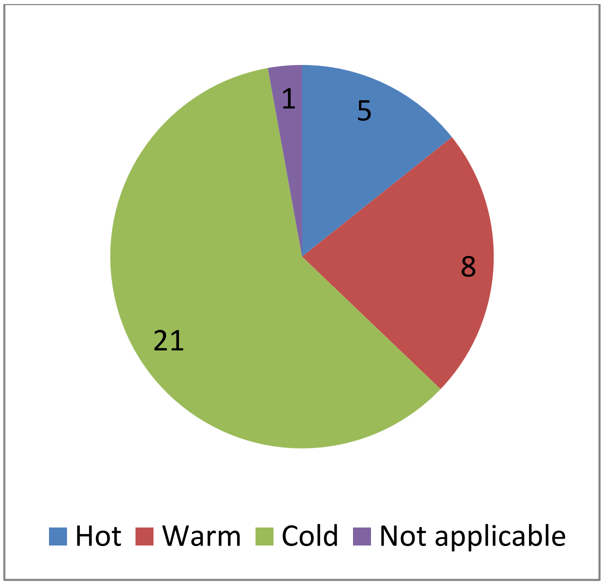

Figure 48. At what temperature water do you wash your clothes? (Please check all that apply.)

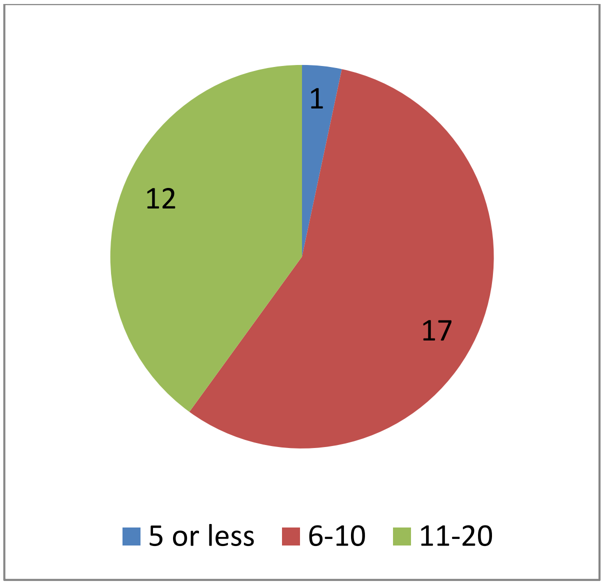

Figure 49. What is the typical duration of a shower in your household (minutes)?

The most common thermostat setpoint range during both heating (20 of 30) and cooling (15 of 30) seasons is 69-72°F (Figure 50 and Figure 51). During the winter, 9 residents use a setpoint of 68 and below, while 7 do during the summer. The residents clearly have a preference for maintaining their homes at cooler temperatures year around, leading to energy saving in the winter and greater energy usage during the summer.

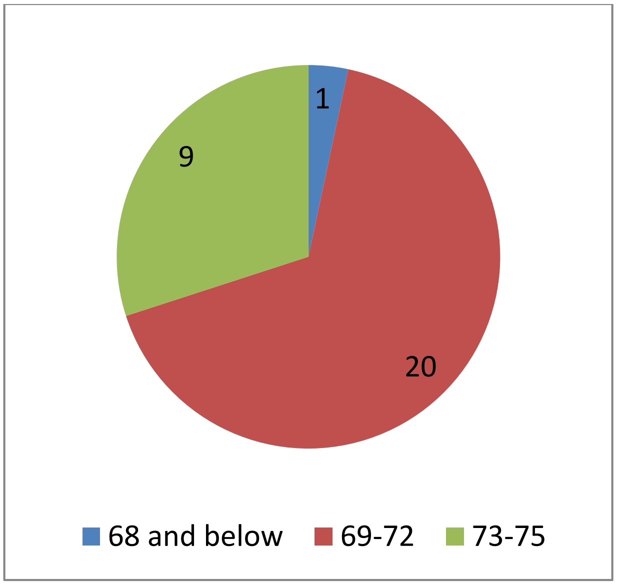

Figure 50. In general, what temperature (in degrees) is your thermostat set to during the winter?

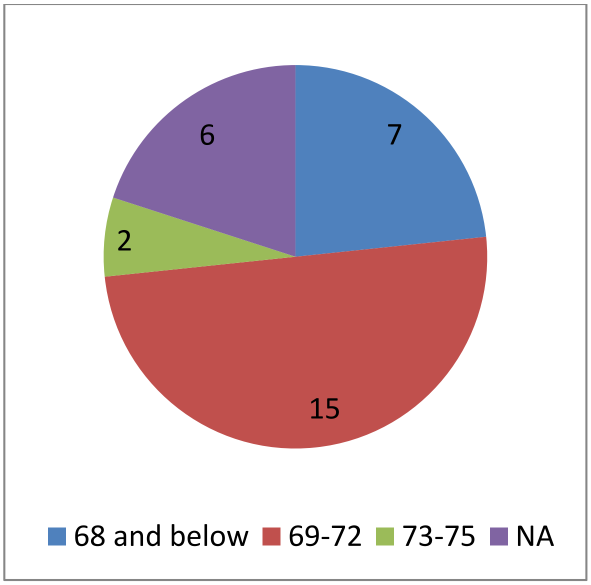

Figure 51. In general, what temperature (in degrees) is your thermostat set to during the summer?

Most residents have not used the setback capabilities of their programmable thermostats (16 of 30) or do not know if they have (3 of 30) (Figure 52).

It is possible that additional resident education could assist residents in lowering their energy consumption and utility costs without significantly sacrificing occupant comfort. Survey results can help identify high impact areas upon which to focus. For instance, taking advantage of the setback capabilities of the programmable thermostats would likely result in significant savings, especially for residents with cooling setpoints at 72°F or less. Similarly, encouraging shorter showers would lead to reductions in both water heating energy and water and sewer usage. Figure 53 shows that while 63% of the population rates their electric bill costs as Low or Fair, a significant portion are unsure or rate them as High (2 of 30), and would likely be receptive to trusted and targeted messaging.

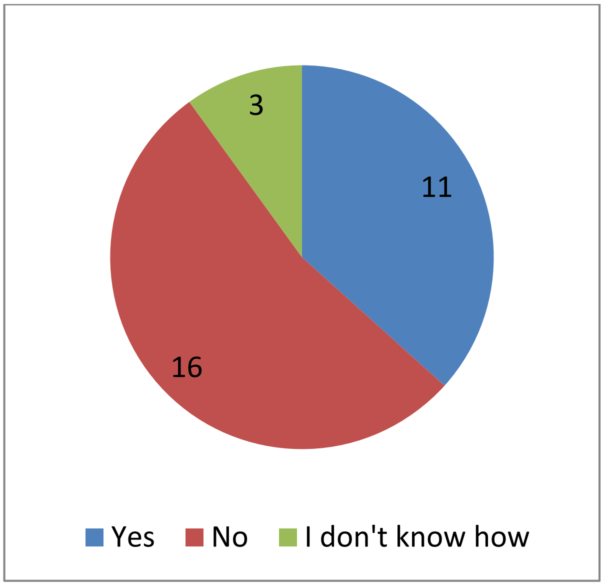

Figure 52. Have you utilized your thermostat's ability to automatically adjust temperature settings throughout the day?

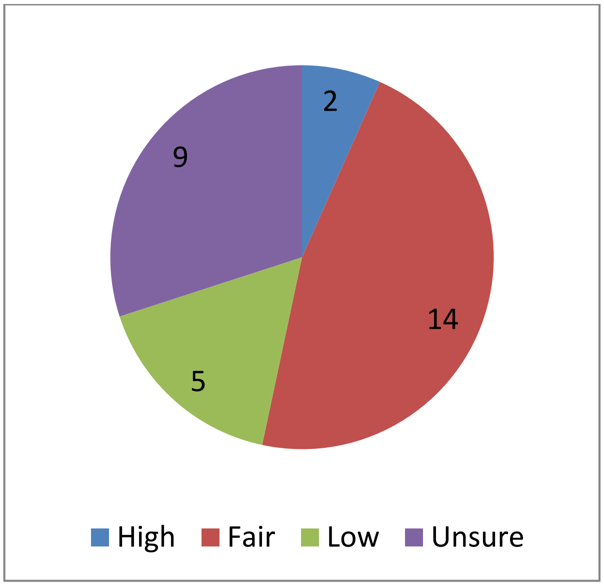

Figure 53. How would you rate the cost of your electric bills?

6.1.2 *Domestic Hot Water Supply Satisfaction*

The HPWHs were set in Efficiency (heat pump-only) mode in order to function most energy efficiently. Water heater temperature was set at 120 degrees Fahrenheit. The residents do not have access to the water heater controls in order to change either mode or temperature. Restricting resident access to mechanical systems is typical in rental apartments, and the LHA is invested in helping residents minimize their utility bills. A resident survey attempted to assess whether or not these settings provided hot water at a sufficient rate to meet the residents' expectations and needs.

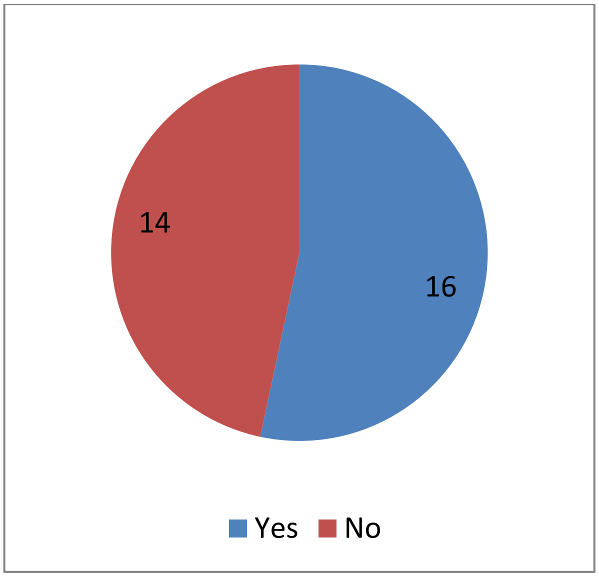

Figure 54. Do you avoid taking consecutive showers to prevent running out of hot water?

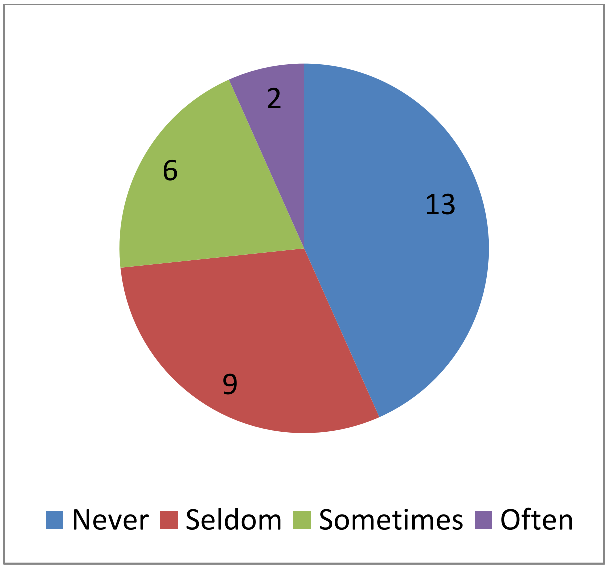

Figure 55. How often, if ever, do you experience shortage of hot water while showering/bathing?

Over ½ of all respondents indicated that they plan their shower timing in order to avoid running out of water (Figure 54). However, over 70% either Never or Seldom have experienced a shortage of hot water while showering/bathing (Figure 55). It cannot be determined from this data whether the respondents' behavior in timing showers is due to experiences in the LaFayette homes or is learned behavior from past experiences, especially since they have lived in these homes for less than one year.

Reported hot water shortages while using the kitchen sink were very rare, 10% answering Sometimes or Often (Figure 56).

Overall satisfaction with hot water supply is very high, with over 93% of residents Agreeing or Strongly Agreeing that they are satisfied (Figure 57). The heat pump water heater in energy efficient mode appears capable of meeting the hot water demands of families in both the 2 bedroom and 3 bedroom duplex apartments. Additionally, LHA has not received any resident complaints or requests with respect to hot water demand.

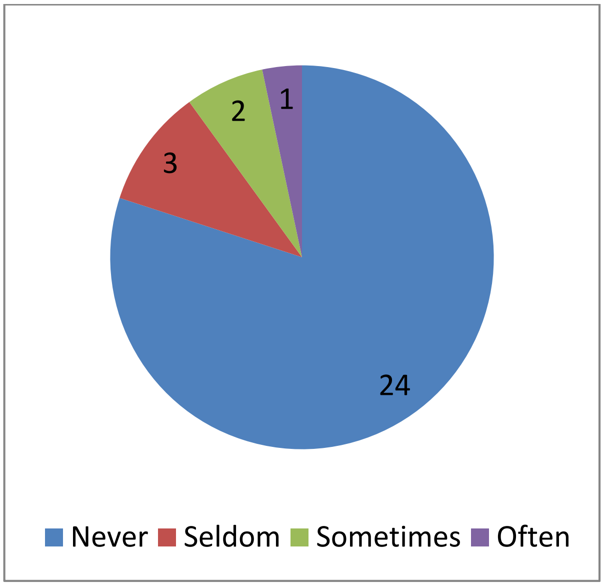

Figure 56. How often, if ever, do you experience a shortage of hot water while using the kitchen sink?

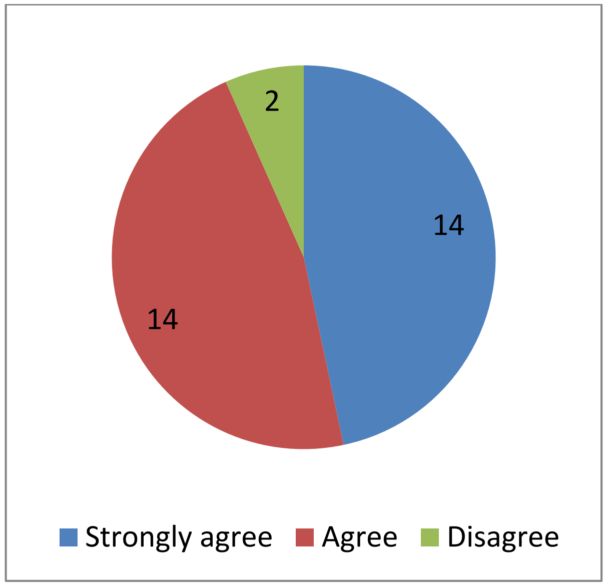

Figure 57. I am satisfied with the supply of hot water in my home.

6.1.3 *Heat Pump Water Heater Noise*

Previous research has identified heat pump water heater operation noise as a barrier to acceptance of installation inside of living space, such as in the utility closets in the LaFayette community(Chasar & Martin, 2013). This was one of the factors leading the research team to recommend a solid door on the utility closet and ducting of the HPWH to/from the encapsulated attic. Both the HPWH and the HVAC air handler were located inside each closet. The resident survey asked several questions to help identify whether or not this particular installation, which runs 100% in heat pump mode, has any negative impact associated with noise.

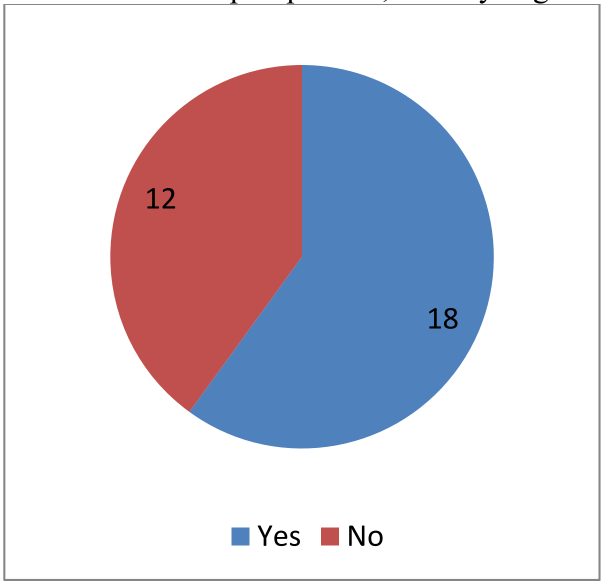

Figure 58. Do you hear noise from the mechanical equipment behind the locked doors in your home?

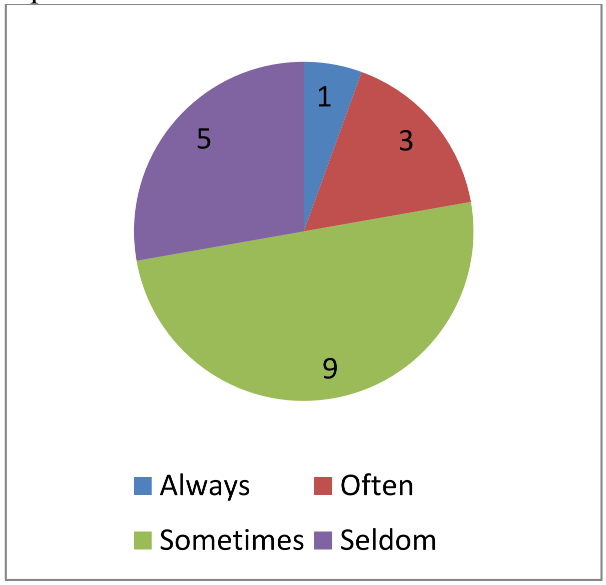

Figure 59. How often do you hear the operation of mechanical equipment behind the locked doors in your home?

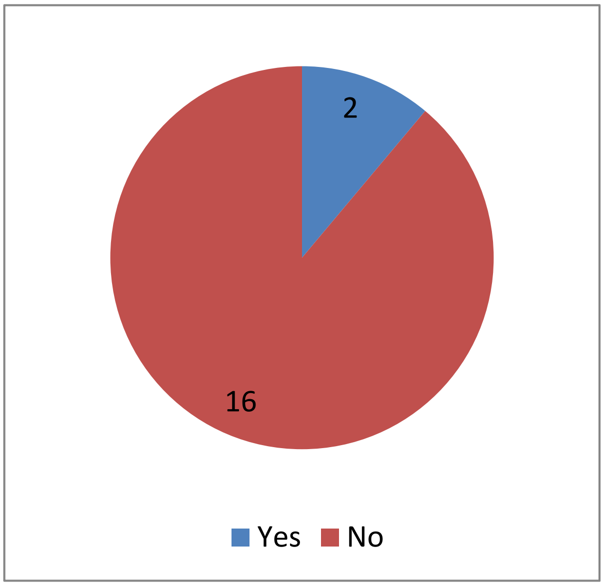

Figure 60. Does the noise disturb your daily activities? If yes, please explain.

Examination of more detailed questions allowed the researchers to identify that, of the 18 residents indicating that they have heard noise from the utility closet, 11 are related to the HPWH, 4 to the AHU, and 3 could be either. Despite the fact that 18 residents reported hearing noise, only 2 indicated that it disturbed their daily activities. The LaFayette Housing Authority has reported that they have not received complaints from residents and does not plan to make changes to HPWH operation based on noise.

6.1.4 *Resident Comfort*

The survey also asked questions to assess the residents' perception of comfort. Results of self-assessments for all 30 homes are shown in the charts below.

All respondents reported that they were comfortable in their homes during every season and that they are satisfied with the overall level of comfort (Figure 61 and Figure 62). Additionally, all but three respondents reported that all rooms in their homes are equally comfortable (Figure 63). Only two respondents reported issues with indoor air quality. The survey did not ask if the residents have known allergies or had had previous IAQ-related issues.

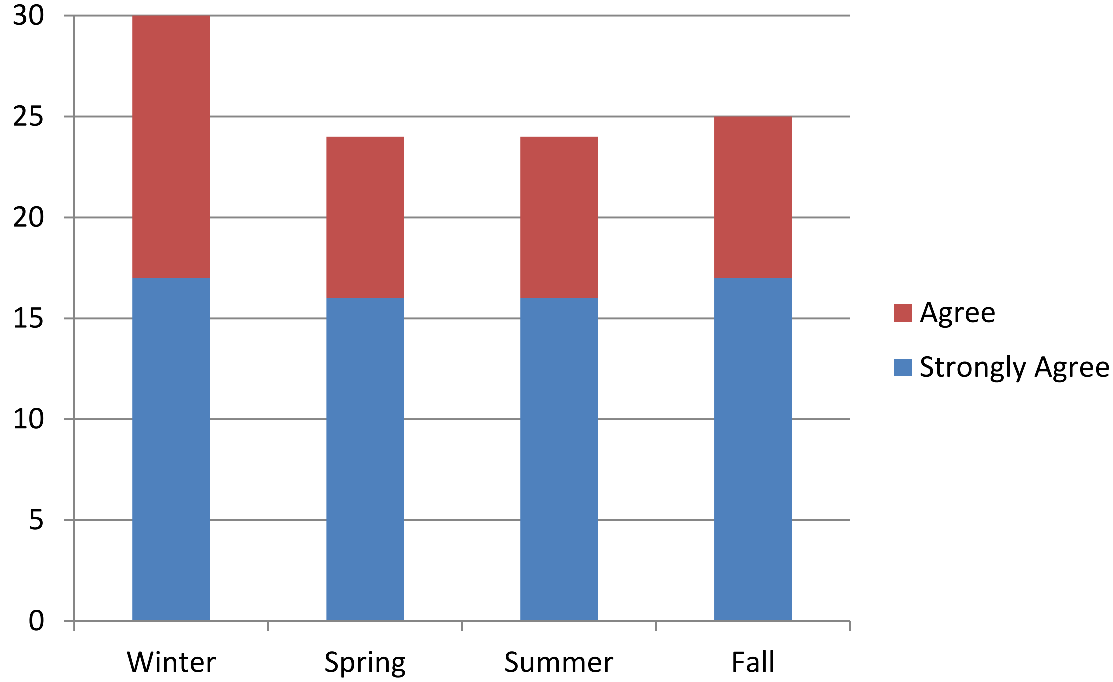

Figure 61. My home feels comfortable during every season: (Winter, Spring, Summer, and Fall).

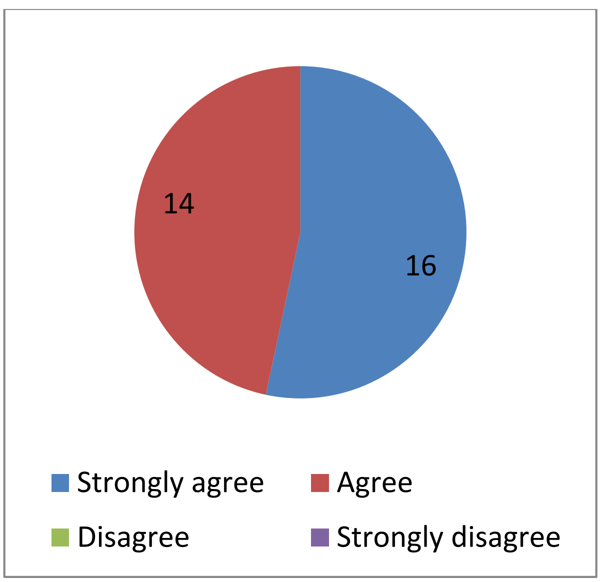

Figure 62. I am satisfied with the overall comfort of my home.

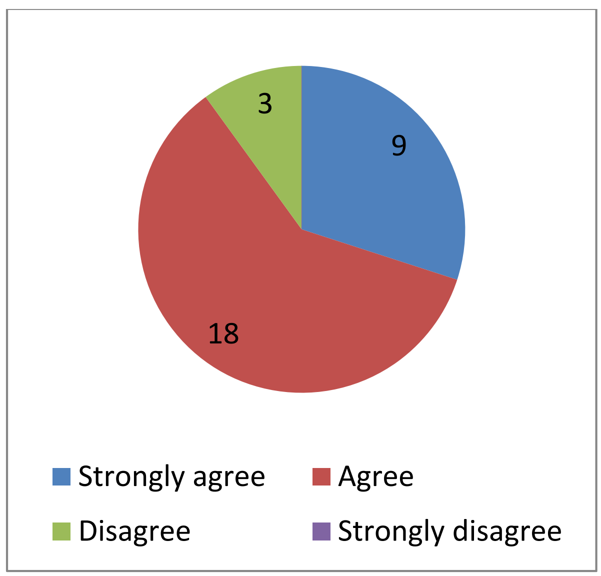

Figure 63. All rooms in my home are equally comfortable.

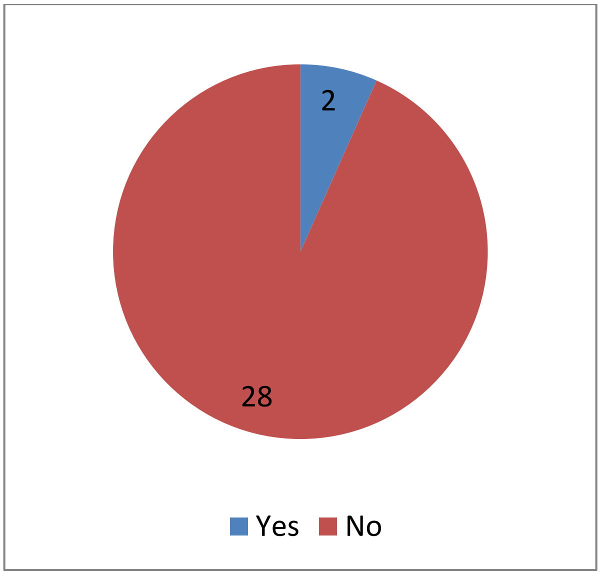

Figure 64. Do you experience issues with the indoor air quality (pollen, allergens, odors, etc.)?

Figure 64 shows that only 2 respondants experienced issues with indoor air quality polutants such as pollen, allergens, and other odors.

7 Successes and Failures

7.1 Savannah Gardens

The BEopt models indicated that slab edge insulation would have resulted in a net annual increase in energy consumption because it would have increased heating loads and decreased cooling loads. a net negative impact on energy consumption due to slab edge insulation because it increased heating loads while decreasing cooling loads. However, when the house was analyzed using REM/Rate software, R-5 slab insulation would have decreased heating loads while not impacting cooling loads, conforming to the EPAct required reductions to qualify for a $2,000 tax credit. On the other hand, BEopt+2.3 predicts decreased heating load, but increased cooling. Additional field research is necessary, particularly on raised slab foundations which are common in the Southeast, to collect data to refine modeling software algorithms and improve consistency across all modeling software platforms.

While the addition of the ZipR sheathing compared to the Zip was not predicted to result in significant annual energy savings (1.5%), measurements reveal significant differences in wall performance, even in the temperate climate of Savannah. Walls with ZipR insulated sheathing experience smaller swings in temperature, less extreme winter and summer peaks, and lower risk of condensation. Preliminary HVAC energy consumption data points to a decrease in total run time and total energy consumption. Additional research is necessary to verify this linkage.

7.2 JMC Patrick Square

While a builder participating in an energy efficiency/green building program may seem an ideal candidate for upgrading their product to ZERH, success lies in execution of multiple details throughout the construction process. ENERGY STAR, WaterSense, Indoor Air Plus and Zero Energy Ready Home have created a comprehensive package of checklists and other project evaluation tools, but these tools cannot be used as a substitute for daily quality assurance and proactive communication to and between trades in order to ensure that changes to standard building practice are being integrated efficiently and successfully. If one relies on the building program checklists to catch errors or mistakes, it is often too late, or prohibitively expensive, to correct the errors. The failure to properly install slab edge insulation is a great example of a costly error that was identified too late to fix, and disconnect between decision makers and those that must execute on the decisions.

The builder did make many improvements in the NCTH relative to the base specifications:

- Sealed attic with R-20 SPF
- Air leakage reduced 64 % compared to average (to 2.5 ACH_{50})
- Ducts in conditioned space
- Duct leakage to outside reduced 100% (to 0)
- Window package improved to meet ENERGY STAR v.3
- SEER 16 air conditioner
- 0.82 EF gas tankless water heater

The cumulative impact predicted by BEopt for all of these changes is a modest 3% savings in total source energy over the base model. The primary driver of this surprisingly low savings improvement is the fact that the base home has R-38 attic insulation, while the NCTH has R-20 roofline insulation. This decrease in total enclosure UA counteracts the impacts of the upgrade measures.

Market-ready solutions for high-R roofline assemblies that will be acceptable to production builders are necessary to reach increased levels of energy savings.

7.3 LaFayette

The kick-off meeting with the subcontractors and A.O. Smith and the subsequent visit from Johns Manville representatives were instrumental in reducing errors during construction. This helped the framers understand advanced framing, the HVAC contractor when and where to install the duct for the HPWH, and the masonry crew to install the slab edge insulation. The product manufacturer representatives gave advice and tools to successfully install their products. Good communication throughout the entire construction process helped find solutions to issues installing the insulation.

The duplex units were completed in early 2014 but remained unoccupied for a few months until the LHA could relocate qualified tenants into the units. During this down time, the LHA was responsible for the utility bills and noticed that the unoccupied units were having electric bills near $70/month. The cause was the ventilation air cycler operating the central fan integrated ventilation system (fresh air ducted to return plenum of air handling unit) for 15 minutes of every hour. The monthly bills alarmed the LHA, who then set the thermostat to temperatures to keep pipes from freezing and reprogrammed the air cycler to never operate. It is unknown if the air cycler was ever reprogrammed when the units became occupied. Communication and education of the facility staff or installation of a lower energy ventilation system might have prevented this problem.

8 Conclusions

What is the average daily HPWH coefficient of performance (COP) as a function of daily hot water use, and real-world variations in use patterns?

- HPWH COP values are dependent on several variables including intake air temperature and humidity, inlet water temperature, number of heat pump operation events, total hot water demand, hot water demand during heat pump operation event, and tank set point temperature (Sweet, Francisco, & Roberts, 2015). Because of this complexity, strong correlations between COP and any single variable were not necessarily established. The values calculated in this study are similar to other field monitoring studies and laboratory studies of unducted HPWHs.

The ability of the HPWH to keep up with hot water demand, and if occupants change the operating mode or temperature set point to ensure they have enough hot water.

- The HPWH satisfied occupant hot water demand in the efficiency operating mode as no complaints were reported to the LaFayette Housing Authority or from the homeowner in Savannah. A survey was administered to the residents in 30 duplex units in LaFayette, and 93% of the tenants agreed that they had satisfactory hot water supply. However, the homeowner in Savannah increased their tank setpoint temperature to 150° from 120°F, but not necessarily due to unsatisfactory supply from the HPWH in efficiency mode since it was turned off for a long period before they increased the setpoint. The increased setpoint reduced the COP from 3.1 to 2.0 and the total hot water consumption by 21.1 gallons per day.

The effect water heater exhaust air has on temperature and relative humidity conditions in the attic space and mechanical closet, and any effect on HVAC system performance which is also located in the encapsulated attic.

- The air conditioning provided by the HPWH only affects the temperature of the mechanical closet and attic space during the time the heat pump is operating. Shortly after the heat pump stops operating, the values return to previous levels. Encapsulated attic peak humidity levels can be reduced if the heat pump operates during the first half of the day compared to when it operates later in the day or compared to an alternative DHW system.

Impact of HPWH ducting on water heater COP.

- Different ducting strategies had no impact on COP. The intake air temperature increased slightly but not enough to increase COP.

How much does the insulated sheathing effect cavity temperature of exterior walls?

- The average ZipR WNW wall sheathing was 6.4°F warmer in the winter and 3.4°F cooler in the summer when compared to the Zip WNW wall sheathing. In addition, the ZipR wall experienced less severe daily temperature fluctuations, as exhibited by its lower daily temperature swing.

Describe behavioral difference of both wall systems under extreme weather conditions to explore issues of resilience.

- The 30-day running average NNE wall temperatures for both homes fell between 41°F and 104°F. In the winter of 2014, both homes' NNE walls maintained 30-day running average humidities below 80%. During the winter the following year, both homes' humidities increased, however only the Zip home's 30-day running average humidity rose above 80%, causing it to fail the ASHRAE 160 standard. The ZipR wall had far fewer hours in conditions susceptible to mold growth than the Zip wall.

The ability of the HPWH to keep up with hot water demand, and if occupants report challenges in meeting hot water demand. Resident acceptance of this emerging HPWH technology, as installed.

- Over ½ of all survey respondents indicated that they plan their shower timing in order to avoid running out of water (Figure 54). However, over 70% either Never or Seldom have experienced a shortage of hot water while showering/bathing. Reported hot water shortages while using the kitchen sink were very rare, 10% answering Sometimes or Often (Figure 56). Overall satisfaction with hot water supply is very high, with over 93% of residents Agreeing or Strongly Agreeing that they are satisfied. The heat pump water heater in energy efficient mode appears capable of meeting the hot water demands of families in both the 2 bedroom and 3 bedroom duplex apartments. Additionally, LHA has not received any resident complaints or requests with respect to hot water demand. Despite the fact that 18 residents reported hearing noise, only 2 indicated that it disturbed their daily activities.

Perceived resident comfort and interaction with energy conservation measures.

- All respondents reported that they were comfortable in their homes during every season and that they are satisfied with the overall level of comfort. Additionally, all but three respondents reported that all rooms in their homes are equally comfortable. Only two respondents reported issues with indoor air quality. The survey did not ask if the residents have known allergies or had had previous IAQ-related issues.

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