Advancing Residential Energy Retrofits

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ABSTRACT

To advance the market penetration of residential retrofits, Oak Ridge National Laboratory (ORNL) and Southface Energy Institute (Southface) partnered to provide technical assistance on nine home energy retrofits in metropolitan Atlanta with simulated source energy savings of 30% to 50%. Implemented measures included sealing HVAC ducts; reducing air infiltration; adding the attic and crawlspace to the conditioned space; and replacing HVAC units, water heaters, lighting and appliances. An overview of the retrofits for each home are presented with a detailed case study of one home. Simulations predicted yearly average source energy savings of 33% (922 MMBtu total), while energy bill analysis from the heating season yielded an average savings of 32%. Based on this initial analysis 30 to 50% source energy savings are achievable during the heating season.

Introduction

As part of a roadmap to foster the implementation of "deeper energy retrofits", the U.S. Department of Energy's Building America program has set research goals to develop and demonstrate market ready retrofit solutions to reduce home source energy use by 30% – 50% (DOE BA 2012). To this end, the Department of Energy is funding research to explore "what it takes" to generate deep energy savings: 1) measures necessary to achieve large energy savings, 2) total costs of these measures, 3) difference between predicted energy savings and actual savings, and 4) the "beyond-energy" benefits of home energy retrofits. Answering these research questions will be an important step in advancing residential retrofits in the U.S.

As part of the national effort to advance residential retrofits, nine homes were retrofitted in the Atlanta, GA, area. An overview of the retrofits and their associated impacts on important home performance metrics, such as air infiltration and duct leakage, for each home are presented with a detailed case study describing expected and realized energy savings of completed retrofit measures of one home. These retrofits are projected to yield source energy savings of approximately 27% or greater based on simulated energy consumption in eight of these homes; the ninth did not meet the targeted savings. Actual average heating season savings based on utility bills was calculated to be 32%.

Methodology

The homes were identified through an interview process and then refined to homeowners who were committed to paying for the energy upgrade work themselves. A whole-house assessment was performed on each home, and then retrofit measures were recommended to the homeowners. The retrofit measures employed were duct sealing, air infiltration reductions, attic sealing and roof deck insulation, crawlspace sealing, HVAC and water heating equipment replacement, and lighting and appliance upgrades.

After the retrofit measures were completed, energy savings were estimated using EnergyGauge® USA ResSimPro v2.8.05 energy simulation tool (EG 2012). A Home Energy Rating Score (HERS) index was also generated through the software (RESNET 2012).

Utility bills were collected for a year before the retrofit as well as after the retrofit, to allow whole house energy savings analysis and comparison. In addition, a commercially-available energy monitor was installed in six of the nine homes to sub-meter various electrical circuits at one minute resolution.

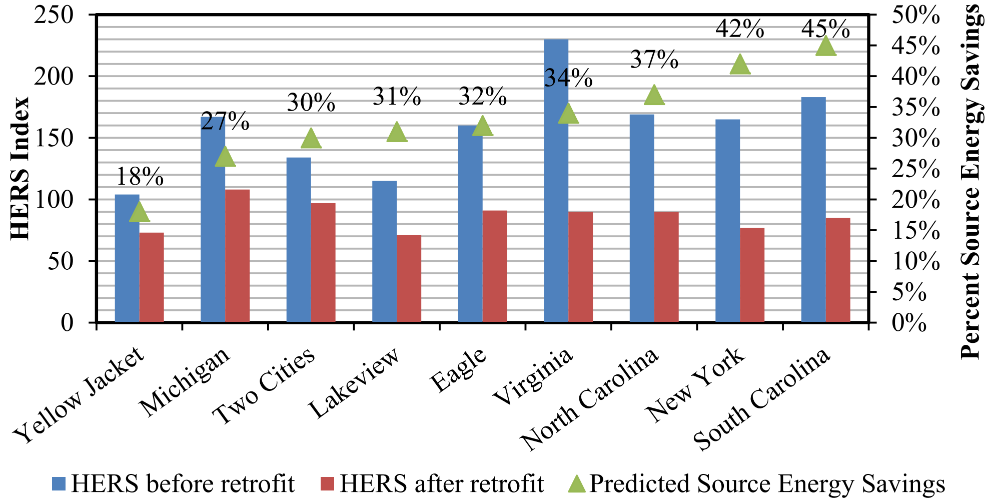
Summaries of Retrofit Measures in Each Home

Brief summaries of the retrofit measures are presented in this section. Detailed descriptions and research approach are described by Jackson et.al. (Jackson et.al. 2012). All of the nine residences are single-family detached homes. Table 1 provides a quick overview of the primary retrofit measures, predicted source energy savings, and total retrofit costs. The home named North Carolina is discussed in further detail with analysis of comfort and space conditioning energy use. Measures in this home were projected to generate site and source energy savings of approximately 45% and 33%, respectively. **Error! Reference source not found.** shows the pre- and post-retrofit estimated HERS indices. The average initial and final HERS indices are 161 and 95, respectively.

Table 1. Overview of the Primary Energy Upgrades Performed in the Homes. The Homes are Ordered Based on Predicted Savings (lowest first to highest)

House	Sealed Attic	Attic Floor Sealing	Wall Insulation	Window Upgrade	HVAC Upgrade	Subfloor Sealing	Sealed Crawlspace	DHW Upgrade	Predicted Source Energy Reduction (%)	Retrofit Cost ($K)
Yellow Jackets	x				x			x	18	28
Michigan		x			x	x			27	28
Two Cities		x	x	x		x			30	11
Lakeview	x				x				31	18
Eagle		x	x		x		x		32	21
Virginia		x		x	x	x			34	38
North Carolina		x			x		x	x	37	36
New York	x		x	x	x		x	x	42	42
South Carolina	x				x	x		x	45	38

Figure 1. Summary of the HERS Indices Before and After the Retrofit, and Total Predicted Source Energy Savings



Yellow Jackets: Estimated Source Energy Savings = 18%   Total Retrofit Cost = $27,720

Originally built in the 1970s, Yellow Jackets is a two-story home with 3,170 ft^2 of living area and an occupancy of three adults. Key retrofit measures included HVAC upgrades and conversion of the attic to an unvented space by insulating the roof deck with R-21 open cell spray foam. Open-cell spray foam was also applied to the garage ceiling and the exposed knee walls to both insulate and air seal. Open-cell foam was applied to the wall separating the garage and the living area to replace the R-11 batts. Additionally, the foundation band joist was sealed and insulated with ~3" of open-cell foam. Through these measures, infiltration was reduced from 14.7 to 5.4 ACH_{50}.

One of the existing HVAC systems (10 SEER air conditioner, 80 AFUE gas furnace) in the attic was brought into the building envelope and was replaced with a 14 SEER air conditioner and 95 AFUE gas furnace. The gas water heater with an efficiency rating of 0.57 EF was replaced with a high efficiency gas water heater with a 90% thermal efficiency. Energy savings of 20% was achieved during the heating season based on energy bill analysis.

Michigan: Estimated Source Energy Savings = 27%   Total Retrofit Cost = $27,950

Built in the 1920s, Michigan is a one-story home with 3,380 ft^2 of living area, a vented attic, a vented crawlspace, and occupied by two adults and one child. Open-cell foam was used to seal the gap at the intersection between the attic floor and the top of the balloon framed wall. Approximately 4" of open-cell foam was also sprayed in the knee walls to replace R-13 fiberglass batts. The R-value of the attic floor insulation was increased from R-18 to R-38 with blown-in fiberglass. Additionally, ~3" of open-cell spray foam was applied on the crawlspace band. The subfloor was already insulated with R-19 fiberglass batts. Through the envelope measures applied, the building air infiltration was reduced from 14.8 to 11.5 ACH_{50}. HVAC improvements included replacing the 9 SEER, and 10 SEER air conditioners for the main and master suite zones, respectively, with two 14.5 SEER systems. A 95 AFUE gas furnace replaced the 80 AFUE unit that initially heated the main zone. Energy savings of 27% was achieved during the heating season based on energy bill analysis.

Two Cities: Estimated Source Energy Savings = 30%   Total Retrofit Cost = $10,620

Two Cities is a 1940s single story with 1,110 ft^2 of living area, a vented attic, a vented crawlspace foundation, and occupied by one adult. The initially un-insulated crawlspace ceiling was insulated with 3" of medium density, open-cell spray foam. Other air sealing measures included installing a damper in the chimney, identifying and sealing major air infiltration bypass, and applying one-part spray foam along the top and bottom wall plates. A drill-and-fill technique was used to dense pack cellulose insulation (~R-13) into the previously un-insulated wall cavities. Two single pane windows in the home were replaced with double pane windows (55 ft^2), while a third single pane (7 ft^2) window was simply removed and replaced with wall framing. The building air infiltration was reduced from 24.9 to 10.4 ACH_{50}.

A programmable thermostat was installed, and these were replaced with ENERGY STAR® units: clothes washer and dryer, ceiling fans, dishwasher, refrigerator and lighting.

Lakeview: Estimated Source Energy Savings = 31%   Total Retrofit Cost = $17,520

Built in 1985, Lakeview is a two-story with 1,710 ft^2 of living area, a vented attic, a slab foundation, and occupied by two adults and one child. The main envelope measure taken in the home was to convert the attic to an unvented space with the roof deck insulated with R-21 open-cell spray foam. This measure resulted in decreasing the building infiltration from 11.7 to 10.1 ACH_{50}.

A variable capacity inverter driven heat pump with an efficiency rating of 18 SEER and 8.9 HSPF replaced the original 12 SEER air conditioner and 80 AFUE gas furnace. A pressurized glycol, solar thermal hot water system consisting of two flat panels (8’ x 4’ for each panel) was also installed on the garage roof.

Eagle: Estimated Source Energy Savings = 32%   Total Retrofit Cost = $20,885

Eagle is a one-story 1,318 ft^2 home built in 1955 with occupancy of two adults. The energy retrofits were completed in conjunction with a planned home renovation which increased the conditioned floor area of the home; this new space was insulated in the walls and ceiling with spray foam. The energy-related retrofits applied to the original living space included increasing the attic floor insulation from R-11 to R-38 with blown-in cellulose. Also, penetrations through the crawlspace ceiling were air sealed, and 3" of closed-cell foam was applied to the foundation band. Furthermore, a drill-and-fill technique was used to dense pack cellulose insulation (~R-13) into the previously un-insulated wall cavities.

The original HVAC system (2.5-ton air conditioner, 9 SEER AC/ 76 AFUE gas furnace) was located in the attic with a duct leakage of 266 CFM_{25}. The HVAC was replaced with a 2-ton 18 SEER, 9.5 HSPF heat pump and relocated to the sealed crawlspace. Energy savings of 43% was achieved during the heating season based on energy bill analysis.

Virginia: Estimated Source Energy Savings = 34%   Total Retrofit Cost = $37,700

Built in 1920s, Virginia is a two-story home with 2,940 ft^2 of living area, a vented attic, a vented crawlspace, and occupied by two adults and two children. Additional fiberglass insulation was blown over the existing R-11 insulation in the attic floor to increase it to R-38. Approximately 4" of open-cell foam was applied in the knee walls to replace the existing R-13 fiberglass batts. In addition to air sealing penetrations through the crawlspace ceiling, 3" of open-cell spray foam was applied on the crawlspace band. The subfloor was already insulated with R-19 fiberglass batts. The building air infiltration was reduced from 14 to 8 ACH_{50}.

Whereas the original HVAC system (56 AFUE gas furnace, 9 SEER AC and 3 window units) supplied conditioned air to both floors, retrofit measures included rezoning the home such that the new 14.5 SEER AC and 95 AFUE gas furnace only conditioned the first floor of the home. The window air conditioning units in the second floor bedrooms were replaced with a 3 ton mini-split heat pump (19.2 SEER, 10 HSPF). Energy savings of 33% was achieved during the heating season based on energy bill analysis.

New York: <u>Estimated Source Energy Savings = 42% Total Retrofit Cost = $41,669</u>

Built in the 1920s, New York is a two-story home with 3,050 ft^2 of living area, a vented attic, a vented crawlspace, and occupied by two adults and three children. The crawlspace was insulated with 3" of open-cell foam on the band and 4" of closed-cell foam on the wall. The attic was enclosed with six inches of open-cell foam applied on the roof deck and gables. Blown fiberglass was dense packed into the exterior walls. The building air infiltration was reduced from 17 to 8.7 ACH_{50}.

A 14.5 SEER AC and 95 AFUE gas furnace replaced the 10 SEER and 80 AFUE units in the attic. Similarly, a 14.5 SEER AC was installed in the crawlspace to replace the 10 SEER unit that served the first floor. Because the attic and crawlspace were encapsulated during the retrofit, both HVAC systems are now located within the thermal envelope. In addition to the ducted system upgrades, a 19.2 SEER, 10.1 HSPF mini-split heat pump was installed in the home office to replace a through-the-wall room AC and Thermador space heater. The gas water heater with an efficiency rating of 0.59 EF was replaced with a 2.4 EF heat pump unit. An energy savings of 36% was achieved during the heating season based on energy bill analysis.

South Carolina: <u>Estimated Source Energy Savings = 45% Total Retrofit Cost = $38,380</u>

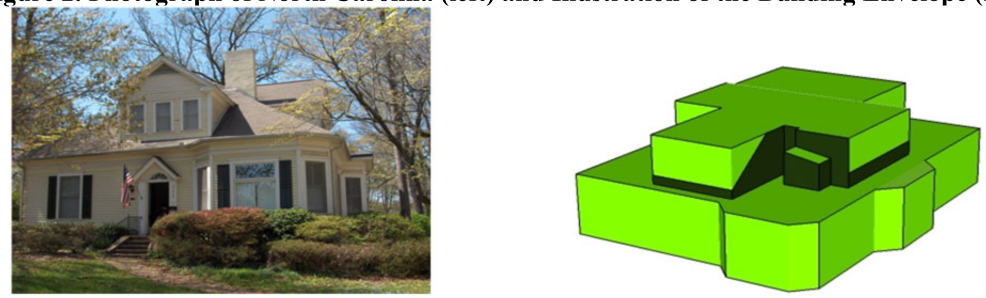
South Carolina is a 1920s single-story home with 2,990 ft^2 of living area and a typical occupancy of 4 or 5 college students. The home has a traditional vented attic and crawlspace. The vented attic was sealed by insulating the roof deck with open-cell foam. The subfloor was already insulated with R-19 fiberglass batts. The final building air infiltration was 16.8 ACH_{50}. While this is a 28% reduction from the original value of 23.3 ACH_{50}, the home remained relatively leaky after all the air sealing measures were taken.

The existing 9 SEER AC and 80 AFUE gas furnace (located in the vented crawlspace) were replaced with a 14.5 SEER AC and 95 AFUE furnace, which were then brought into the conditioned building envelope. In addition to the HVAC upgrade, the gas water heater (0.59 EF) was replaced with a high efficiency water heater with a 90% thermal efficiency. An energy savings of 47% was achieved during the heating season based on energy bill analysis.

North Carolina: <u>Estimated Source Energy Savings = 37% Total Retrofit Cost = $35,750</u>

Built in the 1920s, North Carolina is a two story home with 3,710 ft^2 of living area (1st floor = 2,410 ft^2, 2nd floor = 1,300 ft^2), a vented attic, a vented crawlspace and occupied by two adults and three children (see **Error! Reference source not found.**).

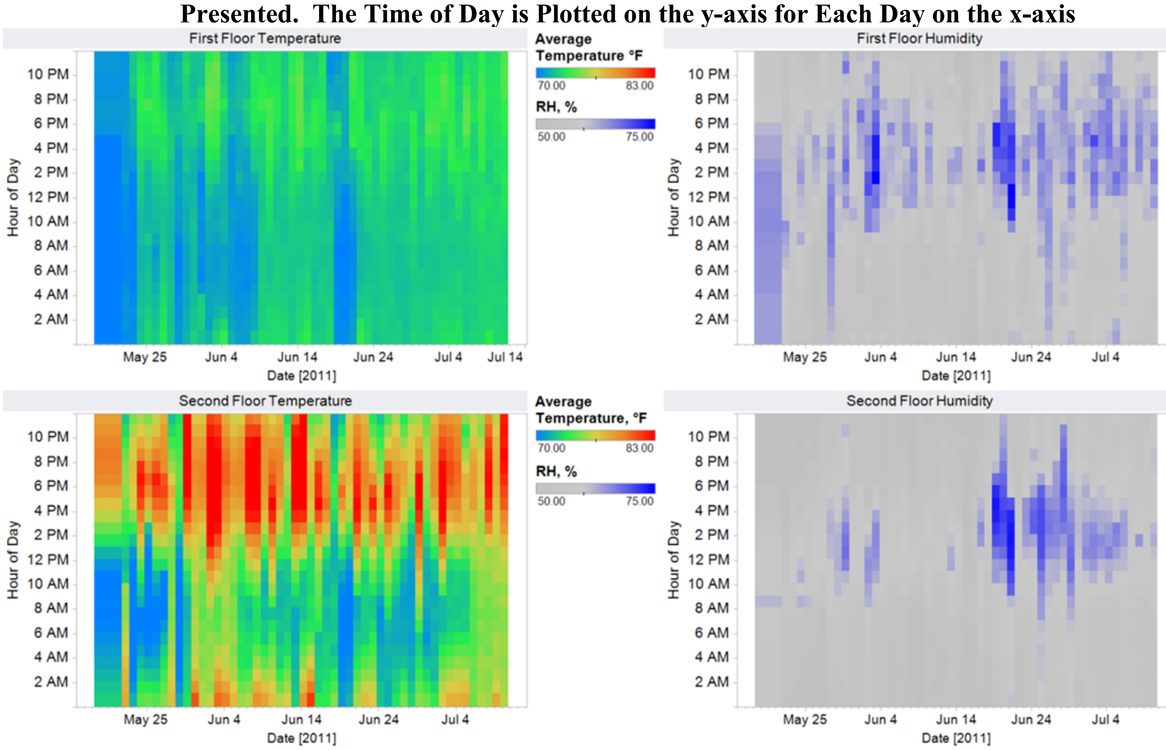
Figure 2. Photograph of North Carolina (left) and Illustration of the Building Envelope (right)



During the initial survey with the family, a primary concern was the high costs of their energy bills. From February 2010 – January 2011, the total energy costs were $6,380 (296 MMBtu of site energy). In spite of the high energy costs, the family expressed significant dissatisfaction with temperature and moisture levels. The second floor temperature levels were often intolerable, such that during the winter the family used space heaters to provide additional space conditioning. Moreover, the summer temperature on the second floor rarely reached the targeted set point and often did not go below 80°F.

During the summer of 2011, temperature and humidity data were collected on the first and second floors of the home prior to completing any retrofit work. As seen in **Error! Reference source not found.**, the temperature on the first floor varied from approximately 70°F to 76 °F during the time period of May 20th through July 9th. Also notice, that on the first floor there were considerable periods when the relative humidity exceeded 60%, which is an upper threshold to prevent warm discomfort. Furthermore, the relative humidity often approached 75%, which when considered in conjunction with temperature, is near or exceeds the recommended humidity ratio for thermal comfort (ASHRAE 2004).

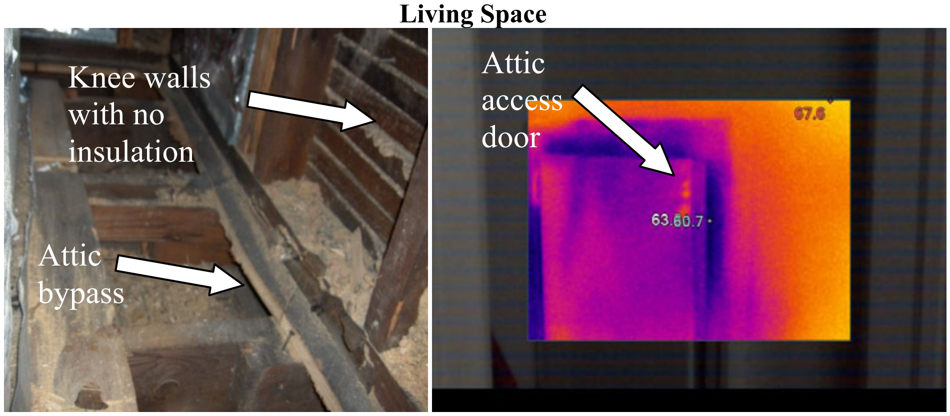
Figure 3. Temperature and Relative Humidity in the Home During the Period of May 20th - July 9th are Presented. The Time of Day is Plotted on the y-axis for Each Day on the x-axis



The second floor temperatures shown in **Error! Reference source not found.** are consistent with the family's observation. Temperatures were typically above 80 °F from afternoon until at least midnight. Additionally, there were periods where the relative humidity exceeded 70% and the dew point was 68°F or higher. Temperatures at the supply registers were likely below the dew point given that auditors found condensation and mildew at these locations .

After an examination of the home, the high energy costs and unsatisfactory comfort levels were not surprising. In the building envelope illustration shown in **Error! Reference source not found.**, the dark green colors represent the attic knee walls, which comprised approximately 60% of the exterior walls on the second floor. Significant heat exchange occurred between the second floor and the attic because the knee walls were mostly uninsulated. Heat was also exchanged between these two spaces through many bypasses, some of which are shown in **Error! Reference source not found.**. In addition to the fact that the attic access shown in the figure was not insulated and was not weather-stripped, there was no mechanism to ensure it remained closed.

Figure 4. Attic Bypasses. Picture on the Right is a Thermal Image of the Attic Access Door Taken in the Winter while the Home was Depressurized. The Blue Color in the Image Shows Attic Air Infiltration into the Living Space



Space conditioning was provided in North Carolina by two forced-air HVAC systems. The first floor had a 3.5 ton, 9 SEER, air conditioner and a 125 kBtuh, 91 AFUE, gas furnace in the crawlspace. The second floor conditioning system consisted of a 2.5 ton, 9 SEER, air conditioner, and a 50 kBtuh, 91 AFUE, gas furnace in the attic.

Leakage tests were conducted to evaluate the airtightness of the building envelope and the ductwork. The blower door tests indicated that the house leakage rate was 12,690 CFM_{50} (20.6 ACH_{50}). The ducts (R-6) for the first floor HVAC system, which were located in the crawlspace, had several disconnected joints that inhibited adequate duct pressurization. The second floor ducts were located in the attic and had a leakage of 280 CFM_{25}, about 22% leakage by serviced floor area.

Building Retrofit

Air sealing and attic insulation were high priority measures for this home. Insulation subcontractors sealed electrical penetrations, can lights, and other typical penetrations to reduce airflow between the attic and the living space. Blown-in fiberglass insulation was subsequently added to the attic floor for a final approximate insulation of R-38. A low density, open-cell spray foam was applied to the knee walls to effectively align the envelope's thermal and air barriers. Additionally, the crawlspace was encapsulated, which is expected to reduce infiltration, improve moisture management, and enhance HVAC performance since the system will now be in a semi-conditioned space. Further details of all envelope measures are discussed by Jackson *et.al*. (2012). After the retrofit was complete, a blower door test indicated a 39% decrease in air leakage, from 12,690 CFM_{50} (20.6 ACH_{50}) to 7,688 CFM_{50} (12.8 ACH_{50}).

Load calculations were completed in accordance with ACCA Manual J (Rutkowski. 2006) based on the expected improvements from envelope measures. Although the second floor zone benefited from the majority of the load reduction, the tonnage of the new 16 SEER air conditioner remained at 2.5 because the original unit was undersized. The load calculation for the first floor suggested that a larger capacity system would be needed to meet the resulting post-retrofit load. Therefore, the old system was replaced with a 4-ton, 16 SEER, system. Additionally, R-8 insulated flex duct was installed throughout the house, which led to duct leakages of 103 CFM_{50} for the first floor system and 43 CFM_{50} for the second floor system. Moreover, the original 0.59 EF gas water heater was replaced with a 50 gallon heat pump water heater (2.0 EF). The total cost of all retrofit measures was approximately $35,750.

Energy Savings

Table **2** shows the expected energy savings from the implemented retrofits as determined by simulating pre-retrofit and post-retrofit energy consumption using EnergyGauge. In total, there is an estimated 38% reduction in source energy use.

Table 2. North Carolina Predicted Energy Savings from EnergyGauge

	Energy Savings (MMBtu)		Energy Savings per Measure (%)	
	Site	Source	Site	Source
North Carolina simulated energy use*	245	478	-	-
+ Envelope improvements	189	394	23	18
++ HVAC system improvements	148	301	17	20
+++ Water heater improvements	134	298	6	1
Total retrofit investment	-	-	45	38

* Each row is a stepwise progression of building retrofit improvements. The "+" symbol is used to indicate that the retrofit improvements of the previous simulation are included.

Since significant air sealing and thermal insulation measures were taken on the knee walls and attic accesses, the predicted source energy savings of 18% are substantial. Additionally, because of the significant amount of duct leakage in the pre-retrofit case, coupled with the poor efficiency of the air conditioning unit, large source energy savings of 20% are projected based on improvements in the HVAC system.

Because the building retrofit was completed in August of 2011, a full year of utility bills is not available to determine the accuracy of the projected energy savings; however, bills from November 2011 through February 2012 can be compared with the previous year's bill to gain insight into the actual energy savings during the heating season. As shown in

Table **3**, there was a 46% reduction in the gas consumption after the retrofit. Since the heating season period after the retrofit was considerably milder than the previous year, the post-retrofit gas consumption has been weather corrected. Also, approximately 130 therms of the reduction in gas use was estimated to be the result of replacing the gas unit with an electric heat pump water heater. Therefore, after adjusting for both factors, a 38% reduction in gas consumption associated with space heating was estimated. A total (gas + electric) source energy savings of 21% was calculated for North Carolina for the heating season.

Table 3. Heating Season Utility Bill Summary

	Pre-retrofit	Post-retrofit*
	(Nov. 2010 - Feb. 2011)	(Nov. 2011 - Feb. 2012)
Electricity Consumption (kWh)	9429	9900
Gas Consumption (therms)	1052	565
Heating Degree Days (HDD)	2591	1841

* Post-retrofit energy consumption has been weather normalized to pre-retrofit heating degree days

Utility bills during the cooling season (i.e. June – August) after the retrofit were not available for analysis. However, because an energy monitor was installed in the home prior to starting the retrofit, sub-metered energy data are available for pre- and post-retrofit analysis.

Table **4** summarizes the average daily HVAC consumption and runtime before and after retrofit measures were in place; both periods had similar outdoor temperatures. Through envelope improvements coupled with air conditioner upgrades, the percent reduction for the first and second floor systems are 66% and 71%, respectively. Furthermore, the total HVAC runtime (a reflection of the ratio of thermal load to HVAC capacity) was reduced by more than half with only a 0.5 ton increase in total HVAC capacity.

Table 4. HVAC Consumption and Runtime During Two Periods of Similar Outdoor Conditions

	Pre-retrofit	Post-retrofit	Reduction (%)
	(June 28 - July 3)	(August 19 - August 24)	
	Avg daily temp = 81.5 °F	Avg daily temp = 81.8 °F	
1st floor avg daily HVAC consumption (kWh)	66.4	22.4	66
1st floor avg HVAC runtime (hours/day)	14.7	6.6	55
2nd floor avg daily HVAC consumption (kWh)	67.2	19.4	71
2nd floor avg HVAC runtime (hours/day)	19.2	8.4	56

Figure **6. Temperature and relative humidity from August 11th through August 31st**
shows the power consumption for 1st and 2nd floor systems on a day before and after the retrofit during the periods described in

Table 3. This figure indicates that the power draw from the new air conditioners are significantly lower than the pre-retrofit units. Additionally, the reduction in total runtime, as well as individual cycle times, can also be seen in the figure. On July 2nd, the air conditioner ran for 15.3 and 22.9 hours on the first and second floor, respectively. In contrast, on August 20th, the new systems only ran for 6.9 and 11.4 hours, respectively for the first and second floor.

Temperature and relative humidity measurements collected after the retrofit are shown in **Error! Reference source not found.**. In contrast with the pre-retrofit conditions shown in **Error! Reference source not found.**, there are no significant periods of time in the first or second floor where the temperature exceeds 75 °F. Additionally, the relative humidity on the first and the second floor is considerably lower. Also, the number of hours when then relative humidity was higher than 60% was minimal. These data clearly indicates that energy retrofits can both decrease energy use and improve comfort.

Figure 5. Compressor Power for the 1st and 2nd Floor HVAC Systems

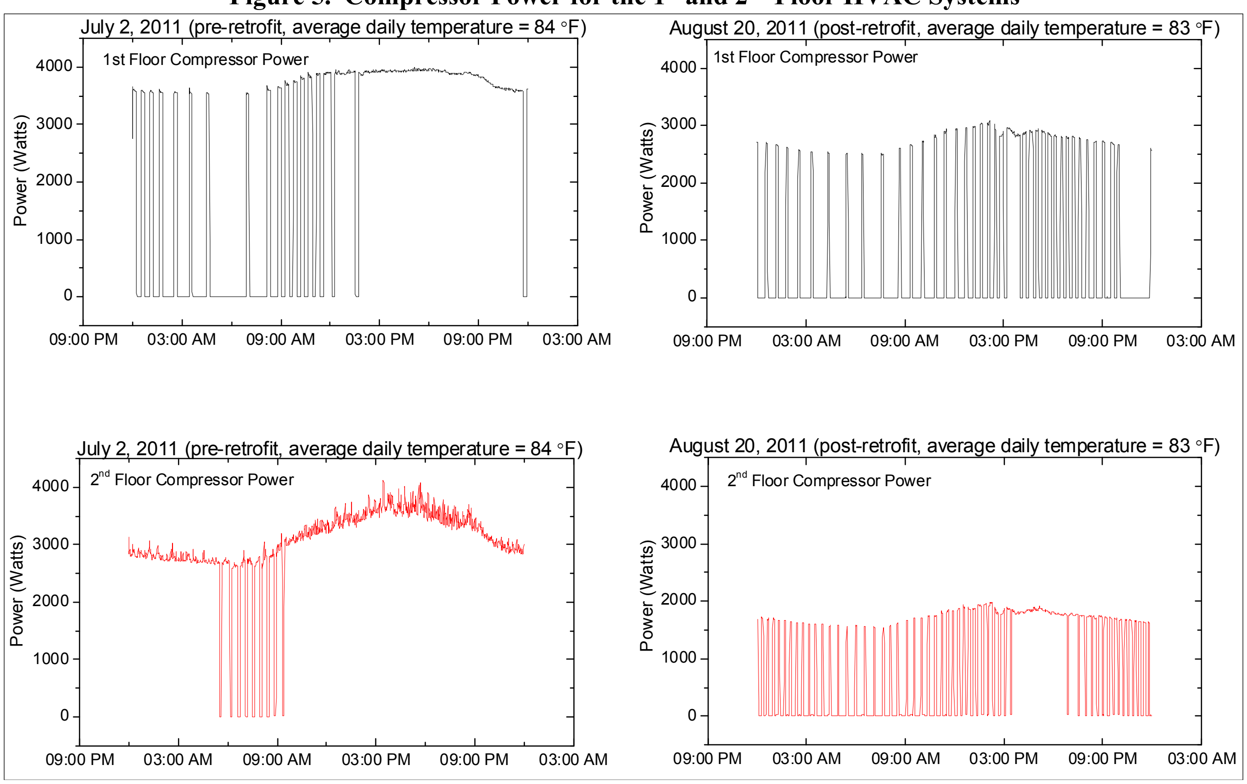
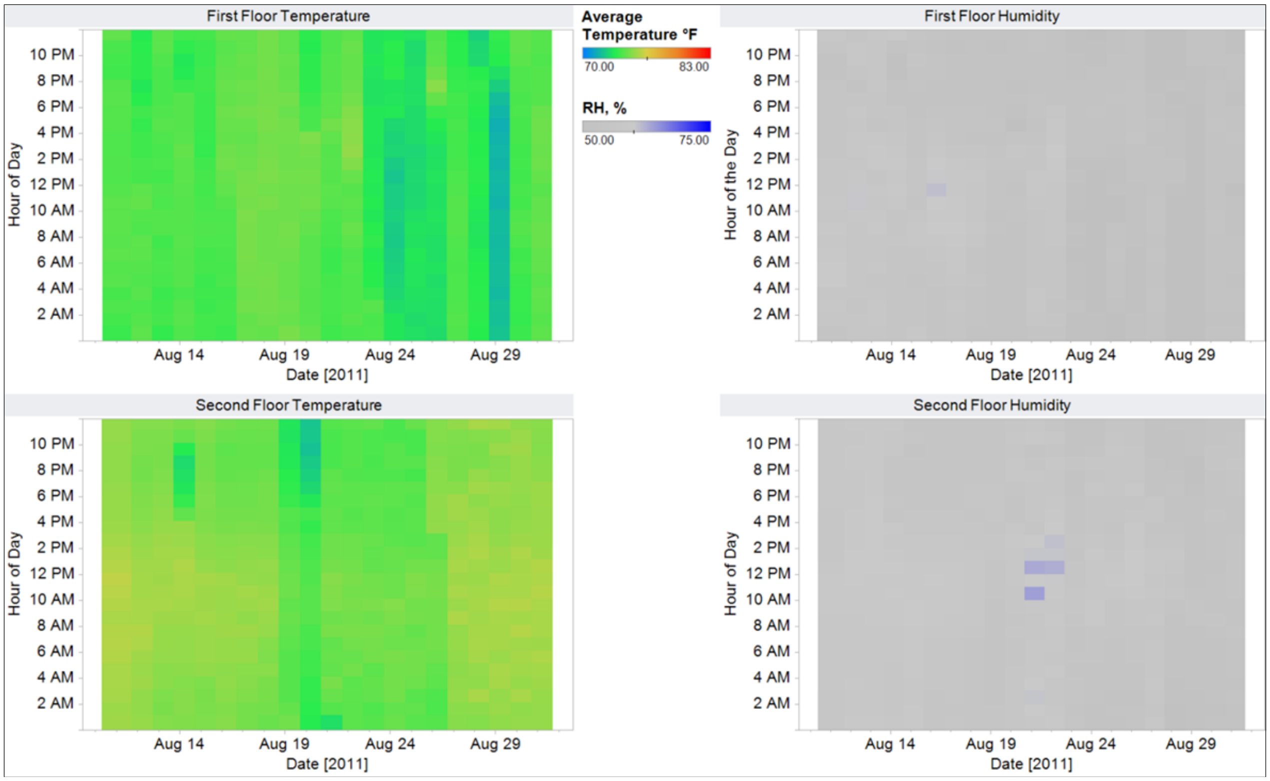


Figure 6. Temperature and relative humidity from August 11th through August 31st



While source energy savings are an important metric for evaluating home energy retrofits, the improvement in comfort, as demonstrated in **Error! Reference source not found.** and **Error! Reference source not found.**, may be of equal significance with regard to the total benefit to the homeowner. It is noteworthy that an investment of $35,750 is expected to generate an average of $2,400 in annual energy savings. However, the fact that the homeowner was able to make that investment to gain the entire 1,300 ft^2 of second floor living area, which was previously only used sparingly and reluctantly, is remarkable.

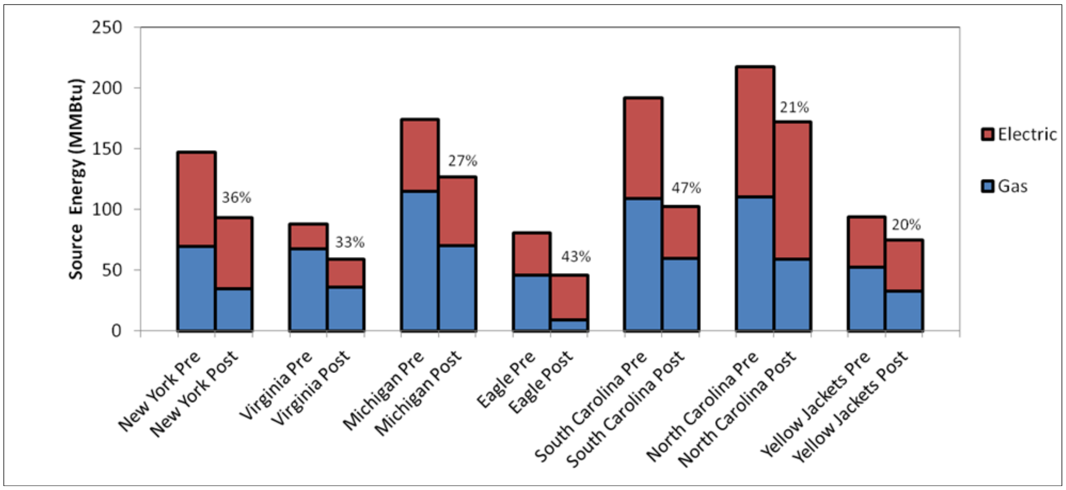
Heating Season Energy Savings

All the retrofits were completed before the 2011-2012 winter, which allows energy bill comparison for the pre- and post-retrofit heating seasons (November – February). Lakeview is not included in this analysis because the pre-retrofit gas consumption was not available at the time of this publication. Two Cities is not included because it was unoccupied before the retrofit.

Energy bill comparison was done by comparing the pre-retrofit energy bills to weather normalized post-retrofit energy bills. The procedure for weather normalizing energy data is a modified version of what is found at degreedays.net (DD 2012). On average, a 32% actual heating season source energy savings results from the retrofit measures in the seven houses (see **Error! Reference source not found.**). Four of the homes saved 33% or more in source energy over the heating season. After a year of post-retrofit data has been collected, the actual energy savings will be compared to the predicted energy savings.

Figure 7: Heating Season (November to February) Source Energy Savings. Lakeview Is Not Included because the Pre-retrofit Gas Consumption Is Not Available. Two Cities Is Not Included because It was

Unoccupied before the Retrofit. The Whole House Percent Energy Savings is Presented Above the Post-Retrofit Bar of Each Home



Summary

Nine homes were retrofitted in the metropolitan Atlanta, GA, region. Seven of the homes are predicted to achieve source energy savings of at least 30% based on simulated energy consumption. Actual heating season source energy savings are higher than 33% for four of the seven homes with available pre-retrofit energy bill data. While conventional retrofit measures, such as air sealing and increased insulation were employed, four homes achieved additional energy savings from converting the attic to an unvented space with roof deck insulation.

While the predicted energy savings of these homes are significant, the beyond-energy benefits of the retrofits could be of equal or more importance to homeowners. Understanding and articulating these benefits will be a key component to advancing residential retrofits across the U.S. More specifically, benefits such as increased comfort may be equally or more important to a large number of homeowners than the prospect of energy bill reductions.

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