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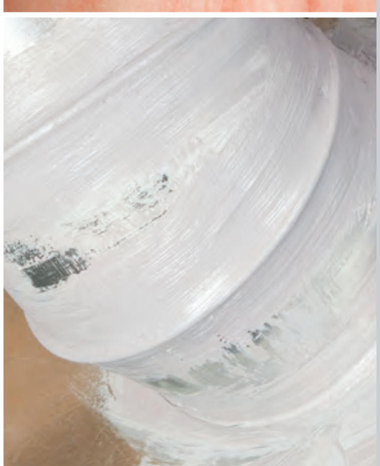

Attic Retrofits Using Nail-Base Insulated Panels

March 2018

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Attic Retrofits Using Nail-Base Insulated Panels

Prepared for:
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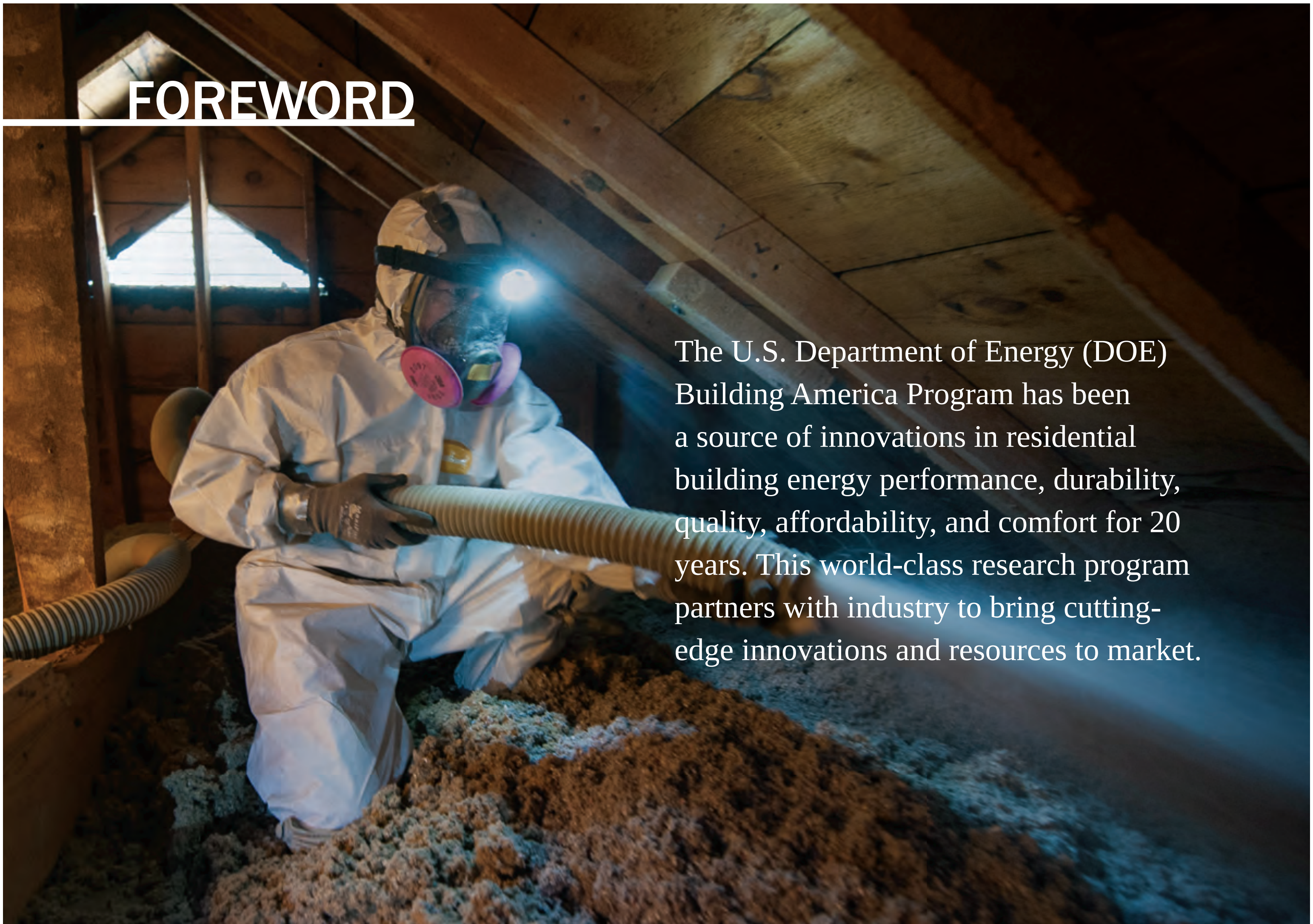
FOREWORD



The U.S. Department of Energy (DOE) Building America Program has been a source of innovations in residential building energy performance, durability, quality, affordability, and comfort for 20 years. This world-class research program partners with industry to bring cutting-edge innovations and resources to market.

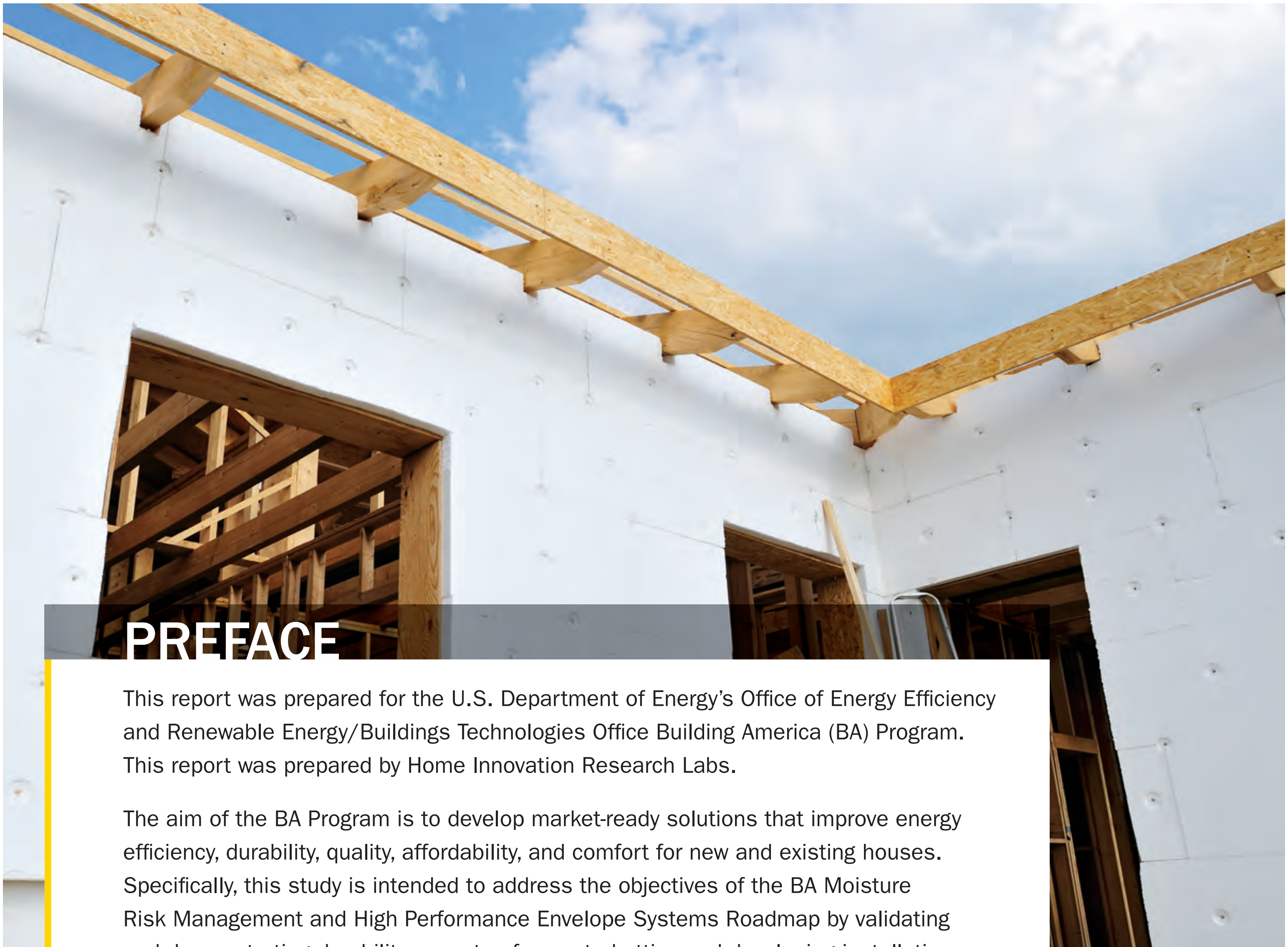
The Building America Program supports the DOE Building Technologies Office Residential Building Integration Program goals to:

1. By 2020, develop and demonstrate cost-effective technologies and practices that can reduce the energy use intensity (EUI) of new single-family homes by 60% and existing single-family homes by 40%, relative to the 2010 average home EUI in each climate zone, with a focus on reducing heating, cooling, and water heating loads.
2. By 2025, reduce the energy used for space conditioning and water heating in single-family homes by 40% from 2010 levels.

In cooperation with the Building America Program, the Building America Partnership for Improved Residential Construction is one of many Building America teams working to drive innovations that address the challenges identified in the Program's Research-to-Market Plan.

This report, "Attic Retrofits Using Nail-Base Insulated Panels," explores the development and demonstration of a roof/attic energy retrofit solution using nail-base insulated panels for existing homes where traditional attic insulation approaches are not effective or feasible. For this study, vented attics were converted to unvented attics where mechanical systems were installed, which was shown in older, existing homes to improve energy savings and comfort as well as air quality.

As the technical monitor of the Building America research, the National Renewable Energy Laboratory encourages feedback and dialogue on the research findings in this report as well as others. Send any comments and questions to building.america@ee.doe.gov.



PREFACE

This report was prepared for the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy/Buildings Technologies Office Building America (BA) Program. This report was prepared by Home Innovation Research Labs.

The aim of the BA Program is to develop market-ready solutions that improve energy efficiency, durability, quality, affordability, and comfort for new and existing houses. Specifically, this study is intended to address the objectives of the BA Moisture Risk Management and High Performance Envelope Systems Roadmap by validating and demonstrating durability aspects of unvented attics and developing installation specifications for a roof/attic energy retrofit solution using nail-base insulated panels for existing homes where traditional attic insulation approaches are not effective or feasible (e.g., attics with cathedral ceilings; habitable space; or heating, ventilating, and air-conditioning equipment/ducts).

Nail-base insulated panels consist of rigid foam insulation laminated to one face of a wood structural panel. The prefabricated panels are installed above the existing roof deck during a reroofing effort. The foam core adds insulation value, and the wood structural panel provides the substrate for the roofing membrane. The potential energy-savings impact of this technology in the market is large: based on the number of existing houses with these attic types and the average reroofing cycle of 21 years, the number of candidate houses for the installation of retrofit panels would be in the hundreds of thousands annually.

ACKNOWLEDGMENTS

Home Innovation Research Labs acknowledges the U.S. Department of Energy Building America Program and the American Chemistry Council for sponsoring this research and the following organizations for their valuable participation: Structural Insulated Panel Association; PanelWrights, LLC; Clifton View Homes; ARES Consulting; APA—The Engineered Wood Association; U.S. Department of Agriculture Forest Products Laboratory; GAF; Dow Building Solutions; DuPont; Owens Corning; Keene Building Products; BASF; and Insulspan.

LIST OF ACRONYMS

ACH	Air Changes per Hour
ACH50	Air Changes per Hour at 50 Pascals
BA	Building America
CDD	Cooling Degree Day
cfm	Cubic Feet per Minute
DP	Dew Point Temperature
EPS	
HDD	Heating Degree Day
HVAC	Heating, Ventilating, and Air Conditioning
MC	Moisture Content
OSB	Oriented Strand Board Sheathing
PVC	Polyvinyl Chloride
RH	Relative Humidity
SIP	Structural Insulated Panel
TDD	Total Degree Day

EXECUTIVE SUMMARY

This project developed and demonstrated a roof/attic energy retrofit solution using nail-base insulated panels for existing homes where traditional attic insulation approaches are not effective or feasible.

Nail-base insulated panels (retrofit panels) consist of rigid foam insulation laminated to one face of a wood structural panel. The prefabricated panels are installed above the existing roof deck during a reroofing effort. The layer of insulation provides the added thermal performance, and the wood structural panel provides the rigid substrate for installation of the roofing membrane. For this study, vented attics were converted to unvented attics.

Retrofits of attics in older, existing homes can improve energy savings and comfort as well as air quality where mechanical systems are installed in the attic. For some attic types, the process is simple—air seal and add insulation at the ceiling—but for many attic types, improvements are more challenging. Three types of attics that require an alternative approach are: (1) attics with cathedral ceilings, (2) attics with habitable space (e.g., Cape Cod design), and (3) attics with equipment/storage. A single solution can be employed to help transform these attics and ultimately the house into a better performing system using the prefabricated retrofit panels.

This report outlines research activities that are expected to facilitate the adoption of energy retrofits by remodeling contractors and roofing contractors using retrofit panels. The results of this research will be applicable to many existing house designs in most climates and markets. The potential energy-savings impact of this technology in the market is large. The current reroofing cycle is 21 years for the average house, and 5.7 million houses had a whole-roof replacement in 2016 (source: Home Innovation Research Labs). If the portion of existing houses with these attic types homes was 10%, the number of candidate houses for the installation of retrofit panels would be 570,000 annually, at an estimated annual heating/cooling energy savings of 10%–15% or more.

The primary research questions regarding retrofit panels are: What are the moisture control and air barrier considerations? What are the appropriate insulation values of the retrofit panels? What are the structural requirements? What are the architectural integration details? Current best practices for constructing unvented attics rely on encapsulating the attic using spray foam applied at the interior side of the roof deck. The application of retrofit panels for roof retrofits distinguishes this project from previous Building America (BA) research. This project benefits from and builds on previous relevant research: moisture performance of sealed attics (Boudreaux, Pallin, Jackson 2013; Puttagunta and Faakye 2015), moisture durability risks with unvented roofs (Uehno and Lstiburek 2015), and high-R roofs using structural insulated panels (Straube and Grin 2010).

This project supports the U.S. Department of Energy BA goal to develop and validate high-performance, moisture-managed building envelope solutions for low-load homes. The goals that distinguish this project include:

1. Demonstrating retrofit panel installations at two occupied residential demonstration sites: one in a cold climate and one in a hot-humid climate.

2. Developing design and architectural integration details for the demonstration sites that address moisture control, air barrier, insulation value, and structural considerations.

3. Documenting the design details, energy performance, moisture performance, costs, and feedback from contractors and occupants. recommendations for manufacturers to improve the latent performance of certain equipment by modifying hardware design and control algorithms.

The results of this project show that an attic retrofit using retrofit panels can be an energy efficient and durable solution for many existing homes. Energy retrofit solutions were developed and demonstrated for two occupied houses: one in a cold climate (Michigan) and one in a hot-humid climate (Georgia). Key project findings include:

- Estimated heating/cooling energy savings were approximately 23% heating and 13% cooling for Michigan and 11% heating and cooling for Georgia compared to the "before" baseline; energy evaluation based on utility bills indicates actual savings might be considerably higher.
- Overall house tightness improved by 29% for Michigan and 12% for Georgia.
- Monitored data collected for one winter and one summer show that moisture conditions at retrofit panels and existing roof decks are well within acceptable limits. Wood moisture content (MC) at the retrofit panels in all cases remained less than 10% during the winter and 8% during the summer; MC at the existing roof decks remained less than 10% during the winter and 8% (Michigan) or 12% (Georgia) during the summer; each house had an outlier that dried to these levels.
- Average relative humidity (RH) within the Georgia attic was higher during the summer after installation (approximately 80% RH) compared to the previous summer; despite the higher RH, attic DP was somewhat lower after installation. It is planned to continue data collection for one additional winter and summer. It is also planned to install

a heating, ventilating, and air-conditioning supply vent to help control RH during summer. The RH within the enclosed rafter assembly in the Michigan addition was well within normal limits.

- Structural reinforcement of the existing roof assembly was minimal for Georgia and not required for Michigan.
- Where shingles were installed over the ventilation mat, the shingles looked normal (not wavy), and the ventilation gap appeared to be maintained at full depth.
- Architectural integration of the retrofit panels was successful: feedback from the homeowners and project teams was very favorable regarding the final appearance of the houses.
- The incremental installed cost ranged from $8–$9/square foot roof area, simple payback ranged from 29–60 years, and return on investment ranged from 1.6%–3.5%. In addition to energy savings, the value of the demonstrated solutions includes significant improvement in comfort of the indoor environment, as reported by homeowners, and durability of the roof assembly.
- For Michigan, ice damming was a problem every winter before installation. However, after installation ice damming was eliminated.
- Based on anecdotal feedback from homeowners, comfort level was greatly improved at both houses, particularly in Michigan (summarized): The house feels warmer during the winter and much less drafty—the comfort factor has changed immensely; the house seems quieter now; we're definitely pleased.

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1 Introduction

1.1 Overview

Purpose. The purpose of this project was to develop, demonstrate, and assess a roof/attic energy retrofit solution using nail-base insulated panels for existing homes where traditional attic insulation approaches are not effective or feasible. This project supports the U.S. Department of Energy Building America Program (BA) goal to develop and validate high-performance, moisture-managed building envelope solutions for low-load homes.

Technology. Nail-base insulated panels (retrofit panels) consist of rigid foam insulation laminated to one face of a wood structural panel. The prefabricated panels are installed above the existing roof deck during a reroofing effort. The layer of insulation provides the added thermal performance, and the wood structural panel provides the rigid substrate for installation of the roofing membrane. For this study, vented attics were converted to unvented attics.

Goals. The three primary goals for the project were to:

- Demonstrate retrofit panel installations at two residential demonstration sites: one in a cold climate and one in a hot-humid climate.
- Develop design and architectural integration details for the demonstration sites that address moisture control, air barrier, insulation value, and structural considerations.
- Develop a case study to document the design details, energy performance, moisture performance, costs, and feedback from contractors and occupants.

Successful results will accelerate the adoption of this technology as a durable and practical energy solution for many climates.

Research questions. The design solution for each demonstration site must address energy efficiency, moisture durability, structural durability, and architectural integration. The research questions that required development and demonstration were:

1. What are the moisture control and air barrier considerations?
2. What are the appropriate insulation values of the retrofit panels?
3. What are the structural requirements?
4. What are the architectural integration details?

Tasks. The project goals were supported through the following tasks:

- Establish an advisory group of industry experts to review the project at critical stages.
- Select demonstration sites and establish project teams for each site.
- Assess the demonstration sites: measure the houses, insulation, and house leakage (before and after retrofits); conduct energy modeling (baseline and with retrofit panels; collect energy bills before and after the retrofits to correlate modeling results); conduct moisture analysis (to understand the moisture performance at the panels); develop design solutions (by the project team); review the design solutions (by the advisory group).

- Conduct observational research at Home Innovation's market research facility to fine-tune the retrofit plans/design solutions and obtain feedback from trades before field deployment.
- Retrofit the demonstration houses: install the retrofit panels; document the design and construction processes; instrument and monitor the sites—for moisture content (MC) of sheathing and framing, and temperature and relative humidity (RH) indoors, outdoors, and within attics.
- Prepare a report to document the energy performance, moisture performance, design and architectural integration details, construction process, cost-effectiveness, and occupant feedback. The report will provide the basis for the BA Solution Center content.

1.2 Background

Present state of the problem. Retrofits of attics in older, existing homes can improve energy savings and comfort as well as air quality where mechanical systems are installed in the attic. For some attic types, the process is simple—air seal and add insulation at the ceiling—but for many attic types, improvements are more challenging. Three types of attics that require an alternative approach are: (1) attics with cathedral ceilings, (2) attics with habitable space (e.g., Cape Cod design), and (3) attics with equipment/storage (Figure 1). A single solution can be employed to help transform these attics and ultimately the house into a better performing system using the prefabricated nail-base insulated panels (Figure 2).

The application of retrofit panels for roof retrofits, and associated attic gable wall upgrades, distinguishes this project from previous BA research. This project benefits from and builds on previous, relevant research: moisture performance of sealed attics (Boudreaux, Pallin, Jackson 2013; Puttagunta and Faakye 2015), moisture durability risks with unvented roofs (Uehno and Lstiburek 2015), and high-R roofs using structural insulated panels (SIPs) (Straube and Grin 2010).

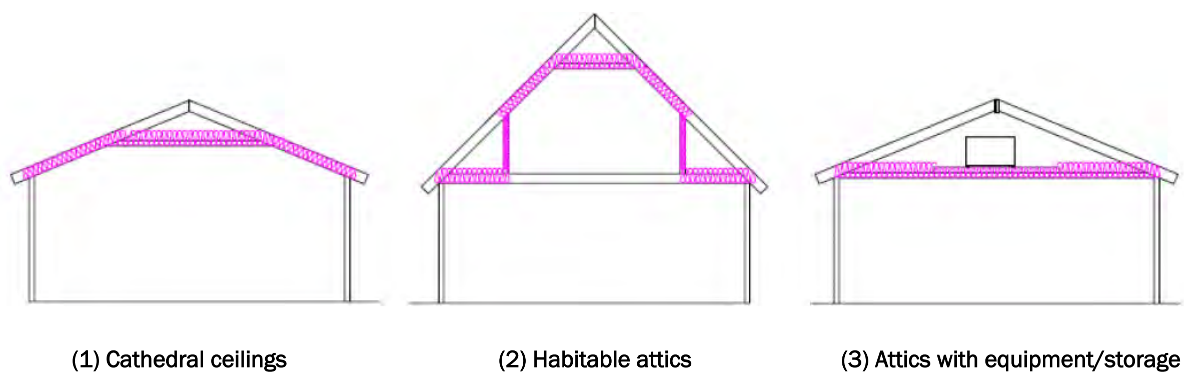


Figure 1. Examples of older attic types not suitable for standard "pile-on" insulation upgrades
(Typical location of existing insulation is shown; insulated panels are not shown.)

Figure 2. Example installation of retrofit panels during a reroofing effort

1.3 Relevance to Building America

The goals for this project align well with the BA goals to develop market-ready solutions that improve energy efficiency, durability, quality, affordability, and comfort for new and existing houses. Specifically, the results of this study address the objectives of the BA Moisture Risk Management and High-Performance Envelope Solutions Roadmap by validating and demonstrating durability aspects of unvented attics and developing installation specifications.

The potential energy-savings impact of this technology in the market is large. The current reroofing cycle is 21 years for the average house, and 5.7 million houses had a whole-roof replacement in 2016 (Home Innovation Research Labs). If the portion of existing houses with these attic types homes was 10%, the number of candidate houses for the installation of retrofit panels would be 570,000 annually, at an estimated annual heating/cooling energy savings of 10%–15% or more.

1.4 Cost-Effectiveness

Cost-effectiveness is based on the incremental cost to install retrofit panels during a reroofing effort and the associated energy savings. Incremental costs do not include removing old roofing or installing new roofing (shingles and underlayment).

The incremental installed cost of retrofit panels varies considerably based on climate requirements, roof slope, house type, access to the site, and regional pricing. The material cost of the retrofit panel depends on the insulation value desired for energy savings for a given climate and application.

Energy savings can vary widely depending on the application and condition of the existing house. Previous BA research commonly reports 15% or more heating/cooling energy savings for a house with an unvented attic compared to the same house with a vented attic (Lstiburek 2013; Roberts and Winkler 2010). The savings can be much more (up to 40%) for poorly sealed or poorly insulated ducts in attics (Shapiro, Magee, and Zoeller 2013).

A cost evaluation is presented in Section 4.4.

1.5 Tradeoffs and Other Benefits

The potential nonenergy benefits include: improved comfort and indoor air quality; improved durability by reducing house leakage and moisture migration caused by air leakage; reduced risk of ice damming during winter in cold climates; reduced heating, ventilating, and air-conditioning (HVAC) equipment capacity requirements (as a result of lower heating/cooling loads) for future equipment replacement; additional storage space (semi-conditioned) or livable floor area (conditioned).

Improving occupant comfort is an important component of installing retrofit panels in older houses. In addition to energy savings, additional insulation and lower house leakage rates can significantly improve occupant comfort because the houses can feel less drafty and warmer during the heating season (because of radiant surface temperature effects) and more comfortable during the cooling season (lower humidity as a result of lower infiltration rates).

The nonenergy issues that must be addressed are potential moisture and structural issues and architectural integration details.

2 Experiment

2.1 Overview

The advisory group included industry experts representing industry associations, product manufacturers, builders, contractors, and consultants.

The advisory group considered several demonstration sites and selected two: one in the hot-humid climate of St. Simon's Island, Georgia, and one in the cold climate of Ann Arbor, Michigan. Selection criteria included climate, house/attic type, roof configuration, roofing type, and whether the site was representative of the market. The Georgia house is a two-story cottage design with an HVAC system within the attic; the attic was converted from vented to unvented. The Michigan house is a two-story contemporary design with cathedral ceilings. This house contained two distinctly different conditions: the roof/ceiling assembly of the main house consisted of 2-in.-thick fiberboard panels supported by a timber frame; the roof/ceiling assembly of a large addition was a more conventional, enclosed rafter assembly that was converted from vented to unvented.

The project teams for each site included the contractor, energy rater, homeowner, panel manufacturer, local building code official, Structural Insulated Panel Association representatives, and Home Innovation staff.

During the initial site visits, Home Innovation gathered detailed information on the houses (Section 2.3), met with the project teams to discuss preliminary design considerations and options, and installed sensors to monitor baseline conditions (Section 2.2). The energy rater conducted house and duct leakage testing.

After the site visits, the project teams developed preliminary design specifications. Home Innovation conducted observational research (Section 2.4), moisture analysis (Section 3.1 energy analysis (Section 3.2), and a review of structural considerations (Section 3.3). After a series of design reviews, the project teams developed the final design specifications (Section 3.4).

2.2 Measurements

Sensors were installed to monitor conditions before and after the retrofit panel installations. The selected sensors measure temperature, RH, and wood MC; the sensors are wireless and communicate with a cellular gateway inside each house that communicates to the Internet. The monitoring equipment was configured to average and record data at a sample interval of 15–30 minutes. Based on manufacturer product data and calculations by Home Innovation, the range of uncertainty for this project is considered ±1°F for temperature data, ±3.5% RH for RH data, ±2% MC for MC data, and ±3°F for dew point temperature (DP) data. (See Appendix A for sensor specifications.)

Baseline sensors were installed at both houses during the initial site assessment to monitor indoor and outdoor temperature and RH conditions. For Georgia, baseline sensors were also installed in the attic at the roof rafters and roof deck, primarily near the ridge where moisture problems are most likely to occur, to measure temperature, RH, and MC. For Michigan, sensors were installed within the enclosed rafter assembly during the retrofit panel installation to measure temperature, RH, and MC.

Sensors were installed within the retrofit panels during installation to monitor MC at the oriented strand board (OSB) skin. These sensors were located both in the center of and near the edge of panels. The panels with sensors were installed primarily near the roof ridge. Temperature and RH probes were also installed just under the shingles during installation to monitor shingle temperature. Solar and wind were not monitored.

Energy usage was measured using utility bills collected before and after retrofits.

Air barrier performance was quantified using blower door testing before and after the retrofits. Testing was specified to measure total house leakage and isolate leakage through the attic. Duct leakage was measured at the Georgia house for the attic ducts. (See Appendix A for test equipment specifications.)

2.3 Site Assessments

The Georgia house is shown in Figure 3 through Figure 5, and the site assessment, including construction details, is summarized in Table 1. The Michigan house is shown in Figure 6 through Figure 8, and the site assessment is summarized in Table 2.

Figure 3. Georgia house

Figure 4. Georgia house attic

Figure 5. Georgia house eaves and roof framing with rafter sensor

Table 1. Georgia Site Assessment Summary

Location	• St. Simons Island, Georgia • BA hot-humid climate; International Energy Conservation Code Climate Zone 2A
Description	• Circa 1946, 2-story, wood-framed, no garage, front faces Southeast • Floor area: first floor 990 ft^2; second floor 774 ft^2; total 1,764 ft^2 • Volume: 15,435 ft^3 (8–9-in. ceilings both levels)
Construction	• Foundation: open pier crawl space • Walls: 2x4—16-in. on-center frame, ¾-in. wood shiplap cladding (no sheathing, no water-resistive barrier) • Attic: vented (see roof construction details below)
Enclosure	• Floors: no insulation, wood flooring over ¾-in. board deck • Walls: R-0 at ½-in. beadboard interior walls; R-13 at drywall (rear third of house) • Ceiling: R-19 cellulose • Windows: U-0.31, double pane, vinyl
Roof Construction	• Slope: main gable roof 7:12; first-floor shed roof 3:12 • Sheathing: ¾-in. thick 1x10 boards (not tongue and groove) • Roofing: asphalt shingles over felt • Framing: 2x6 rafters 24 on-center, mostly do not align with 2x6 ceiling joists • Collar tie: (1) collar tie, near the front of the house • Bracing: (2) diagonal 1x8 braces (1 on each side of roof) spanning 8 rafter bays, 1 nail/rafter
HVAC	• First floor: 2.5-ton packaged heat pump; R-4 ducts in crawl space • Second floor: 2.5-ton split heat pump system; air handling unit and R-4 ducts in the attic • Exhaust fan: first-floor bath
Test-in results	• House leakage (blower door) test: 4,584 cfm50; 17.8 ACH50 • Note: attic could not be tested independently; house P wrt attic: -48.2 Pa • Duct leakage (duct blaster) test: 66.0 cfm25 total; 42.8 cfm25 outdoors

Figure 6. Michigan house

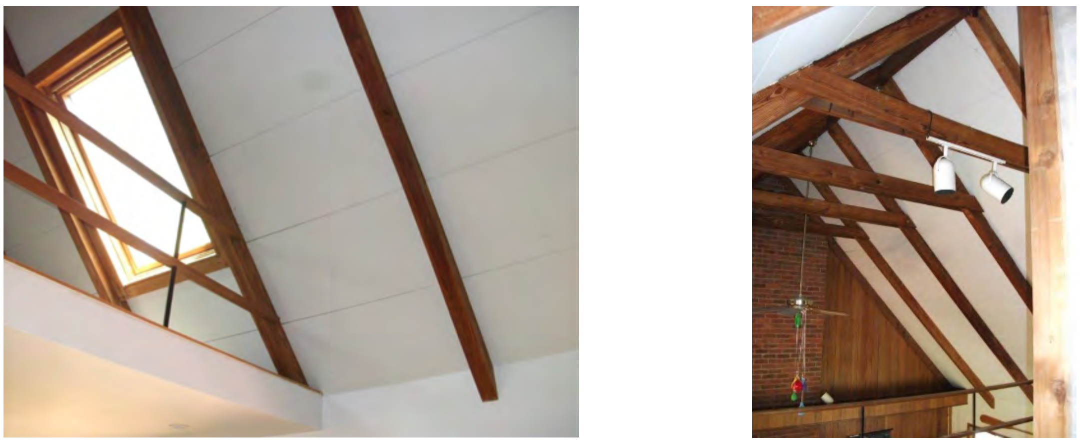


Figure 7. Michigan house cathedral ceiling

Figure 8. Michigan main house existing fiberboard roof deck/ceiling

Table 2. Michigan House Site Assessment Summary

Location	• Ann Arbor, Michigan • BA cold climate; International Energy Conservation Code Climate Zone 5A
Description	• Circa 1968 2-level contemporary, formerly a duplex, main level (above lower level bedrooms) and addition wing (circa 1980, above lower level garage) with lofts and cathedral ceilings; front faces West • Floor area: main level 1,364 ft²; lower level 1,040 ft²; total 2,404 ft² (does not include lofts) • Volume: 28,652 ft³
Building Enclosure	• Foundation, lower level: 8-in. block wall, drywall over furring strips, no insulation • Walls, main level: 2x4—16-in. on-center wood frame, plywood sheathing, R-13 cavity insulation • Cathedral ceiling, main house: fiberboard panels, est. R-5 (tongue and groove, 24-in. wide, 2-in. thick)—both roof deck and ceiling surface (painted) • Cathedral ceiling, addition: R-30 batt, no vapor retarder, enclosed rafter assembly (vented) • Windows: U-0.32, double glass, vinyl
Roof Construction	• Main gable roof 12:12; addition gable 8:12 front, 12:12 rear • Roofing: asphalt shingles over felt • Framing, main: 4x6 (3.5x5.5) rafters, 4-ft. on-center with (2) 2x6, 8-ft long collar ties, 3 nails per collar tie • Framing, addition: 2x10 rafters—16-in. on-center
HVAC	• Left side of house: gas furnace (90% annual fuel utilization efficiency) and air conditioner, all ducts inside conditioned space. Right side of house: same as left. • Exhaust fans: kitchen and all bathrooms (operated with local on-off switch)
Test-in results	• House leakage (blower door) test: 4,422 cfm50; 9.26 ACH50 • Duct leakage (duct blaster) test: NA (inside conditioned space)

2.4 Observational Research

The goal of the observational research task was to fine-tune the retrofit strategies and obtain feedback from the trades prior to field deployment. This task was conducted in Home Innovation's laboratory facility that is specifically designed for technology evaluations under semi-controlled conditions prior to product or technology deployment by manufacturers in the marketplace.

One specific, common component identified early during the design phase by the project teams for observational research was a ventilation/drainage mat product. The ventilation mat is installed above the roofing underlayment and retrofit panels and below the roof shingles. The ventilation mat is intended to facilitate outward drying and reduce shingle temperature, so it is potentially important for moisture control and durability. The ventilation mat product (CDR Vent™ by Keene Building Products) is a drainage and ventilation product designed to eliminate moisture and water vapor in roofing and siding applications; it is a 0.30-in.-thick polypropylene mesh similar to some rain-screen products installed exterior to the drainage plane of exterior walls; the product is marketed for use with metal roofing and cedar shingle roofing and siding but is not currently marketed for use with asphalt shingles; wind resistance performance information is not available for this assembly; the shingle manufacturer does warranty this assembly.

The specific purpose of the observational research was to assess the constructability of the ventilation mat. The associated tasks included engaging the product manufacturer, building a mock-up roof deck, and observing roofers as they installed the roofing materials. The mock-up roof deck was 8 ft. wide with a 16-ft. rake on each side (128 ft^2 each side) and constructed using 7:12 roof trusses and 7/16-in. OSB sheathing. Note: installing retrofit panels on top of the mock-up roof was not considered relevant to assess the constructability of the ventilation mat; the mat was installed above underlayment as it would be in the field.

A roofing contractor installed roofing on the mock-up roof deck assembly on September 12, 2016. The ventilation mat was installed over #15 felt underlayment. Standard 3-tab shingles were installed on one side, and architectural shingles were installed on the other side of the assembly. The shingles and vent mat were attached using 1.25-in. roofing nails installed with a pneumatic nail gun. Drip edge at the rake was installed before (underneath) the vent mat on the 3-tab shingle side and after (over) the vent mat on the architectural shingle side to cover the edge of the vent mat. Drip edge at the eave was installed underneath the vent mat on both sides. A rigid-type ridge vent was installed over the vent mat. Some shingles were left off to allow for inspection of the roofing layers. The roofing installation sequence is shown in Figure 9 through Figure 13.

Figure 9. Mock-up roof deck assembly and installation of underlayment

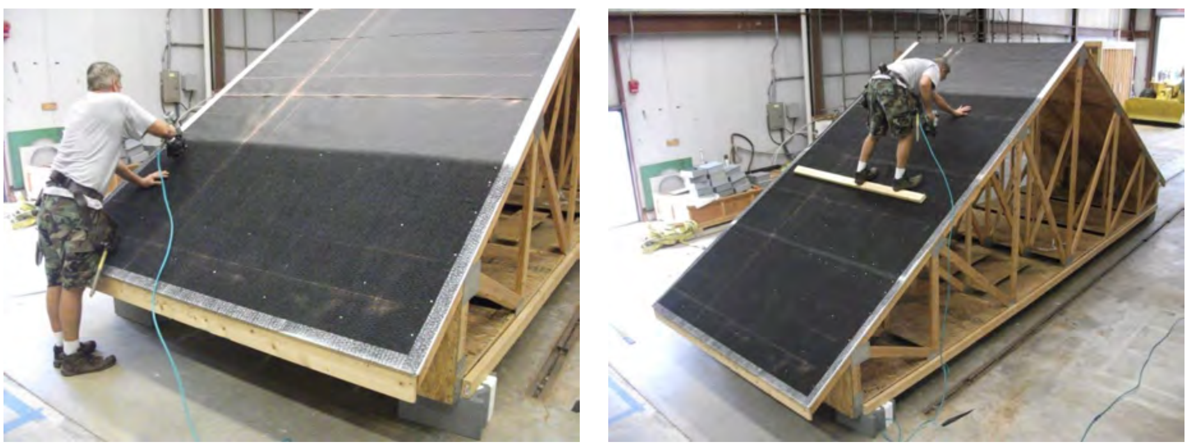


Figure 10. Installation of ventilation mat

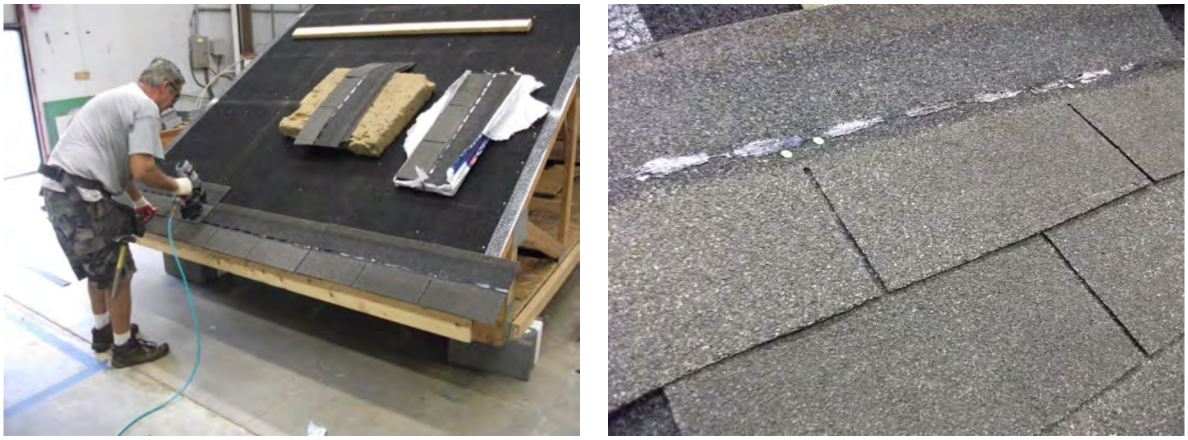


Figure 11. Installation of shingles

Figure 12. Installation of shingles and ridge vent

Figure 13. Roofing complete showing standard shingles and architectural shingles

Key observations:

- The vent mat felt somewhat slippery and spongy, so the roofer felt the need to install a 2x4 ledger for safety on the first side of the roof; he did not install a ledger on the second side of the roof (both sides have a slope of 7:12).
- At an initial air compressor outlet setting of 120 pounds per square inch gauge pressure (psig), the nails tended to punch through the shingles. The pressure was reduced to 110 psig and then to 100 psig. The 100 psig setting worked well and did not punch nails through the shingles.

Key results:

- The overall takeaway was favorable.
- The shingles on both sides looked normal (not wavy).
- The ventilation gap appeared to be maintained at full depth.

3 Analysis

3.1 Moisture Analysis

Home Innovation conducted moisture analysis during the design stage to predict moisture performance at the roof assemblies, particularly at the OSB sheathing areas, for before and after retrofit cases. For Georgia, the predicted wood MC in all cases did not exceed 10%. For Michigan, the predicted MC did not exceed 12%.

Concurrently, Home Innovation conducted energy analysis (Section 3.2). The project teams considered the results of both analyses as they developed the retrofit designs to balance energy savings and avoid excessive moisture levels at the roof deck and within attic spaces. The project team also developed an air sealing strategy to control moisture migration caused by air leakage at the roof deck, panel joints, eaves, and gable walls (Section 3.4).

The analysis included the air gap provided by a ventilation mat product, installed between the shingles and underlayment that was intended to facilitate drying to the outdoors (the vent mat was also expected to reduce shingle temperatures). For Michigan, analysis was conducted with and without the ventilation mat. The project teams specified graphite-enhanced expanded polystyrene (EPS) for the rigid foam insulation core based on its relatively high permeance and insulation value: R-4.5/in. versus R-4.0/in. for standard EPS, and water vapor permeability of 2–4 perm-in.

For the addition roof in Michigan, the minimum insulation value of the retrofit panel to reduce the risk of condensation above the structural roof sheathing was calculated and selected in accordance with the 2015 International Residential Code Section R806.5: Unvented attic and unvented enclosed rafter assemblies. The calculation was based on R-30 insulation within the enclosed rafter assembly, an indoor temperature of 68°F, and the monthly average outdoor air temperature for the three coldest months of 30.3°F (Residential Energy Dynamics). The calculated value to maintain the monthly average at the existing roof deck during the three coldest months higher than 45°F was R-18; the project team selected a panel with a 4.5-in.-thick insulation core and an assembly insulation value of R-21. For the main roof in Michigan, the insulation value of the selected retrofit panel resulted in a calculated average temperature of 63°F at the existing roof deck.

The moisture analysis was conducted using WUFI Pro 6.0 software. Outdoor boundary conditions were the closest ASHRAE location. For Michigan, indoor boundary conditions were the worst case of the WUFI default library. For Georgia, actual data from nearby projects monitored by Home Innovation were used for the before condition in the attic; for the after condition in the attic, indoor conditions were adjusted to be warmer during the cooling season, cooler during heating season, and more humid year-round. A variety of simulations were run for each house: baseline (vented attic for Georgia and vented enclosed rafter assembly for the Michigan addition); after retrofit panel installation (unvented attic and enclosed rafter assembly); after retrofit panel with ventilated shingles (ventilation mat installed between shingles and underlayment); after retrofit panels installed above existing shingles and no ventilation mat for Michigan.

The moisture analysis inputs and results are summarized in the following tables. For the range of results, the low MC value corresponds to summer conditions, and the high MC value corresponds to winter conditions. The inputs include the actual retrofit panel thickness selected for the final designs; the vapor permeance of the EPS foam core (at 2–4 perm-in.) has an approximate range of 0.7–1 perm for Georgia, 0.3–0.5 perm for the Michigan main roof, and 0.8–1.5 perm for the Michigan addition roof; the vapor permeance of the OSB skin has a range of 1–2 perms up to 50% RH (up to approximately 5 perms at 75% RH); the underlayment is approximately 5 perms for #30 felt (Georgia) and 16 perms for the synthetic vapor permeable underlayment (Michigan).

Table 3. Georgia Moisture Analysis Inputs

Georgia Conditions	Existing Materials (Exterior to Interior)	Retrofit Materials (Exterior to Interior)
Roof slope: 30°	Asphalt shingles	Asphalt shingles
Roof orientations: Northeast, Southwest	#15 felt underlayment	Air gap, 10 mm (vent mat)
Exterior: Savannah, Georgia (Climate Zone 2A)	Southern yellow pine roof deck	#15 felt
Interior: attic		7/16-in. OSB
		5.5-in. BASF EPS (R-25)
		¾-in. southern yellow pine roof deck

Table 4. Georgia Moisture Analysis Results

Georgia Analysis Description	Roof Direction	MC at Existing Roof Deck (%)	MC at Retrofit Panel OSB (%)
Existing (baseline)	Northeast	5–12	NA
	Southwest	4–9	NA
With retrofit panel (without vent mat)	Northeast	6–9	5–10
	Southwest	6–9	5–10
With retrofit panel and vent mat	Northeast	6–8	6–10
	Southwest	6–8	6–10

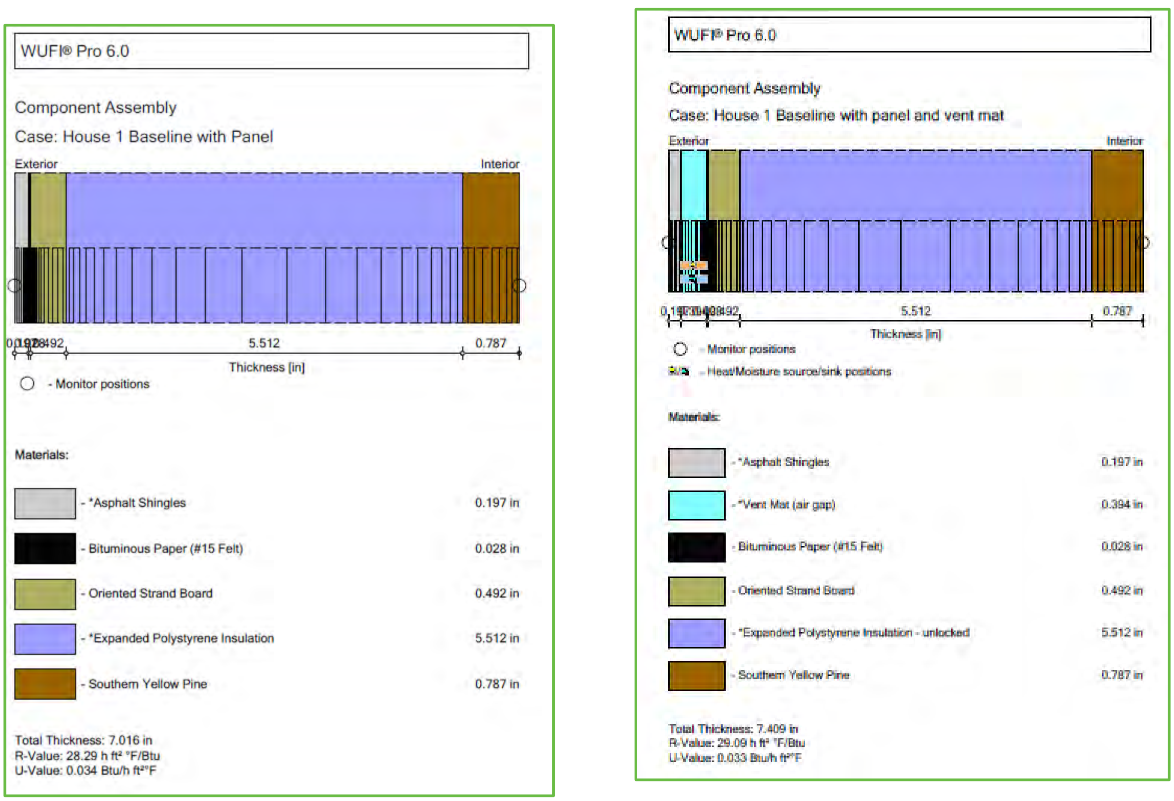


Figure 14. Component assembly for the Georgia house

Table 5. Michigan Main Roof Moisture Analysis Inputs

Michigan Main Roof Conditions	Existing Materials (Exterior to Interior)	Retrofit Materials (Exterior to Interior)
Roof slope: 45°	Asphalt shingles	Asphalt shingles
Roof orientations: East, West	#15 felt underlayment	Air gap, 10 mm (vent mat)
Exterior: Detroit, Michigan (Climate Zone 5A)	Cellulose fiberboard, 2-in. thick, est. R-5	#15 felt
Interior: conditioned space	Paint	7/16-in. OSB
		7.5-in. BASF EPS (R-34)
		Asphalt shingles/#15 felt
		2-in. cellulose fiberboard, R-5
		Paint

Table 6. Michigan Addition Roof Moisture Analysis Inputs

MI House: Addition Roof Conditions	Existing Materials (Exterior to Interior)	Retrofit Materials (Exterior to Interior)
Roof slope: 45° South facing	Asphalt shingles	Asphalt shingles
Roof slope: 35° North facing	#15 felt underlayment	Air gap, 10 mm (vent mat)
Exterior: Detroit, Michigan (Climate Zone 5A)	7/16-in. OSB	#15 felt
Interior: conditioned space	1-in. air space (vented rafters)	7/16-in. OSB
	R-30 fiberglass batt	4.5-in. BASF EPS (R-20)
	½-in. drywall, painted	Asphalt shingles/#15 felt
		7/16-in. OSB
		1-in. air space (unvented rafter)
		R-30 batts
		Drywall, painted

Table 7. Michigan Main Roof Moisture Analysis Results

Michigan Main Roof Analysis Description	Roof Direction	MC at Existing Roof Deck (%)	MC at Retrofit Panel OSB (%)
Existing (baseline)	West	5–9	NA
	East	4–9	NA
With retrofit panel	West	4–6	6–11
	East	4–6	6–11
With retrofit panel and vent mat	West	4–6	5–9
	East	4–6	5–9
With retrofit panel over existing shingles but without vent mat	West	4–6	7–10
	East	4–6	7–10

Table 8. Michigan Addition Roof Moisture Analysis Results

Michigan House Addition Roof: Run	Roof Direction	MC at Existing Roof Deck (%)	MC at Retrofit Panel OSB (%)
Existing (baseline)	North	7–16	NA
	South	7–9	NA
With retrofit panel	North	7–14	7–11
	South	7–12	7–10
With retrofit panel and vent mat	North	7–12	5–10
	South	7–12	5–9
With retrofit panel over existing shingles but without vent mat	North	8–12	7–12
	South	8–12	7–12

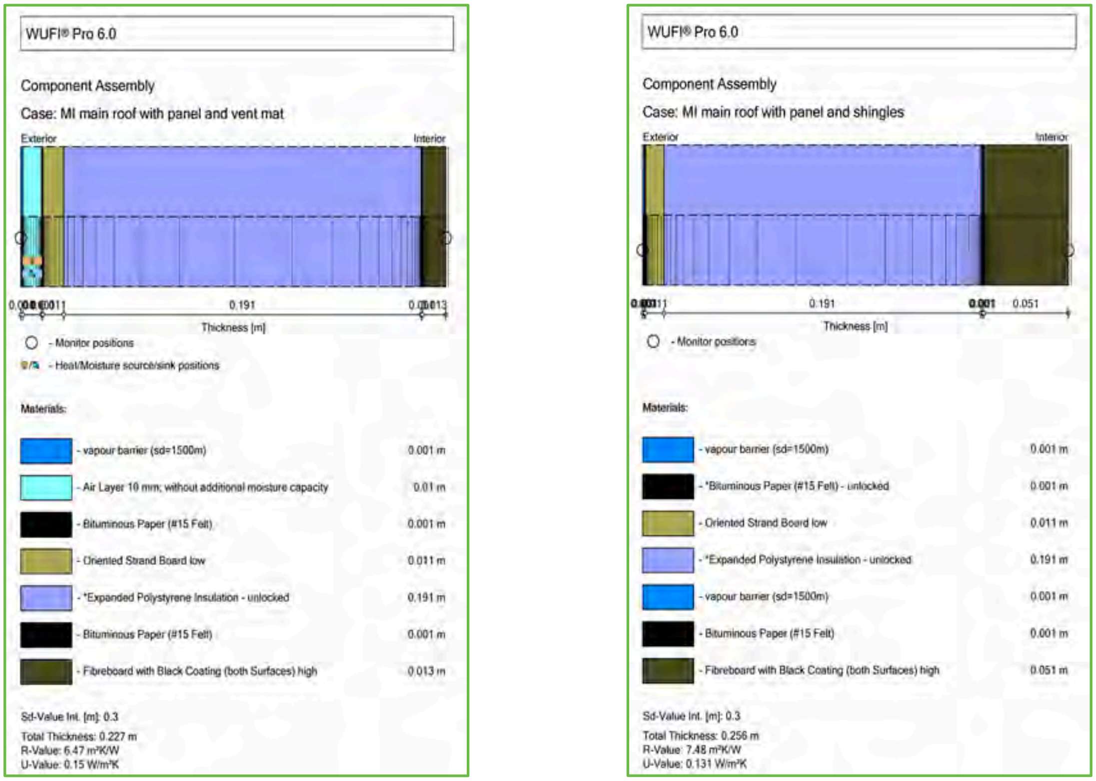


Figure 15. Main roof component assembly for the Michigan house

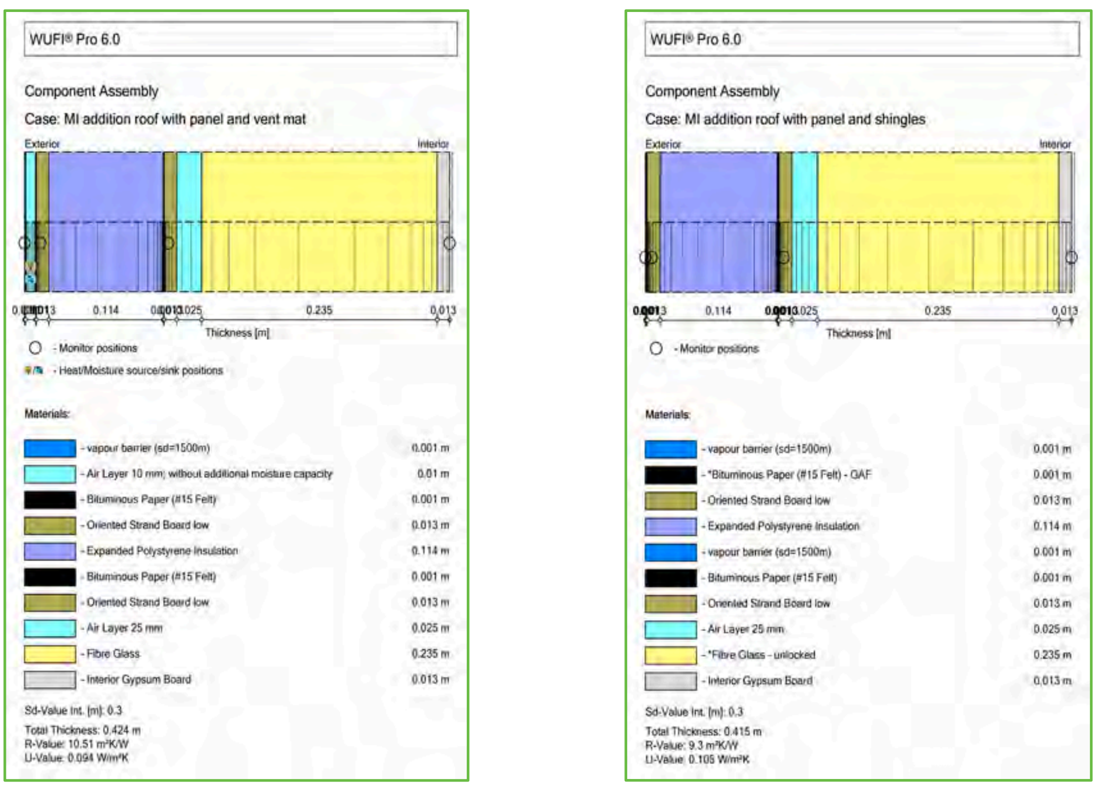


Figure 16. Addition roof component assembly for the Michigan house

3.2 Energy Analysis

Home Innovation conducted energy modeling during the design stage to predict energy performance and help determine the optimum insulation value of the retrofit panels within architectural constraints. Based on the retrofit panels selected for the final designs, the estimated heating/cooling energy savings were 20.8%/13.6% for Michigan and 13.8%/12.8% for Georgia.

The “before” (existing house) baseline energy performance was estimated based on-site assessment measurements and house leakage and duct leakage test-in results. The “after” energy performance was estimated based on retrofit panels with various insulation values and with and without an assumed 20% improvement in house leakage. For Georgia, the insulation value of the attic gable wall was specified and installed to match the insulation value of the retrofit panel.

The energy simulations were performed using REM/*Rate*™ v15.1 software. The estimated heating/cooling energy savings compared to the baseline houses are summarized in Table 9.

Table 9. Estimated Heating/Cooling Energy Savings

	LOADS (MMBtu/y)		SAVINGS	
Michigan Retrofit Options	**Heating**	**Cooling**	**Heating**	**Cooling**
0. Baseline (existing house)	180.1	5.5	NA	NA
1. 7.5-in." main roof panel (R-34), 4.5" addition roof panel (R-20), 9.26 ACH50 (measured at test-in)	151.1	4.8	16.1%	14.6%
2. Same panels as option 1, 7.4 ACH50 (20% improvement)	142.6	4.8	20.8%	13.6%
3. 9.5-in. main panel (R-43), 4.5-in. addition panel, 7.4 ACH50	141.5	4.8	21.5%	14.1%
Georgia Retrofit Options	**Heating**	**Cooling**	**Heating**	**Cooling**
0. Baseline (existing house)	20.3	14.6	NA	NA
1. 3.5-in. panel (R-16), 17.8 ACH50 (measured at test-in)	18.8	13.4	7.0%	8.3%
2. 3.5-in. panel (R-16), 14.0 ACH50 (20% improvement)	17.7	12.9	12.6%	11.8%
3. 5.5-in. panel (R-25), 14.0 ACH50	17.5	12.8	13.8%	12.8%
4. Theoretical: same as Option 3 except compared to new baseline with R-13 walls and R-19 floors (12.0/12.4 heating/cooling MMBtu/y)	9.6	10.6	20.0%	14.5%

For Michigan, the panels shown in Option 2 were selected for the final design. The thicker panel for the main roof shown in Option 3 did not appear to be practical based on the estimated energy savings and concerns with the appearance of that thicker panel.

For Georgia, the panel shown in Option 3 was selected for the final design. That 5.5-in.-thick core insulation panel improved estimated energy savings by only approximately 1% compared to the 3.5-in. panel, but the homeowners thought energy costs were likely to rise, the appearance would work well for their house, and the improved savings were worth the low estimated incremental cost.

The energy codes prescriptively require ceiling insulation values for new construction of R-38 in International Energy Conservation Code Climate Zone 2 (Georgia house) and R-49 in Climate Zone 5 (Michigan house). Although insulating to these values is desirable, doing so is not required for a retrofit project and is not necessarily practical. For Georgia, the R-25 retrofit panel was considered a good balance between energy efficiency and architectural integration (the house was further separated from outdoors with the existing R-19 ceiling insulation that was left in place). Same for the Michigan main roof with R-34 retrofit panels above the existing R-5 assembly; for the addition roof, the R-20 panels above the existing enclosed rafter assembly with R-30 batts clearly exceeded prescriptive requirements.

3.3 Structural Considerations

The project team specified the structural attachment and fastening details for retrofit panels based on building code requirements, manufacturer recommendations, and industry best practices. The final design was approved by the local building code official.

The retrofit panels must be structurally fastened at the panel-to-panel joints and to the roof framing to ensure integrity of the roof system in accordance with panel manufacturer instructions. For panel attachment to the roof, the project teams specified SIP screws of sufficient length to ensure a minimum penetration of 1 in. into the existing roof framing. The panel-to-panel connections are detailed in Section 3.4 and Section 4.1.

For Georgia, Home Innovation recommended reinforcement of the existing roof framing. The 2x6 roof rafters 24-in. on-center did not consistently align with, and therefore typically were not connected to, the 2x6 ceiling joists. The rafters were connected (toe-nailed) to top plates at eave walls in some places using only one nail. The rafter/ridgeboard connection was a more robust 3–5 nail toe-nail connection (Figure 17). Home Innovation recommended collar ties at every other roof rafter and hurricane clips at the rafter/top plate connections.

Figure 17. Georgia roof framing

For Michigan, Home Innovation recommended structural review by a design professional for the existing main roof assembly (2-in.-thick fiberboard panels on 4x6 rafters 4-ft on-center, ridge beam and collar ties for all rafters) (Figure 18) and addition roof assembly (enclosed rafter assembly, 2x10 rafters 16-in. on-center, OSB roof deck) (Figure 19) to support the retrofit panels. For the main roof, the estimated weight of the 2-in.-thick fiberboard panel was 5 lbs/ft^2. The 8-in. thick retrofit panel weighed 2.5 lbs/ft^2 (7/16 in. OSB at 40 lbs/ft^3 and 7.5 in. Neopor at 1.35 lbs/ft^3), so the retrofit panel represented an approximate 5%–7% increase relative to total design load.

Figure 18. Michigan main roof framing

Figure 19. Michigan addition roof
(Rafters shown are decorative.)

3.4 Architectural Considerations and Final Designs

The thickness of the retrofit panels was determined based on moisture analysis, energy analysis, and the specific architecture of each house. The trim boards at the eaves and rakes were selected by the homeowners, with input from the contractors, to visually integrate the thickness of the panels with the existing structure. Aesthetically, the installation of the ventilation mat was not considered an issue. The design details addressed the retrofit panel interface at eave/gable areas, intersecting walls, skylights, and other roof penetrations.

The final design solutions were specific to each house. The design process was considered successful because the solutions balanced energy efficiency, moisture control, cost, and architectural integration. The specifications for the final design solutions are summarized in Table 10; the final design solutions are illustrated in Figure 20 for Georgia through Figure 22 for Michigan.

Table 10. Summary of the Final Design Specifications

Step	Installation Specification	Notes/Product Specification
1	Remove existing roofing (shingles, underlayment) and gutters	Michigan: gutters to be reinstalled. Georgia: gutters will not be reinstalled.
2	Install and seal eave insulation (Georgia, Michigan addition)	See eave insulation details in the following section. Leave existing ceiling insulation.
3	Install and seal gable wall insulation (Georgia, Michigan addition)	See gable wall insulation details. R-value to match panel R-value. Ignition barrier as required.
4	Install structural modifications	Georgia: install collar ties (every other rafter) and hurricane clips (at rafter/top plate) during steps 2 and 3 while access is most favorable.
5	Extend plumbing vents as required to accommodate retrofit panel thickness	If solar panels are planned, reroute as practical to not interfere with panel location.
6	Install air barrier membrane, vapor permeable, above existing roof deck	Not required.
7	Install retrofit panels; pre-route EPS core at roof perimeter for dimensional lumber (curb) to attach trim/gutters; pre-drill holes for plumbing vents or other roof penetrations	Insulspan nail-base insulated panels: 7/16 OSB skin; BASF NEOPOR EPS core, R-4.5/in.; Panel size: 4x8 in.; Pre-routed for OSB surface spline; Pre-routed foaming channel at center of foam; Georgia: 6-in. R-25 panels (5.5-in. core) Michigan main roof: 8-in. R-34 panels (7.5-in. core) Michigan addition: 5-in. R-21 panels (4.5-in. core)
8	Install perimeter curb (EPS core of retrofit panel is pre-routed so panel OSB fits over curb)	Georgia: install curb before retrofit panels MI: install curb after retrofit panels
9	Attach panels to roof	SIP screws, 12-in. typical spacing, length to ensure minimum 1-in. penetration, washers at roof perimeter and panel-to-panel edges
10	Structurally interconnect panels	Install 7/16 x 3 OSB splines during panel installation, nail-off through OSB skin, 4-in. typical spacing.
11	Seal panels to the existing roof deck at the perimeter above eave and gable walls	Apply two-part expanding polyurethane foam (spray foam) to areas above eave walls and gable walls as panels are installed.
12	Seal panels at panel-to-panel edges: at the foaming channel along the middle of the EPS core and at the OSB surface spline; seal openings for plumbing vents and other roof penetrations; seal panels at ridge (panels cut at an angle so vertical surfaces meet at ridge)	Georgia: "drill and fill" spray foam method after panel installation. Michigan: apply SIP sealant at OSB splines and spray foam at foaming channels as panels are installed.
13	Install skylights (Michigan)	Remove existing skylight just before installing retrofit panel; install retrofit panel; cut rough opening in retrofit panel; let-in 2x bucks in perimeter using hot knife; seal opening; install skylight per manufacturer's instructions; finish interior of opening with drywall.
14	Install architectural trim boards	Georgia: PVC, ¾-in. thick Michigan: wood, to be stained
15	Install vapor permeable roofing underlayment and ice/water shield as required	Georgia: #30 roofing felt Michigan: GAF DeckArmor (16 perms) Ice/water shield: GAF StormGuard
16	Install ventilation mat above underlayment (before shingles)	Keene CDR ventilation mat (not installed in Michigan)
17	Install roofing: asphalt shingles, ridge vent, and flashing as required	Shingles, Michigan: GAF Timberline HD Shingles, Georgia: GAF Timberline Cool Ridge vent: GAF Cobra Exhaust Vent

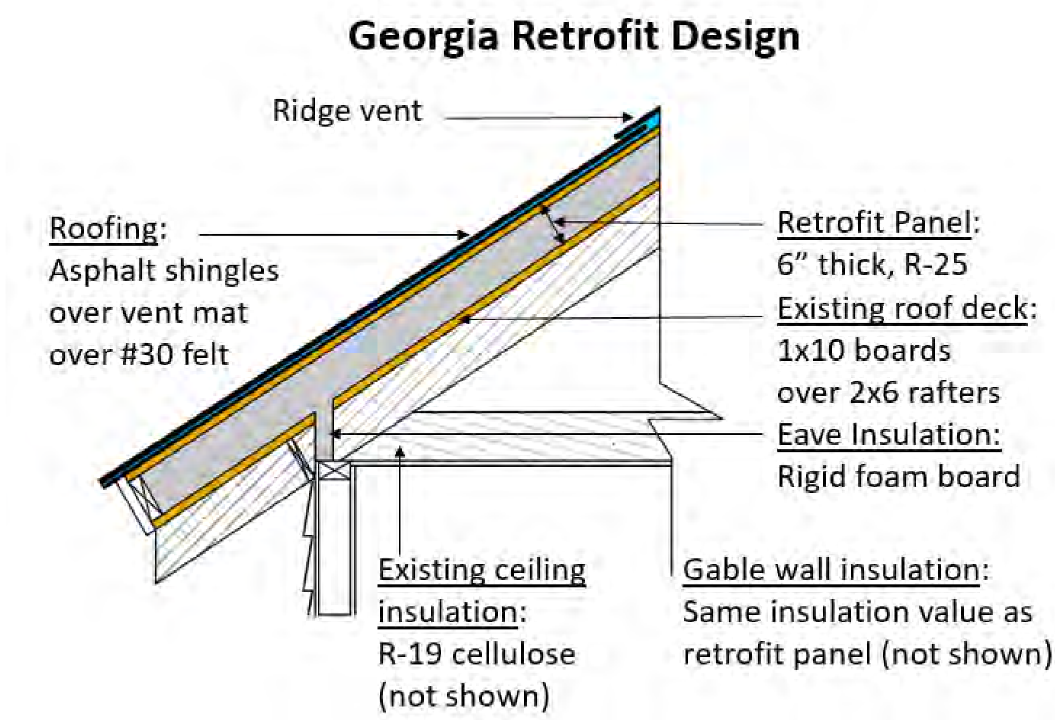


Figure 20. Georgia design solution

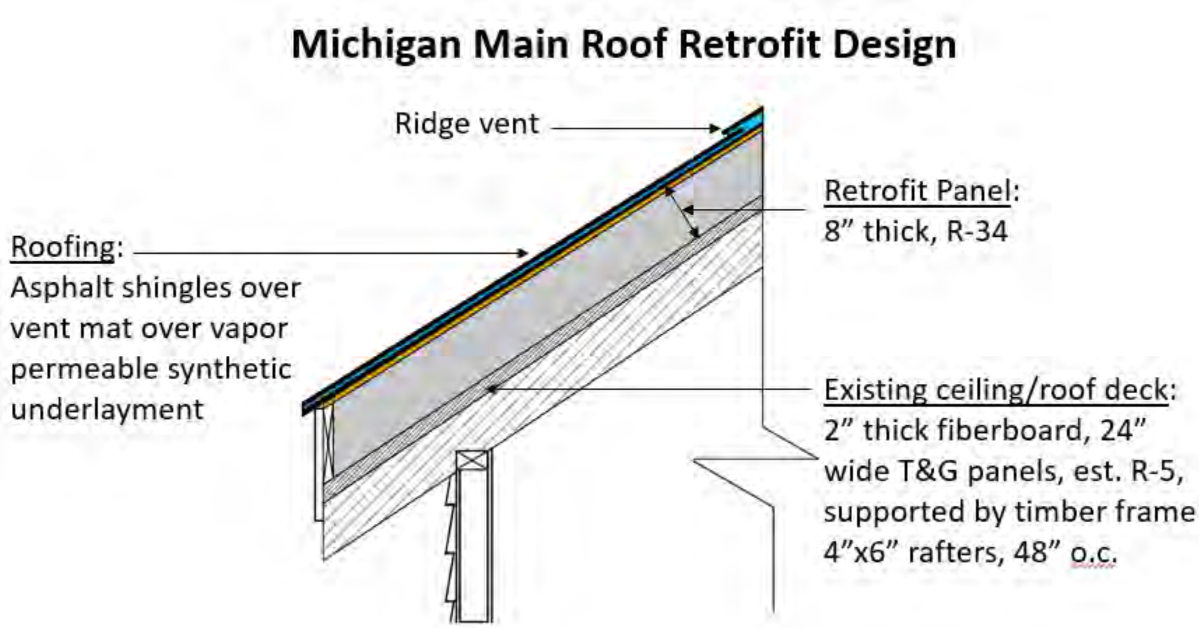


Figure 21. Michigan main roof design solution

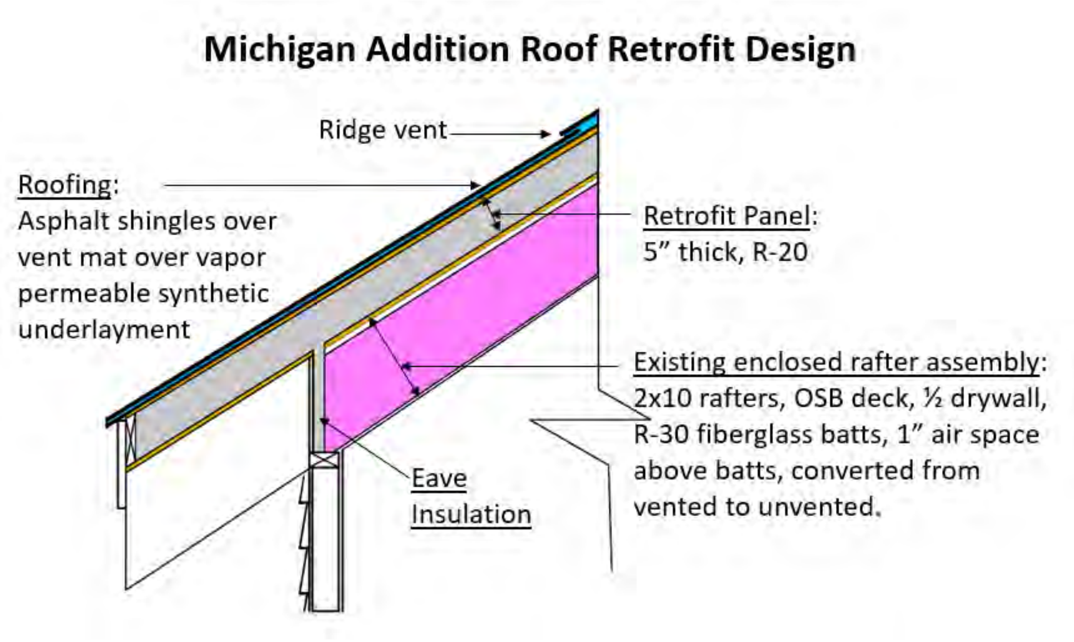


Figure 22. Michigan addition roof design solution

The eave area is a critical area to insulate and air seal but can be difficult to reach during a retrofit. Figure 23 shows an example method to insulate and seal this area to maintain continuity of insulation between the existing wall and the new roof retrofit panel. The sequence: cut and remove the lower portion of the roof deck sheathing for access (retain this section of sheathing—it will be trimmed by the width of the foam board and reinstalled); install foam board vertically between roof rafters, above the eave wall top plates, projecting just above sheathing; seal foam board at rafters and top plates; trim the sheathing that was removed to accommodate the foam and reinstall; trim foam board slightly proud of sheathing; seal top edge of foam board at sheathing; install sealant or gasket above foam board just before installing the retrofit panel.

Figure 23. Example eave insulation method

The gable walls of an unvented attic are also important to insulate and seal. Figure 24 shows an example method to insulate and seal this area. The sequence: remove a section of roof deck sheathing for access (easier than crawling through the attic and cleaner than walking materials through the house); seal the rake from inside the attic; install and seal rigid foam insulation at gable walls (same insulation value as panels); from the roof, install gasket or sealant on the roof deck sheathing above the gable wall just before installing retrofit panels.

Figure 24. Example gable wall insulation method

4 Results and Discussion

4.1 Construction

All sensors, retrofit panels, and roofing were installed at both sites by mid-January 2017.

Georgia: Construction began on January 3 and proceeded as planned: all shingles were removed; eaves and rakes were insulated and sealed; attic gable walls were insulated and sealed; vent stacks were extended; retrofit panels were installed on the existing roof deck and sealed (details follow); architectural trim, underlayment, flashing, ventilation mat, ridge vent, and shingles were installed.

After the shingles were removed, a portion of roof deck was removed to provide convenient access to the attic for workers and materials (Figure 25). This step was important to minimize construction traffic through the house and allowed full-size gable rigid insulation panels for the gable walls.

Figure 25. Construction access to attic at roof deck

Collar ties were installed at every other rafter to reinforce the roof framing (Figure 26). In lieu of hurricane clips, screws were installed through the rafters into the top plates.

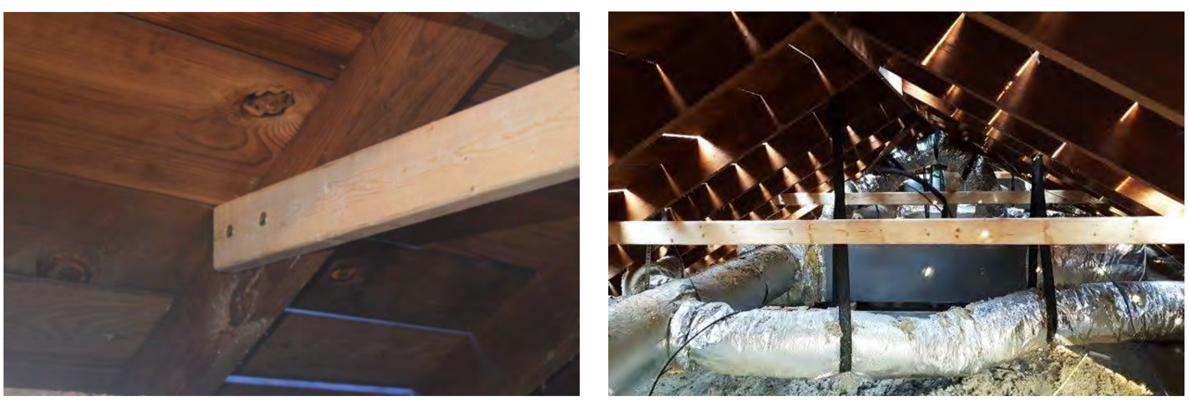


Figure 26. Collar ties installed at roof rafters

At the attic gable walls, rigid foam sheathing was installed and sealed (Figure 27). At the eaves, a lower portion of the roof deck, above and along the eave wall, was removed, and foam boards were installed vertically between the roof rafters and sealed at the rafters and top plates (Figure 28). The foam board was trimmed flush to the top of the roof deck, and this area was sealed again using spray foam just before the retrofit panel was installed.

Figure 27. Rigid foam insulation at attic gable walls

Figure 28. Rigid foam insulation at eaves

A 2x8 “curb” was installed at the roof perimeter before the retrofit panels (Figure 29). The curb provides a nailing surface for trim and gutters. The foam core was routed at the edge of the panel so the edge of the panel OSB would sit on top of the curb (Figure 30).

Figure 29. A 2x8 “curb” was installed before the retrofit panels

Figure 30. The first retrofit panel was placed on the one-story roof

The retrofit panels were **interconnected** at panel-to-panel edges using OSB surface splines (Figure 31). The factory-provided 7/16-in.-thick by 3-in. wide splines were installed into factory prerouted recesses in the foam just below the OSB skin and nailed off through the OSB skin. The 6-in.-thick retrofit panels were **attached** to the roof rafters using 8-in.-long SIP screws (Figure 32). The retrofit panels were **sealed** at panel-to-panel edges using the “drill-and-fill” method (Figure 33): vertical holes were drilled every few inches through the OSB down to a foaming channel that runs horizontally along the center of the foam at all edges; two-part expanding polyurethane foam (spray foam) was injected into every other hole—foam exited the adjacent hole to indicate the foaming channel was completely sealed. The retrofit panels were also **sealed** to the existing roof deck at the perimeter above the eave and rake walls as the panels were installed.

The areas that were sealed as described previously were considered critical areas to minimize air leakage and moisture migration between the existing roof deck and new retrofit panels. The panel-to-panel sealing method seals the top panel edge at the OSB skin and at the foaming channel along the middle of the panel, but it does not seal the bottom edge of the panel at the existing roof deck (a full SIP panel is commonly sealed here, but this area is not accessible for a retrofit panel). An air barrier membrane between the existing roof deck and retrofit panels was considered during the design stage, but the team decided this was not necessary.

Polyvinyl chloride (PVC) trim boards were installed over the curbs (Figure 34). Roofing (drip edge, underlayment, ventilation mat, and shingles) was installed next (Figure 35). The ventilation mat was installed above the underlayment and drip edges, so it is open at the bottom, top via the ridge vent, and rake edges to improve drainage at the underlayment and drying. With the vent mat below the shingles, the crew found that an 80-psi air compressor setting worked best for installing roofing nails without punching the nails through the shingles. The vent mat was open at the bottom, sides, and top via the ridge vent and the gap appeared to be maintained at full thickness (0.30 in.). For the second-story roof, the gap represented 4.3 ft^2 of ventilation, not including the open rake areas, for a ventilation-to-ceiling area ratio of 1:180. The completed installation for the one-story roof is shown in Figure 36. The completed roofing assembly looked good (the shingles were not wavy) and appeared to be durable.

Figure 31. Oriented strand board surface spline and sealant at deck above rake wall

Figure 32. Panels were screwed into rafters

Figure 33. Retrofit panels sealed at panel-to-panel edges

Figure 34. Polyvinyl chloride trim board was installed over the curbs

Figure 35. Ventilation mat and shingles on one-story roof

Figure 36. First-story roof complete

Sensors to monitor moisture conditions at the OSB skin were installed within the retrofit panels as the work progressed, as shown in Figure 37. With the panel on the ground, a hot-wire knife was used to plunge-cut into the foam down to the OSB to create an approximate 4-in.^{2} opening in the foam. The wireless sensor was screwed to the OSB—a washer was installed between the sensor and OSB to create a 1/8-in. gap. The foam plug that was removed was then reinstalled and sealed. Some retrofit panels received two sensors—one near the middle of the panel and one near an edge—and the sensors were located and marked to miss the roof rafters and panel attachment screws. Sensors were also installed within the ventilation mat to monitor roof shingle temperature. Sensors were previously installed during the site assessment to monitor indoor, outdoor, and attic conditions.

Figure 37. Sensor installation within retrofit panels

The retrofit panels for the second-story roof were installed in the same way. Most screws were installed while the panels were still on the ground to speed the process along for the workers on the roof (Figure 38). The workers on the roof provided rafter measurements so the workers below could locate the screw accurately. The panels at the top row on each side were cut at an angle so the vertical surfaces met at the ridge; gaps were filled and sealed at the ridge using spray foam. Figure 39 through Figure 43 show the installation for the second-story roof.

Figure 38. Pre-installed screws
(Note the sensor location marked on the OSB next to the cleat.)

Figure 39. Panels were hoisted manually to the second-floor roof

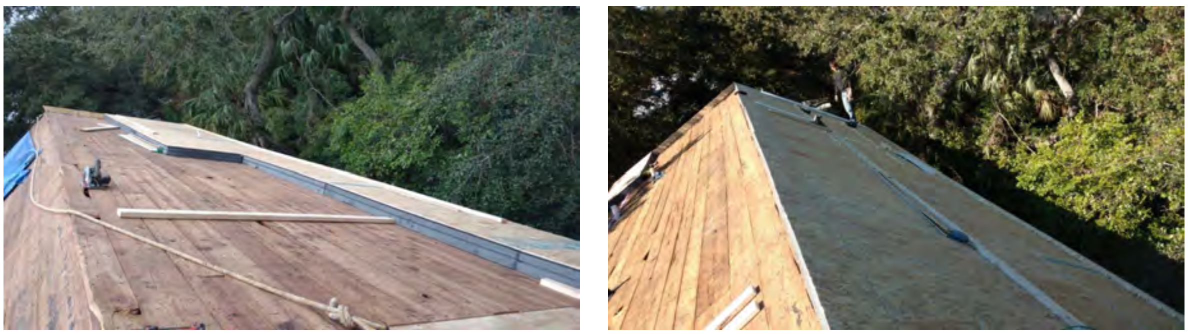


Figure 40. Panel installation progress on the second-story roof

Figure 41. Ventilation mat and shingle installation

Figure 42. Panel and roofing during installation

Figure 43. Second-story roof complete

Michigan: construction began December 5 on the rear roof of the main house. Construction for the rest of the house was postponed because of weather until December 19.

The installation crew removed all shingles from the rear roof of the main house, but the contractor became concerned with damaging the roof deck and safely walking on the roof. The main house roof deck/ceiling consists only of 2-in.-thick fiberboard composite panels supported by timber frame rafters 4 ft on-center, which felt somewhat spongey, particularly in front. The contractor also became concerned with safely working on the ventilation mat for this steep roof (12:12) and the potential for durability issues for the asphalt shingles (resulting from ventilation mat compression during installation), even though he was initially on board with the design. Based on these safety and durability concerns, the shingles on the front roof of the main house were not removed, and the ventilation mat was not installed (front or rear). The decision was also made to leave the existing shingles and not install the ventilation mat on the addition roof—shingles there were removed only as required to insulate and seal the eave and rake areas.

Otherwise, the project proceeded as planned. The retrofit panels were interconnected at panel-to-panel edges using OSB surface splines, the same as in Georgia. The Michigan team added SIP sealant to the splines, and the panels were sealed at panel-to-panel edges using spray foam as the panels were installed (Figure 44). Panels were attached to rafters using screws: 12-in.-long screws for the 8-in. panels on the main roof, 8-in.-long screws for the 5-in. panels on the addition roof. The nailing curbs, “two-by” (1.5-in. wide) lumber precut at the factory, were installed after the panels (Figure 45) and later covered with wood trim.

Figure 44. Retrofit panel installation on back of main roof

Figure 45. Nailing curbs installed after the retrofit panels

The skylights were removed just before panel installation. After panel installation, openings were cut for the skylights from inside, structural support blocking was let-in to the foam, and the skylights were reinstalled and flashed (Figure 46).

Figure 46. Skylights were removed and reinstalled after panels

Ice and water shield membrane was installed as required at eaves and valleys, and vapor permeable synthetic underlayment was installed above the retrofit panels (Figure 47).

Figure 47. Roofing the back of the main roof

Infrared images were taken from indoors after the retrofit panels were installed on the rear side of the main roof (Figure 48). The insulation benefit is obvious for the insulated side of the roof (yellow) compared to the uninsulated side (purple). Figure 49 shows work in progress and the installation complete (the trim boards were stained later to match the color of the existing house).

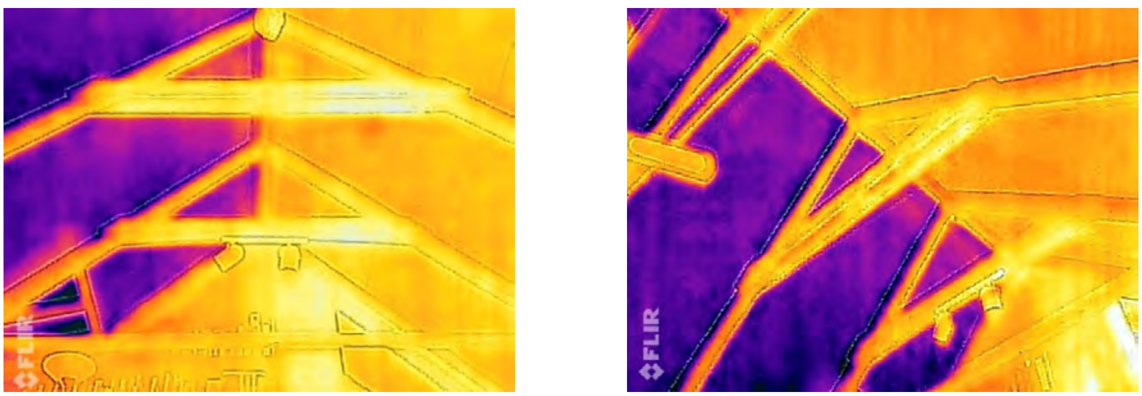


Figure 48. Infrared images

Figure 49. Installation progress and installation complete

Sensor locations.

For Georgia, nine sensors were installed within the retrofit panels. For the second-story gable roof, four were installed on the southwest roof, and four were installed on the northeast roof. One sensor was installed for the first-story shed roof that faces northwest. Sensor locations are shown in Figure 50 for the retrofit panel sensors, attic sensors (at existing roof deck and rafters) installed during the site assessment, and shingle sensors; indoor and outdoor sensors are not shown (Figure 50).

For Michigan, 12 sensors were installed within the retrofit panels. Four sensors were installed for each roof orientation: main roof front (west), main roof rear (east), addition roof left (north), addition roof right (south). Sensor locations are shown (Figure 51).

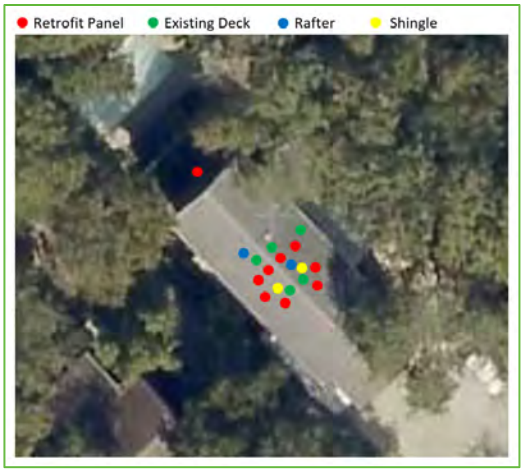


Figure 50. Sensor locations: Georgia

Figure 51. Sensor locations: Michigan

4.2 Moisture Performance Data

The results of the monitored data for wood MC, temperature, RH, and DP are presented in this section.

Georgia: The MC at the nine retrofit panel sensors (at the OSB layer) remained less than 9% during the winter and less than 8% during the spring and summer except for one outlier. At the outlier sensor, very close to the ridge on the north side of the roof, the MC rose to nearly 14% over a few weeks and then dried over a few weeks (Figure 52).

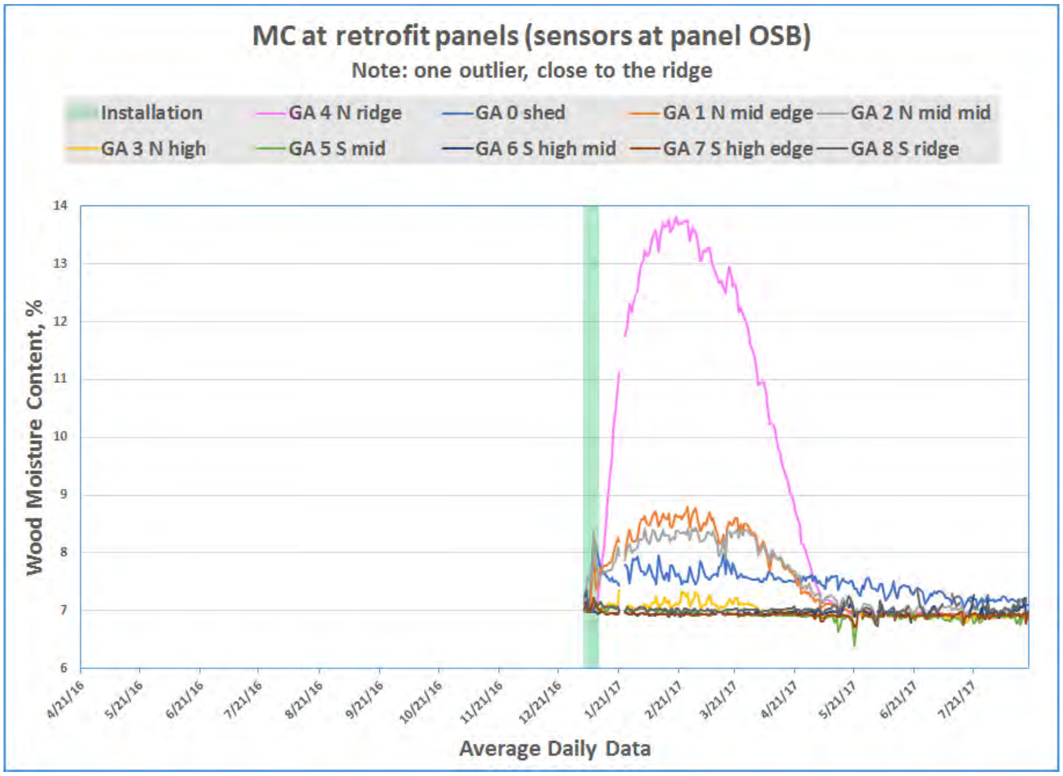


Figure 52. Georgia moisture content at retrofit panels

The MC at the existing roof deck and rafter sensors in the attic was mostly much less than 10% before installation. After installation, the MC was higher but remained less than 10% during the winter and less than approximately 12% during the summer. One outlier spiked to more than 30% just after installation but dried quickly. This sensor was installed low, near the ceiling, at the roof deck, and it had rained the night before, so it appears this area became wet from the rain (Figure 53).

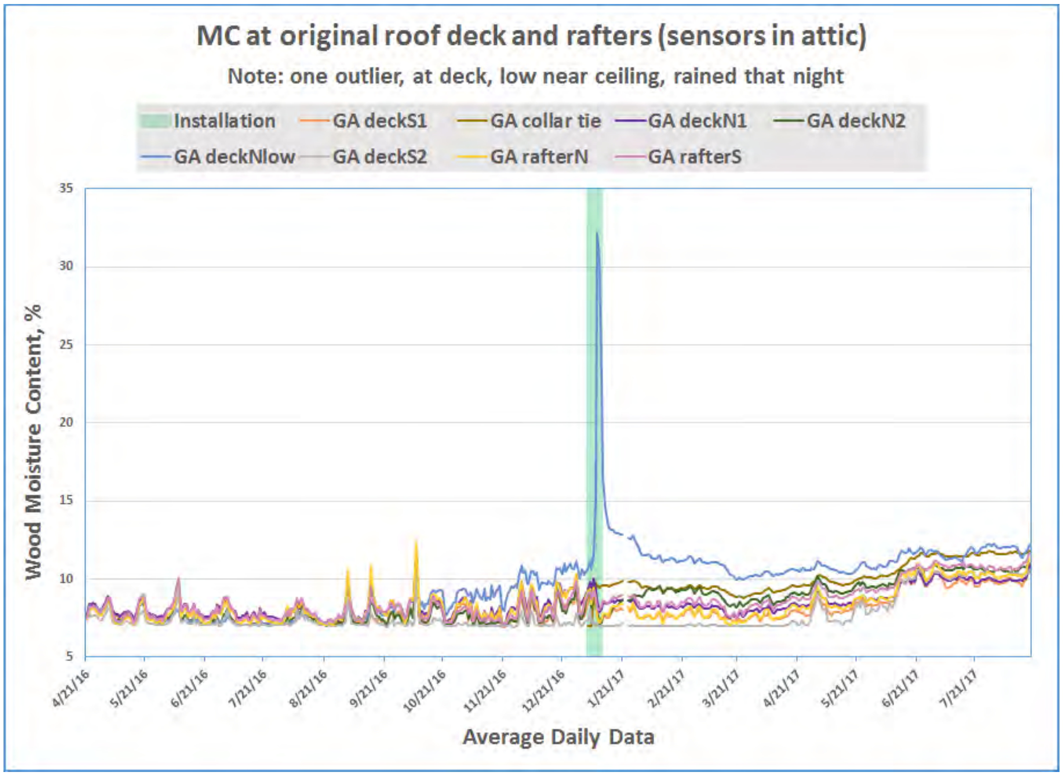


Figure 53. Georgia moisture content at original roof deck and rafters

For the Georgia attic, average RH levels after installation closely tracked indoor house RH levels during the winter and spring but became high during the summer compared to the previous summer (Figure 54). As expected, attic temperature was much lower during the summer after installation (Figure 55); despite the higher attic RH, the attic DP was somewhat lower compared to the previous summer (Figure 56).

Before installation, the attic RH levels had a large diurnal range of approximately 25%–85% (Figure 57); after installation, the range was a tighter 75%–85% RH with a higher average of approximately 80% RH (Figure 58). The indoor RH was roughly the same before and after installation; the large swings and average more than 60% RH indicate oversized air-conditioning equipment and inconsistent air-conditioning operation. The homeowner was apprised and plans to install an HVAC supply vent in the attic to help control RH in the attic.

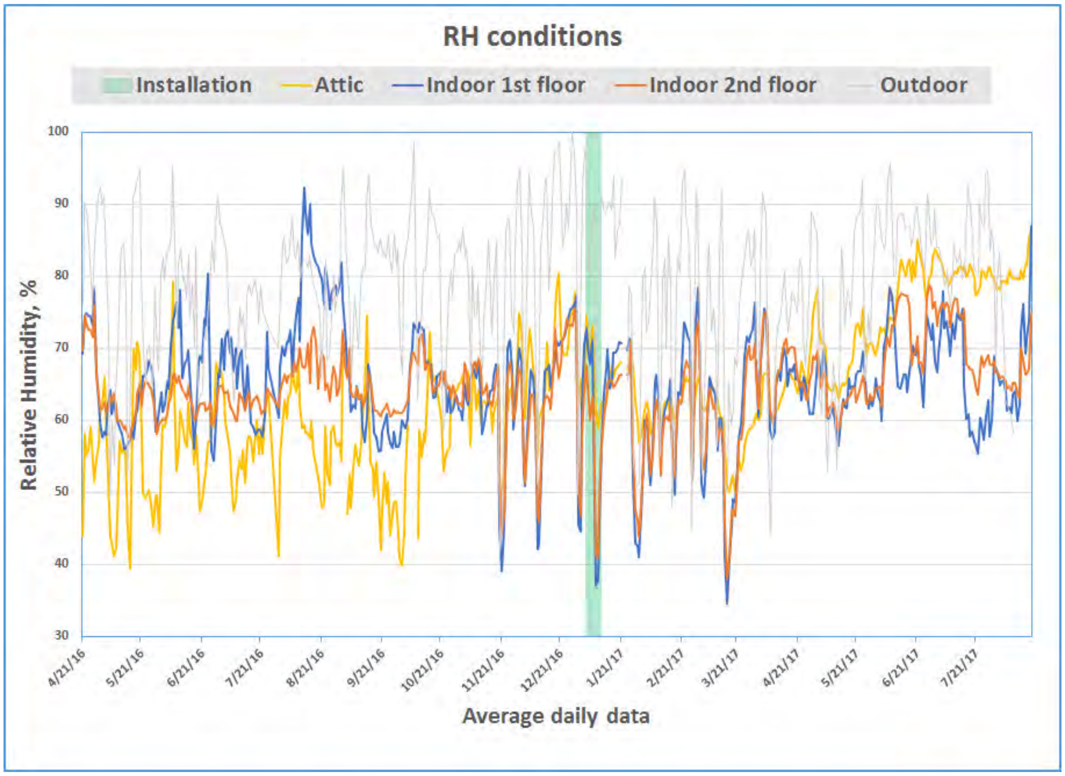


Figure 54. Georgia relative humidity conditions

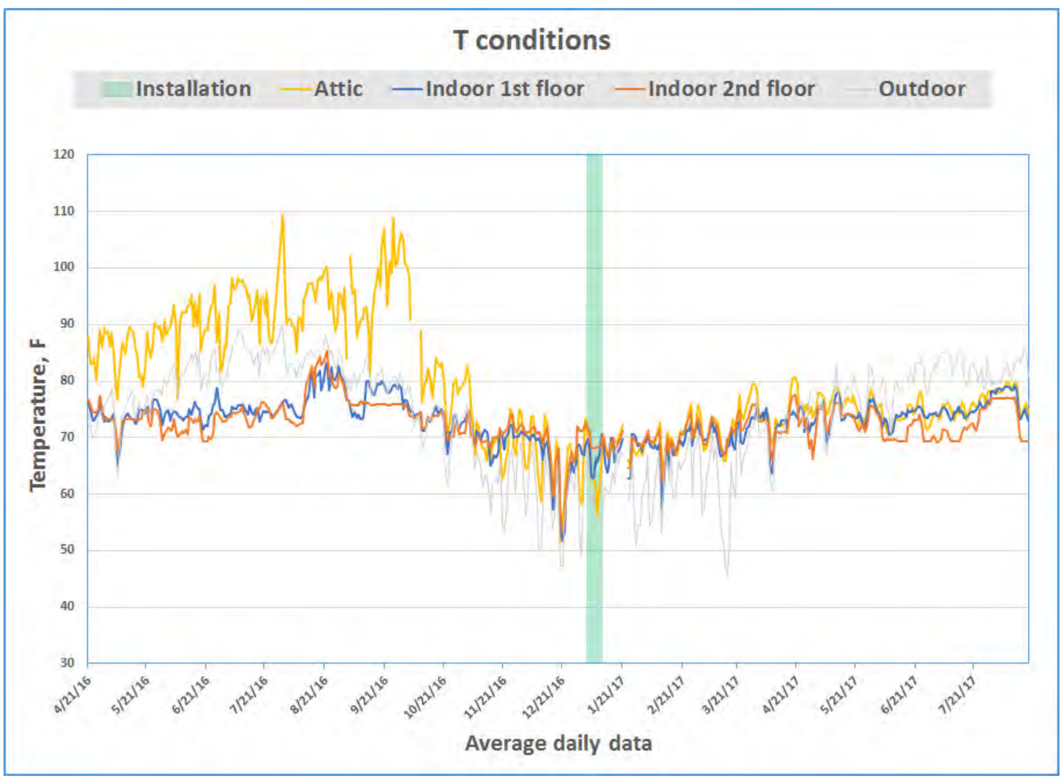


Figure 55. Georgia temperature conditions

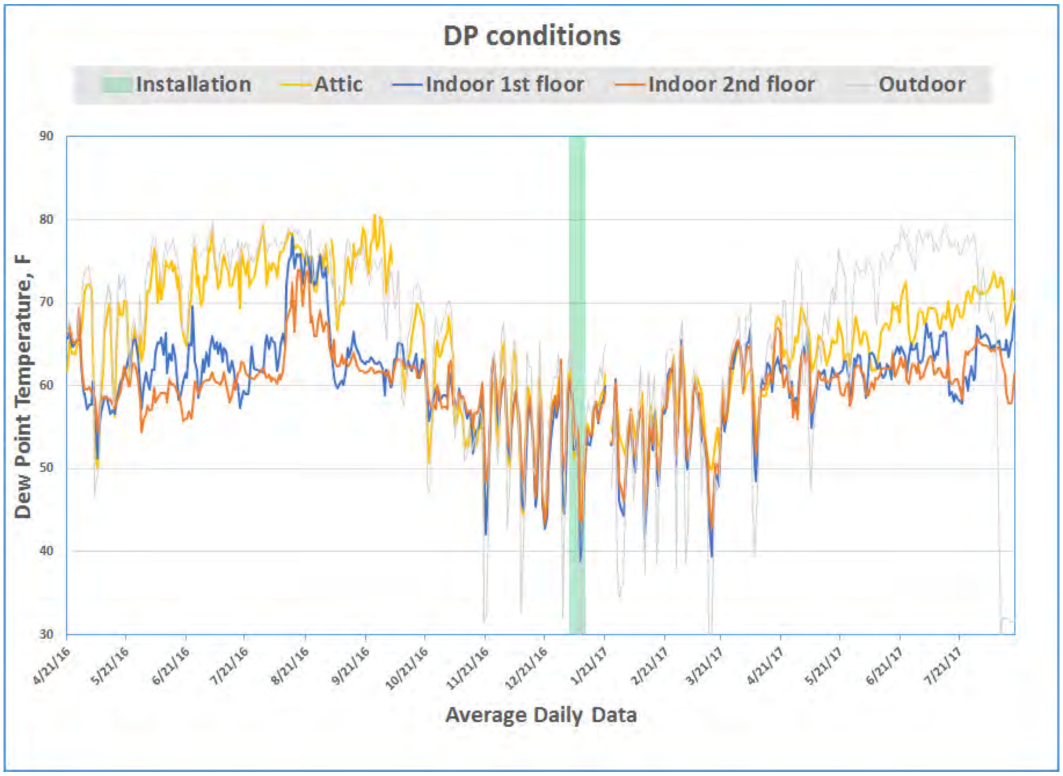


Figure 56. Georgia dew point temperature conditions

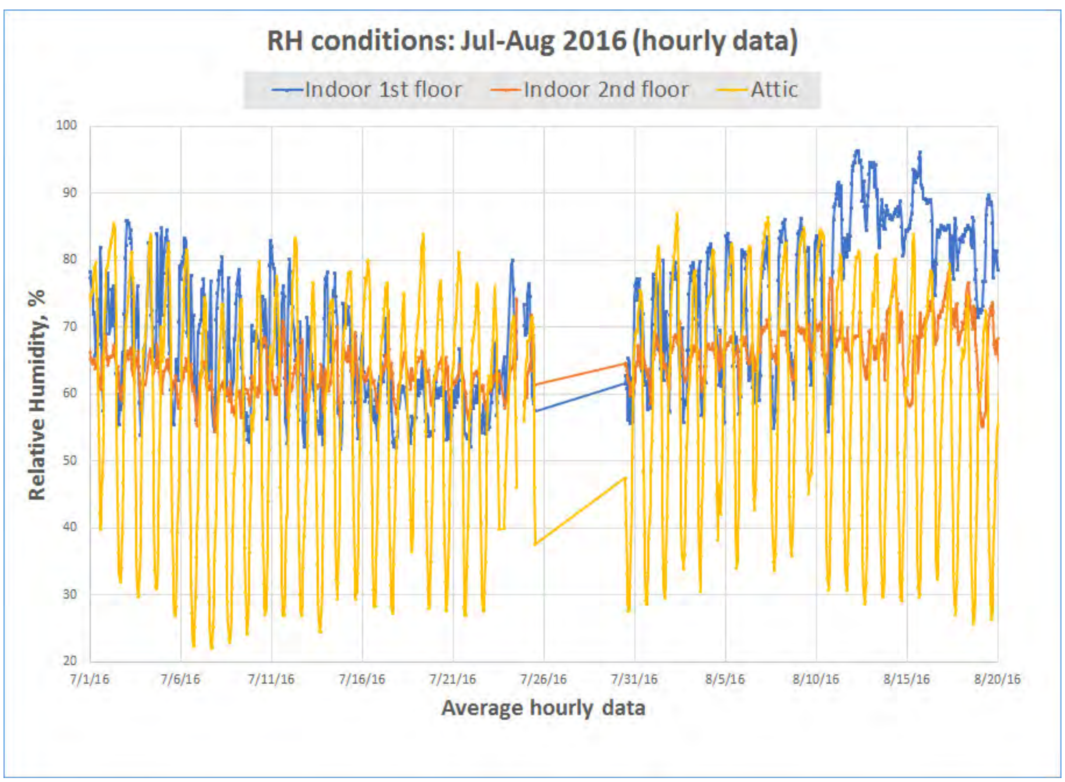


Figure 57. Georgia relative humidity conditions before retrofit panels

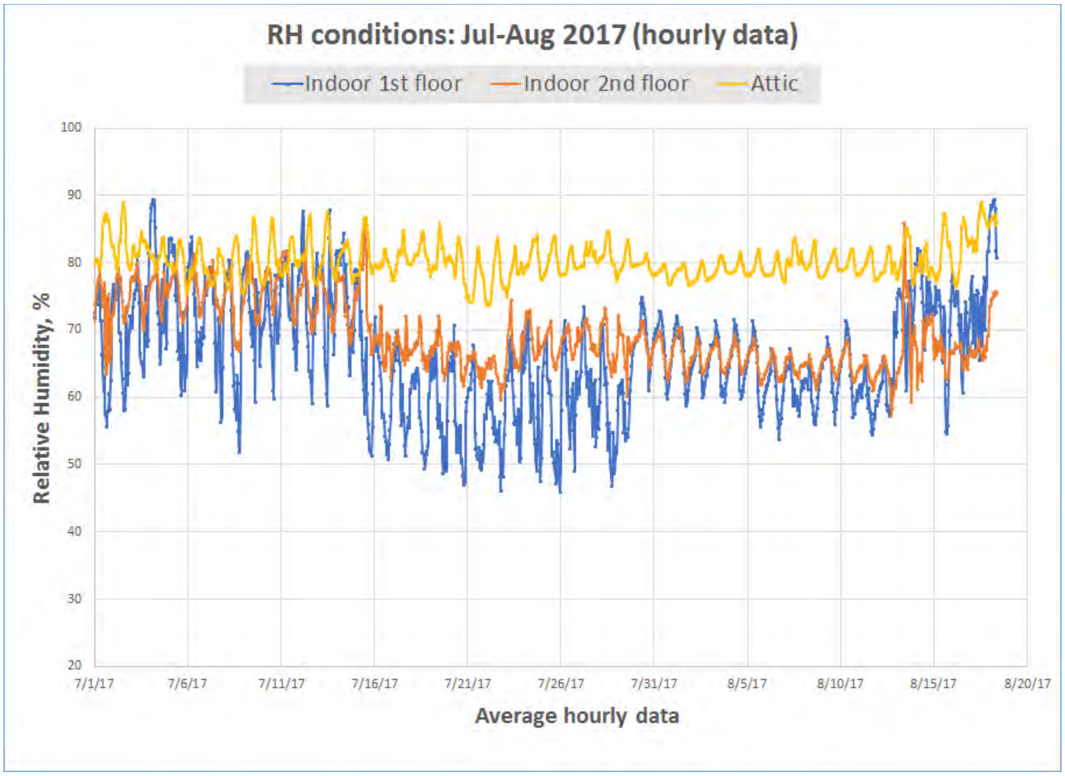


Figure 58. Georgia relative humidity conditions after retrofit panels

Michigan: MC at the 12 retrofit panel sensors remained less than 10% during the winter, except for three outliers, and less than 8% during the summer (Figure 59). The three outlier sensor locations (MI 10 S, MI 11 S, and MI 12 S) are all on the south face of the addition roof; the MC spike indicates that the panels were likely wet at installation. Two of the outlier sensors failed (MI 10 S and MI 11 S); the third spiked to more than 24% but dried to less than 20% during the next couple of weeks and continued to dry to less than 8%.

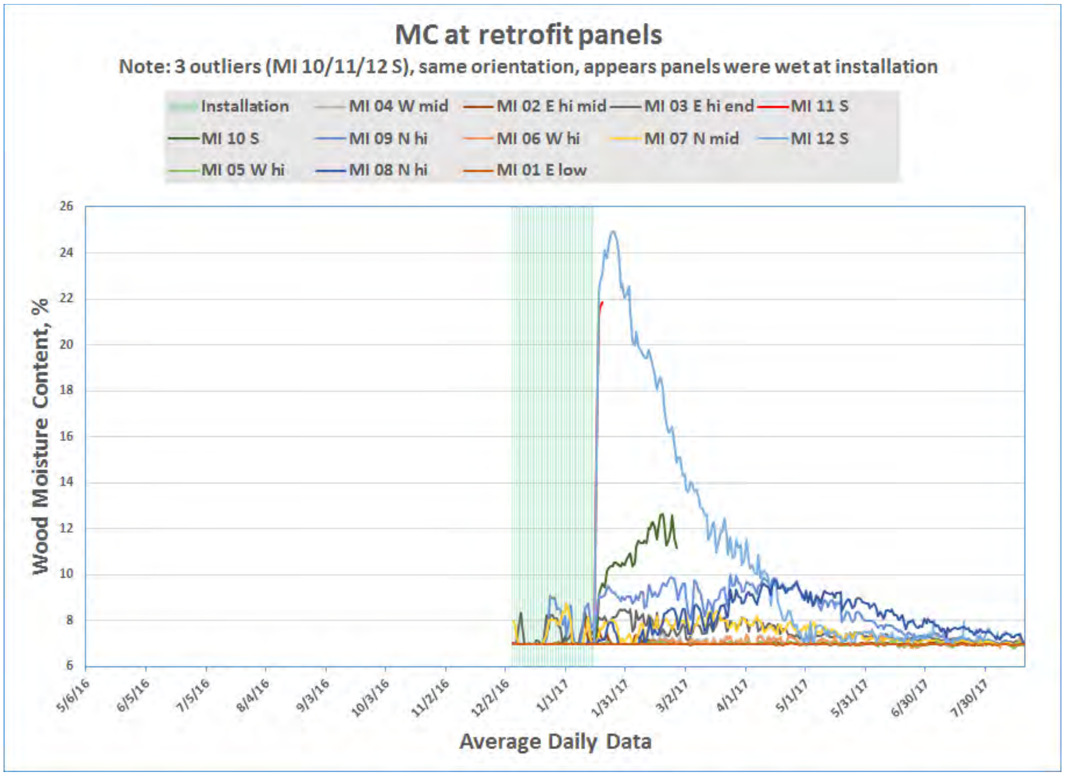


Figure 59. Michigan moisture content at retrofit panels

Two sensors were installed at the existing roof deck within the enclosed rafter assembly of the addition roof. These sensors failed after about four months, but average RH there during the winter ranged from approximately 35%–65%, with one brief spike to more than 70% (Figure 60, sensors MI 13 deck and MI 14 deck; note: these two sensors track exactly, so it is difficult to distinguish those in the graph). The MC at these sensors remained less than 8%.

As mentioned, the existing shingles were left on the addition roof (north and south orientations) and front of the main roof (west orientation). This resulted in a less vapor-permeable (but not impermeable) layer at the existing roof deck; this was considered more of a concern for the addition roof (because of potential moisture migration from air leakage at the drywall ceiling, potentially leading to excessive moisture accumulation within the enclosed rafter assembly) than the main roof (the 2-in.-thick fiberboard panels are adjacent to conditioned space). Also, as mentioned, the vent mat intended to facilitate drying to the outdoors was not installed at Michigan. Despite these design changes, moisture conditions at the retrofit panels were well within acceptable limits (the noted outliers eventually dried).

The RH conditions indicate that the house might be somewhat less humid during the summer after the retrofit panel installation (Figure 61), during a period when the temperature conditions appear to be about the same (Figure 62).

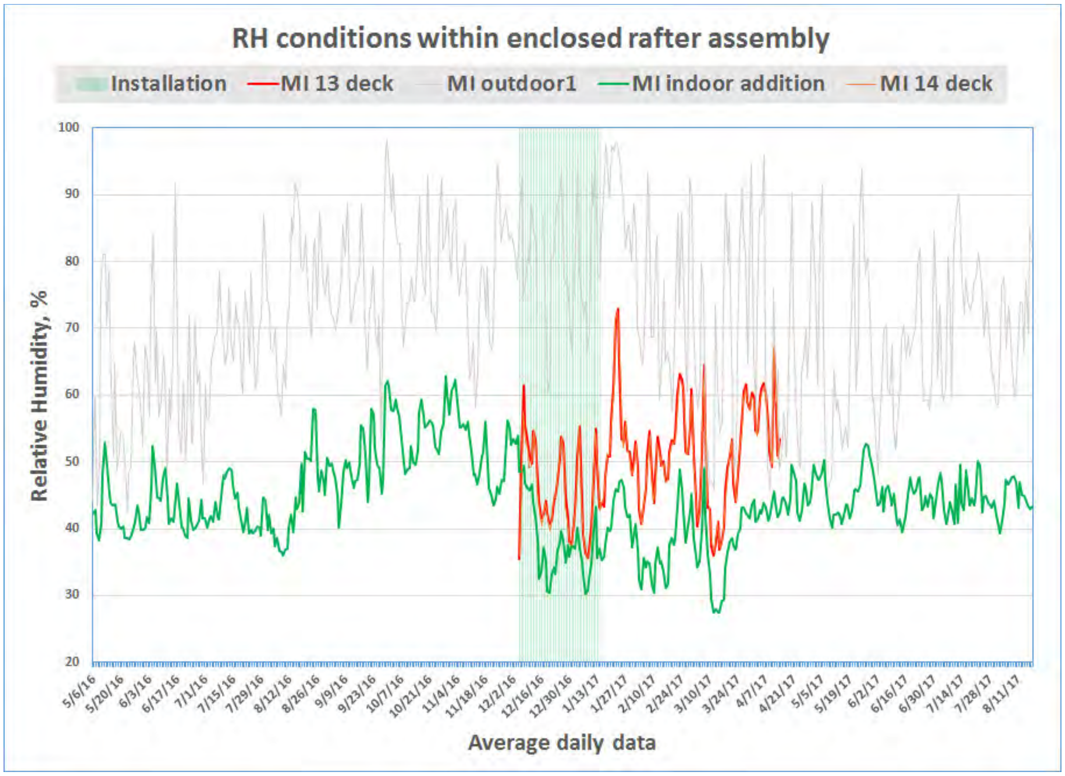


Figure 60. Michigan relative humidity conditions: addition roof assembly

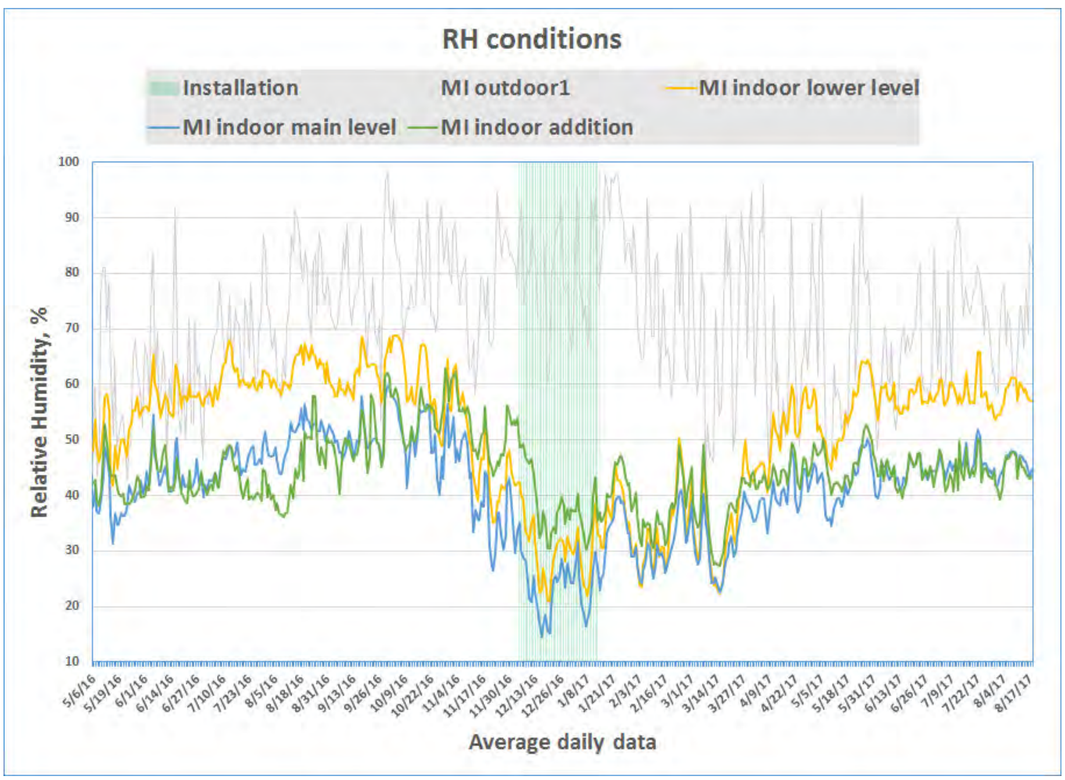


Figure 61. Michigan relative humidity conditions

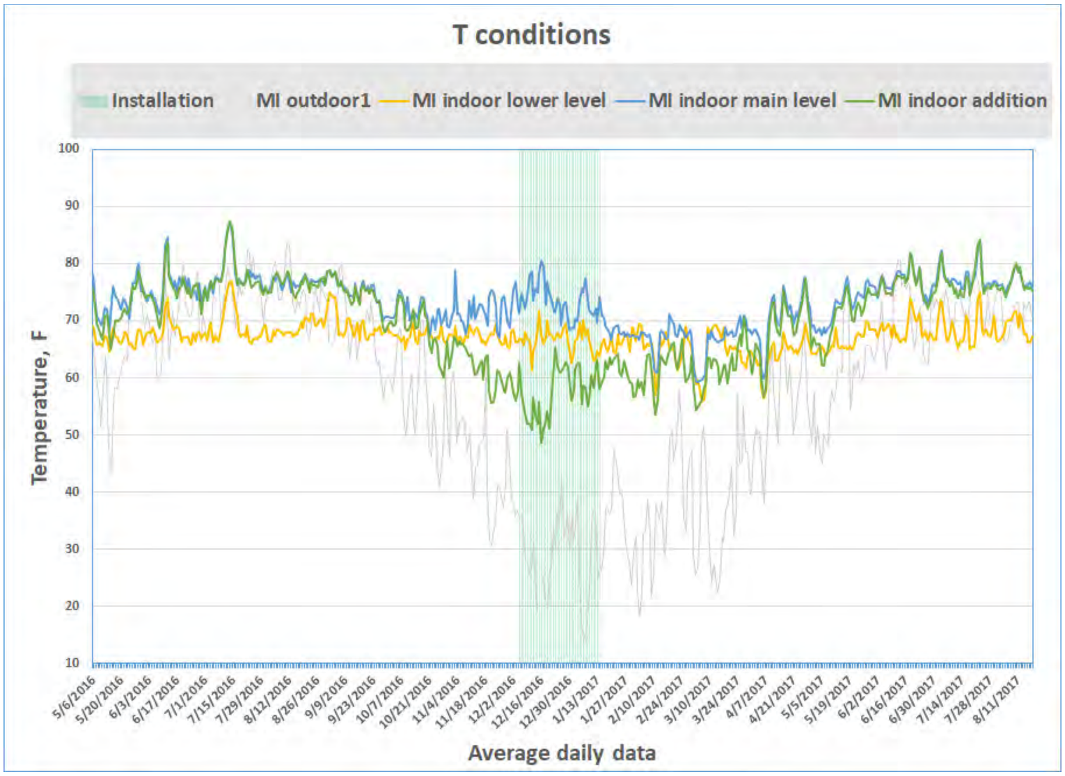


Figure 62. Michigan temperature conditions

<u>Shingle temperatures</u>: Temperature/RH probes were installed under the shingles near the ridge for the north and south orientations for both houses. For Georgia, the probes were placed within the vent mat (Figure 63). The wireless sensors installed in the attic serve the cabled temperature/RH probes installed on the roof. For Michigan, the probes were placed at the top of a shingle and covered with the next course. The probes had cables that were connected to wireless sensors within the attics.

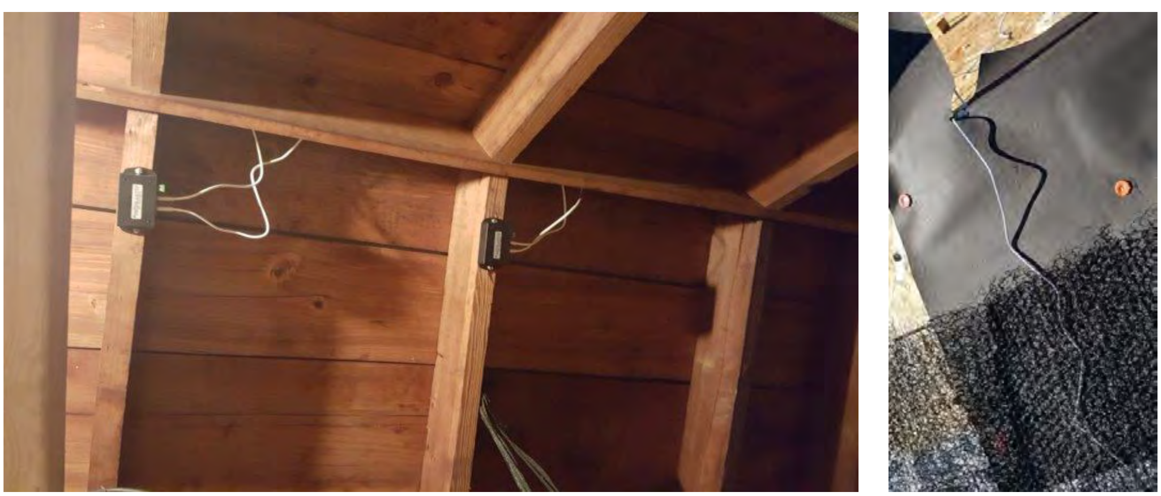


Figure 63. Georgia shingle temperature sensors and probes

For Georgia, the shingles were light in color and “cool” (reflective) rated. For Michigan, the shingles were medium-dark in color. The temperature data are shown for nearly one month during the summer after installation (Figure 64 and Figure 65). These shingles installed above unvented roof assemblies do not appear to experience excessive temperatures; although there are no before data, the results appear to correlate well with prior research that shows shingle temperatures increase slightly with unvented attics, but the color of the shingles and roof orientation have a more significant effect on shingle temperature and durability (Parker 2005).

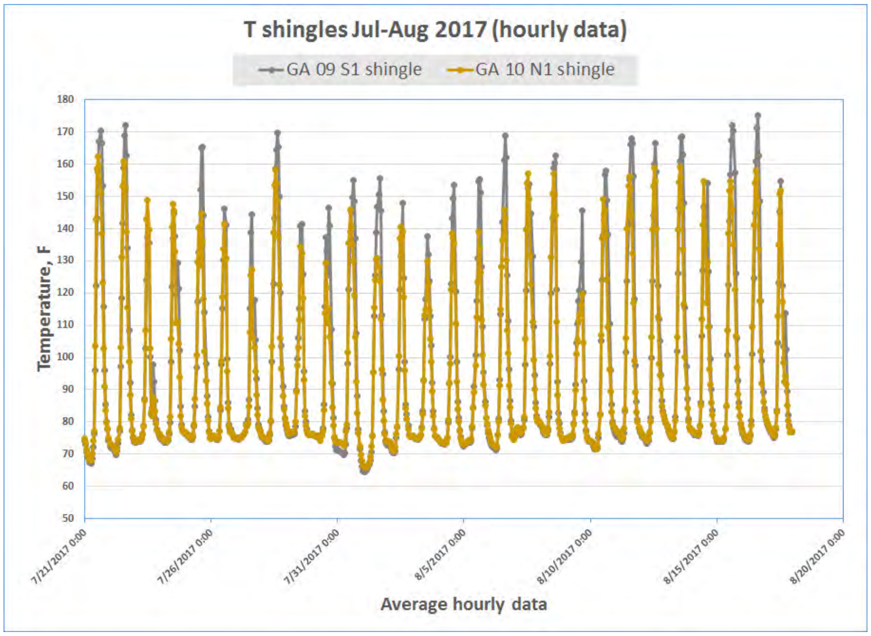


Figure 64. Georgia shingle temperatures

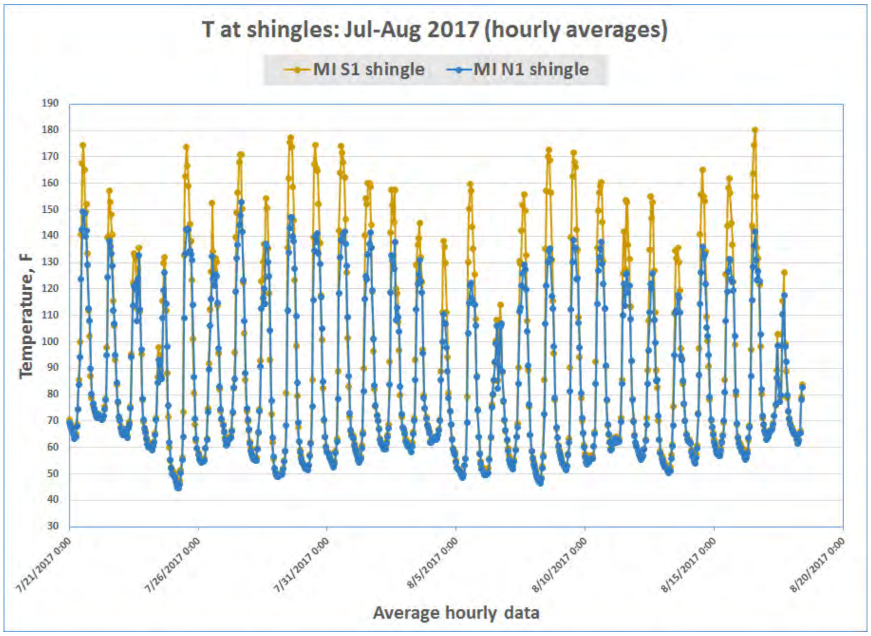


Figure 65. Michigan shingle temperatures

4.3 Energy Evaluation

Energy performance was measured using utility bills collected before and after retrofits. Energy performance data were normalized based on actual degree-days.

Final house tightness testing was conducted in April. Test-in and test-out results are shown in Table 11.

Table 11. House Tightness Test Results

Location	Test-In result	Test-Out result	Improvement
Michigan	9.26 ACH50	6.61 ACH50	29%
Georgia	17.82 ACH50	15.69 ACH50	12%

The measured house tightness improvement was better than expected for Michigan and less than expected for Georgia (20% improvement was estimated for both). (Note: for Georgia, the walls and floors, it turns out, are very leaky; if the house was a more typical 8.9 ACH50 at test-in, half of actual, the same effort would have provided a 24% improvement.) At test-in, the Georgia attic could not be depressurized independently of the house; attic pressure with respect to the house was 48.2 Pa at test-in and 23.8 Pa at test-out; the attic leakage ratio (attic-to-house: attic-to-outdoors) was approximately 1:8.5 at test-in and 1.1:1 at test-out, indicating there still is leakage to the outdoors but the attic communicates much more closely with the house.

The energy models were run again using the measured test-out house tightness results to estimate heating/cooling energy savings. Table 12 shows the original and adjusted estimated energy savings for both houses. For Georgia, the theoretical conditions are included to indicate potential savings for a house with more typical insulation and tightness.

Table 12. Original and Adjusted Estimated Heating/Cooling Energy Savings

Michigan: 8-in. Main Roof Panel (R-34), 5-in. Addition Roof Panel (R-20)	Heating	Cooling
Original est. savings (7.4 ACH50)	20.8%	13.6%
Adjusted est. savings (6.61 ACH50)	22.9%	13.1%
Georgia: 6-in. Panels (R-25)	**Heating**	**Cooling**
Original est. savings (14.0 ACH50)	13.8%	12.8%
Adjusted est. savings (15.69 ACH50)	11.3%	11.0%
Theoretical savings 1 (14.0 ACH50, R-13 walls, R-19 floors)	21.0%	15.3%
Theoretical savings 2 (8.9 ACH50, R-13 walls, R-19 floors)	34.5%	20.9%

The energy evaluation is based on utility bills (site energy) and local weather data: heating degree days (HDD65) and cooling degree days (CDD65) in Michigan and total degree days (TDD65) for Georgia (Weather Data Depot 2018). Total degree day data include heating and cooling and are used for Georgia because most winter months include some cooling degree day data.

The evaluation considers mid-January 2017 and forward as after-panel installation and compares these data to the corresponding period in 2016. Actual energy used during 2016 and 2017 are adjusted for seasonal usage. The adjusted data for 2017 is then normalized for weather—based on heating degree days, cooling degree days, or total degree days—for comparison to the adjusted data for 2016. It is acknowledged that this is a rather coarse method to calculate energy savings compared to results from power metering; nonetheless, this method is considered a reasonable check to compare energy trends and savings predicted by modeling.

For Michigan, the heating energy savings for three months during the winter was 40.4% (Table 13). This is considerably better than the predicted savings of 22.9%. The heating adjustment in the table deducts the average natural gas usage for hot water and cooking, based on summer usage, to isolate heating energy use. The cooling energy savings for three months during the summer was 16.8% (Table 14), better than the predicted savings of 13.1%. The cooling adjustment in the table reduces electric usage based on winter electric usage to isolate cooling energy use.

Table 13. Michigan Heating Energy Savings

Michigan Heating Period	HDD 2016	HDD 2017	2016 Natural Gas (CCF) Actual	2016 Natural Gas (CCF) Adjusted	2017 Natural Gas (CCF) Actual	2017 Natural Gas (CCF) Adjusted	2017 Natural Gas (CCF) Normal	Heating Savings
January–February	1,225	1,088	249		162			
February–March	1,059	840	202		99			
March–April	736	939	163		122			
Total	**3,020**	**2,867**	**614**	**532**	**383**	**301**	**317**	**40.4%**

Table 14. Michigan Cooling Energy Savings

Michigan Cooling Period	CDD 2016	CDD 2017	2016 Electricity (kWh) Actual	2016 Electricity (kWh) Adjusted	2017 Electricity (kWh) Actual	2017 Electricity (kWh) Adjusted	2017 Electricity (kWh) Normal	Cooling Savings
May–June	36	23	1,277		1,147			
June–July	92	114	1,251		1,288			
July–August	245	172	1,523		1,490			
Total	**373**	**309**	**4,051**	**576**	**3,925**	**397**	**479**	**16.8%**

For Georgia, the heating and cooling energy savings for the six-month period from February through July was 15.8% (Table 15) compared to the predicted savings of 11.0%–11.3%. The adjustment in the table for electric energy was based on the predicted ratio of heating/cooling energy to total energy (54.3% for 2016 and 51.4% for 2017).

Table 15. Georgia Heating and Cooling Energy Savings

Georgia Heat Cool Period	TDD 2016	TDD 2017	2016 Electricity (kWh) Actual	2016 Electricity (kWh) Adjusted	2017 Electricity (kWh) Actual	2017 Electricity (kWh) Adjusted	2017 Electricity (kWh) Normal	Heating and Cooling Savings
February	311	140	1,649		1,076			
March	170	239	1,146		1,346			
April	146	213	1,220		1,523			
May	321	368	1,688		2,114			
June	514	463	4,069		2,993			
July	641	590	3,997		2,795			
Total	**2,103**	**2,013**	**13,769**	**7038**	**11,847**	**5,675**	**5,928**	**15.8%**

4.4 Cost Evaluation

The cost evaluation focused on the incremental cost to install retrofit panels during a reroofing effort. Therefore, the incremental costs did not include removing the existing roofing or installing the new roofing (drip edges, underlayment, flashing, ridge vent, shingles). Incremental cost includes labor and material for exterior trim to cover the retrofit panel edges.

For those materials that were donated for this project, the material costs were based on the estimated cost of this type of package from the panel manufacturer and purchases of other materials. Incremental materials include the retrofit panels, screws, spray foam, gable/eave insulation, curbs, trim, and ventilation mat.

Generally, labor cost is primarily a function of roof pitch and secondarily a function of travel distance to the job. Based on discussion with the contractors, incremental labor for installing retrofit panels generally ranges from \$1/ft^2 for a 4:12 roof, to \$1.50–\$2/ft^2 for a 7:12 roof, to \$3/ft^2 for a 12:12 roof. Labor cost might need to be adjusted, or travel expenses added, depending on proximity.

For Michigan, the value of all incremental materials was \$15,000, or \$5.77/ft^2. Incremental labor for this steep roof was \$7,800 based on \$3/ft^2. The total incremental installed cost for evaluation purposes was \$22,800, or \$8.77/ft^2. The resultant added incremental annual mortgage, at 4% over 30 years, would be \$1,323. With an estimated annual energy cost savings of \$803, this would result in a negative annual cash flow of \$520, a simple payback of 29 years, and a simple return on investment of 3.5%.

For Georgia, the total incremental installed costs for evaluation purposes was \$13,866, or \$8.67/ft^2, including the ventilation mat at \$1/ft^2 (material and labor) and incremental labor at \$2/ft^2. The resultant added incremental annual mortgage, at 4% over 30 years, would be \$794. With an estimated annual energy cost savings of \$228, this would result in a negative annual cash flow of \$566, simple payback of 60 years, and a simple return on investment of 1.6%.

4.5 Feedback

The homeowners were very pleased with the results of the project. Home Innovation asked the homeowners for feedback using a series of questions regarding comfort, HVAC system operation, the construction process, and overall results. The questions and responses are presented as follows.

Questions:

- Did the house feel warmer this winter?
- Did the house feel less drafty this winter?
- Does the house seem quieter now?
- Does the house seem less humid/more humid/about the same?
- Did the heating system seem to operate less this winter?
- Was the thermostat setting this winter about the same as last winter?
- Were your utility bills less this winter?
- Did the work proceed as expected?
- Any construction related issues?
- Are you satisfied with the final appearance (architecturally)?

- Michigan: any ice damming this winter?
- Do you have any cooling season observations to share?
- Overall are you pleased with the results?
- Do you have any additional comments?

Michigan feedback summary:

The house feels warmer during the winter and far less drafty—the comfort factor has changed immensely; the house seems quieter now, the whole place feels tightened up; the furnace definitely ran less this winter, and the bills seemed lower; the house has settled, and the roof rafters were missed by the panel screws sometimes, from outside it can be hard to line up on thin rafters; the roof is thicker so we have a more prominent fascia, but it all looks great; no ice damming whatsoever, we had them literally every other winter however much snow had fallen, and one year it ripped off the gutters and crashed through our deck railings; we're definitely pleased, it's a pricey retrofit, but it feels like a no-brainer, our house was a particularly bad "before" case, however; all in all, seems totally worth it.

Georgia feedback summary:

The house definitely feels warmer during the winter; the house feels less drafty but marginally so as a result of the very leaky walls (same for questions regarding sound level and humidity); it was very noticeable how much less the heating system ran this winter, prior to the retrofit panel installation, during the coldest parts of the winter, the HVAC rarely shut off and barely maintained a comfortable temperature, now I would estimate the HVAC runs about half the time on the coldest days, and the thermostat setting was about the same; the utility bills are lower, but I have not summarized or analyzed those yet; the work proceeded as expected, although some miscellaneous materials were not on-site and the scope of work should have been better defined to expedite the work; satisfied with the final appearance and overall very pleased with the results; I hope in the future to upgrade the walls and floors and replace the HVAC with an optimal size and efficiency system; solar photovoltaics would be a final step in striving for net zero/positive; the entire team (Structural Insulated Panel Association, U.S. Department of Energy, Home Innovation, Insulspan, and PanelWrights) did a fine job.

5 Conclusions

5.1 Research Questions

What are the moisture control and air barrier considerations?

The unvented roof assemblies were designed to facilitate drying and sealed to minimize moisture migration due to air leakage. The data set collected for one winter and one summer indicates the retrofit designs (installed as designed at the Georgia demonstration house and as modified at the Michigan demonstration house) successfully controlled moisture levels at the retrofit panels and existing roof decks to well within acceptable limits (Section 4.2). The monitored data correlated well with the moisture levels predicted during analysis (Section 3.1). The project teams plan to monitor conditions at both houses for one additional winter and summer.

The house tightness test results and the moisture performance data indicated that the air sealing effort was successful at controlling air leakage paths into the roof assembly. The panels were sealed at the panel-to-panel edges at two places: (1) at the foaming channel along the middle of the EPS core (prerouted at the factory) using two-part expanding polyurethane foam (spray foam) and (2) at the OSB surface spline just below the OSB skin using spray foam or SIP sealant. The panels were sealed to the existing roof deck at the perimeter above the eave and gable walls using spray foam. The panels were also sealed at openings for plumbing vents and other roof penetrations before roof flashing was installed.

For the Georgia attic, average RH levels after installation closely tracked indoor house RH levels during the winter and spring but became high during the summer compared to the previous summer. As expected, attic temperature was much lower during the summer after installation; despite the higher attic RH, the attic DP was somewhat lower compared to the previous summer. Before installation, the attic RH levels had a large diurnal range of approximately 25%–85%; after installation, the range was a tighter 75%–85% RH with a higher average of approximately 80% RH. The indoor house RH was roughly the same before and after installation; the large swings and average more than 60% RH indicate oversized air-conditioning equipment and inconsistent air-conditioning operation. It is planned to install an HVAC supply vent in the attic to help control RH in the attic.

For the Michigan enclosed rafter assembly of the addition roof, RH and MC at the existing roof deck were normal and showed no signs of moisture accumulation, indicating the panel insulation level was sufficient to prevent condensation as intended.

To facilitate drying to the outdoors, a ventilation mat was installed between the shingles and underlayment at the Georgia house (like a rain-screen product on a wall). The vent mat was also expected to reduce shingle temperatures. A side-by-side comparison with and without the vent mat and for the same orientation would have been valuable but was not possible for this project. The vent mat was open at the bottom, sides, and top via the ridge vent, and the gap appeared to be maintained at full thickness (0.30 in.); for the second-story roof, the gap represented a vented air space of 4.3 ft^2 (based on eave and ridge areas but not including the open rake areas), for a ventilation area ration of 1:180 (vented air space area: ceiling area).

What are the appropriate insulation values of the retrofit panels?

Home Innovation conducted energy modeling during the design stage to predict energy performance and help determine the optimum insulation value of the retrofit panels within architectural constraints (Section 3.2). Based on the retrofit panels selected by the project teams for the final designs, the estimated heating/cooling energy savings were 20.8%/13.6% for Michigan and 13.8%/12.8% for Georgia (Section 3.2). Based on measured house tightness at test-out, the adjusted estimated savings were 22.9%/13.6% for Michigan and 11.3%/11.0% for Georgia.

Energy performance was measured using utility bills collected for periods before (one year) and after (six months) retrofits. The utility data were adjusted for seasonal use and normalized based on actual degree days. It is acknowledged that this was a simplified method to calculate energy savings compared to results from power metering; nonetheless, this method was considered a reasonable check to compare energy savings predicted by modeling. Based on the utility bill evaluation, the estimated heating/cooling energy savings was 40.4%/16.8% for Michigan and 15.8% heating and cooling for Georgia, all significantly better than predicted by modeling.

The project teams specified graphite-enhanced EPS for the rigid foam insulation core based on its relatively high permeance and insulation value (R-4.5/in. versus R-4.0/in. for standard EPS).

For Michigan, the enclosed rafter assembly of the addition was already insulated with R-30 fiberglass batts. The additional insulation value of the retrofit panels was not considered important here compared to the main house, and the priority was to install retrofit panels to improve airtightness. The team selected 5-in.-thick, R-21 retrofit panels because the minimum insulation value to avoid condensation at the existing roof deck was R-18 (R-20 prescriptively). The existing roof panels of the main house (2-in.-thick fiberboard panels, estimated R-5), on the other hand, called for as much insulation value as practical considering aesthetics and budget. The team selected 8-in.-thick, R-34 retrofit panels; 10-in.-thick, R-43 panels showed a relatively small increase in energy savings and were considered too thick aesthetically. Condensation at the existing roof deck resulting from the additional insulation was not a concern here based on the ratio of panel-to-existing insulation value.

For Georgia, the team selected 6-in.-thick, R-25 retrofit panels; these panels improved estimated energy savings by only an additional approximate 1% compared to 4-in., R-16 panels, but the homeowners thought energy costs were likely to rise, the appearance would work well for their house, and the improved savings were worth the low estimated incremental cost. Condensation at the existing roof deck resulting from the insulation value of the retrofit panel was not a concern in this climate.

What are the structural requirements?

The primary structural considerations to ensure the integrity of the roof assemblies were panel-to-panel connection, panel-to-existing roof connection, shingle attachment over the ventilation mat, and reinforcement of the existing roof.

The retrofit panels were interconnected at the panel-to-panel joints using OSB surface splines installed within grooves (prerouted at the factory) just below the OSB skin and nailed off through the OSB skin. The retrofit panels were attached to the existing roof using SIP screws, typically 12-in. on-center, with screw length to ensure a minimum penetration of 1 in. (for the main roof in Michigan, the screw length was selected to go through the 2-in.-thick structural fiberboard deck and at least 1 in. into the wood rafter).

Shingles were installed above the ventilation mat using a pneumatic nail gun. The crew found that an 80-psi discharge pressure setting at the air compressor was sufficient to install the roofing nails without punching the nails through the shingles (Section 4.1). During the observational research, a pressure setting of 100 psi was found to work well (Section 2.4). Nail length was selected to ensure penetration through the sheathing by at least 1/4-in. (3/4-in. into and through the 7/16-in.-thick OSB). Note: wind resistance performance information is not available for the shingle/ventilation mat assembly; this study did not include wind resistance testing.

For Georgia, the existing roof assembly was structurally reinforced. Collar ties were installed on rafters, and screws were installed through rafters into wall top plates to improve that connection. For Michigan, the existing roof assemblies were not structurally reinforced.

What are the architectural integration details?

The thickness of the retrofit panels was determined based on moisture analysis (Section 3.1), energy analysis (Section 3.2), and the specific architecture of each house (Section 2.3). The trim boards at the eaves and rakes were selected by the homeowners, with input from the contractors, to visually integrate the thickness of the panels with the existing structure (Section 4.1). Aesthetically, the installation of the ventilation mat did not detract from the final appearance (Section 2.4 and Section 4.1). The design details addressed the retrofit panel interface at eave/gable areas, intersecting walls, skylights, and other roof penetrations. The final design solutions (Section 3.4) were specific to each house, but the details would apply to many house designs—panel insulation value/thickness, and the eave insulation approach, would depend on climate and roof/attic type.

5.2 Key Findings

The results of this project show that an attic retrofit using nail-base insulated panels (retrofit panels) can be an energy efficient and durable solution for existing homes where traditional attic insulation approaches are not effective or feasible. Energy retrofit solutions were developed and demonstrated for two occupied houses: one in a cold climate (Michigan) and one in a hot-humid climate (Georgia). Key project findings include:

- Estimated heating/cooling energy savings were approximately 23% heating, 13% cooling for Michigan and 11% heating and cooling for Georgia; energy evaluation based on utility bills indicates actual savings might be considerably higher.
- Overall house tightness improved by 29% for Michigan and 12% for Georgia. For Georgia, the walls and floors were very leaky; if the house was a more typical 8.9 ACH50 at test-in (half of actual), the same effort would have provided a 24% improvement (the homeowner was notified of the opportunities to improve air sealing of walls and floors).
- Monitored data collected for one winter and one summer show that moisture conditions at retrofit panels and existing roof decks are well within acceptable limits. Wood MC at the retrofit panels in all cases remained less than 10% during the winter and 8% during the summer; MC at the existing roof decks remained less than 10% during the winter and 8% (Michigan) or 12% (Georgia) during the summer; each house had an outlier that dried to these levels.
- Average RH within the Georgia attic was higher during the summer after installation compared to the previous summer (although attic DP was somewhat lower after installation; indoor house RH was also higher than typical). It is planned to continue data collection for one additional winter and summer. It is also planned to install an HVAC supply vent to help control RH. The RH within the enclosed rafter assembly in the Michigan addition was well within normal limits.
- Structural reinforcement of the existing roof assembly was minimal for Georgia and not required for Michigan.
- Where shingles were installed over the ventilation mat, the shingles looked normal (not wavy), and the ventilation gap appeared to be maintained at full depth.
- Architectural integration of the retrofit panels was successful: feedback from the homeowners and project teams was very favorable regarding the final appearance of the houses.
- The incremental installed cost ranged from \$8–\$9/ft^2 roof area; simple payback ranged from 29–60 years, and return on investment ranged from 1.6%–3.5%. In addition to energy savings, the value of the demonstrated solutions includes significant improvement in comfort of the indoor environment, as reported by homeowners, and durability of the roof assembly.

- For Michigan, ice damming was a problem every winter before installation; but after installation, ice damming was eliminated.
- Based on anecdotal feedback from homeowners, comfort level was greatly improved at both houses, particularly in Michigan (summarized): the house feels warmer during the winter and far less drafty—the comfort factor has changed immensely; the house seems quieter now; we’re definitely pleased.

References

Boudreaux, P., S. Pallin, and R. Jackson. 2013. *Moisture Performance of Sealed Attics in the Mixed-Humid Climate*. Oak Ridge, TN: Oak Ridge National Laboratory. http://info.ornl.gov/sites/publications/files/Pub46670.pdf.

Dwyer, S., A. Harper, W. Lindau, T. Bosiljevac, K. Schindel, and E. Richards. 2011. *Structural Considerations for Solar Installers* (Technical Report SAND2011-9066). Albuquerque, NM: Sandia National Laboratories. http://prod.sandia.gov/techlib/access-control.cgi/2011/119066.pdf.

Home Innovation Research Labs. *Builder Practices Survey 2017*. Home Innovation Research Labs: Upper Marlboro, MD.

Lstiburek, J. 2013. "Duct Dynasty." Building Science Corporation: BSI-074, December 2013. https://buildingscience.com/documents/insights/bsi-074-duct-dynasty.

Parker, D. 2005. *Literature Review of the Impact and Need for Attic Ventilation in Florida Homes* (FSEC-CR-1496-05). Cocoa: FL. http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1496-05.pdf.

Puttagunta, S., and O. Faakye. 2015. *Interaction of Unvented Attics with Living Space in Three Northeast Homes*. Norwalk, CT: Steven Winter Associates, Inc. of the Consortium for Advanced Residential Buildings. http://www.nrel.gov/docs/fy15osti/63477.pdf.

Residential Energy Dynamics. 2017. *Weather Station Data Tool*. http://www.residentialenergydynamics.com/

Roberts, D., and J. Winkler. 2010. "Ducts in the Attic? What Were They Thinking?" Paper presented at ACEEE Summer Study, Pacific Grove, California, August 15–20, 2010.

Shapiro, C., A. Magee, and W. Zoeller. 2013. Reducing Thermal Losses and Gains with Buried and Encapsulated Ducts in Hot-Humid Climates (Technical Report DOE/GO-102013-3719). Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

Shelly, M. 2011. "Internal Wood Blocking for Roof-Mounted PV." *Solar Professional* 4.6. http://solarprofessional.com/articles/design-installation/internal-wood-blocking-for-roof-mounted-pv/page/0/1#.Wocsa2f-tVZ.

Straube, J., and A. Grin. 2010. *Building America Special Research Project: High-R Roofs Case Study Analysis* (Technical Report BA-1006). Westford, MA: Building Science Corporation. http://buildingscience.com/documents/bareports/ba-1006-ba-high-r-roofs-case-study-analysis/view.

U.S. Environmental Protection Agency. 2011. *Solar Photovoltaic Specification, Checklist, and Guide*. Washington, D.C. https://energy.gov/sites/prod/files/2013/11/f5/rerh_solar_electric_guide.pdf.

Uehno, K., and J.W. Lstiburek. 2015. *Field Testing Unvented Roofs with Asphalt Shingles in Cold and Hot-Humid Climates* (Technical Report BA-1409). Westford, MA: Building Science Corporation..

Weather Data Depot. 2018. http://weatherdatadepot.com/.

Appendix A: Testing and Monitoring Equipment

The testing and monitoring equipment used for this project is described in Table A-1.

Table A-1. Testing and Monitoring Equipment

Measurement	Equipment Needed; Range/Accuracy
Building airtightness Duct airtightness	Minneapolis Model 3 blower door system; 30–6,100 cfm (to measure building airtightness)
	Minneapolis Model B duct blaster system (to measure duct leakage)
	Minneapolis DG700 manometer; 0–1,250 Pa/greater of ±1% of reading or 2 Pa
Temperature, RH, and MC	Omnisense S-2-2 wireless sensors with probes (at roof shingle locations) and S-1-3.5 wireless sensors (at all other locations); T: -40 – 85°C/±0.4°C, 2°C max RH and MC: 0%–100%/ ±3.5%, ±5% max
	Omnisense G-3-C-VZW cellular gateway

Appendix B: Solar-Ready Considerations

This section provides recommended measures to consider during an attic energy retrofit using nail-base insulated panels (retrofit panels) if the homeowner plans to install a solar energy system on the roof in the future. Taking measures now, during the retrofit panel installation, will make the solar system installation easier and less expensive later.

The recommendations presented here are for informational purposes only, and they are not intended to address all aspects of installing a solar energy system. A complete solar energy system design would include the designated location, orientation, pitch, and area of the solar array; shading characteristics and solar energy potential; structural considerations; designated areas for the power inverter and wiring conduits; modifications to the electrical service panel; and flashing details. A valuable resource for additional information on solar energy systems is the *Solar Photovoltaic Specification, Checklist, and Guide* developed by the U.S. Environmental Protection Agency for the U.S. Department of Energy Zero Energy Ready Home Program (U.S. Environmental Protection Agency 2011).

Recommended measures for future installation of solar photovoltaic or solar thermal (hot water) systems:

- Identify the location of the solar array: the ideal orientation is south; the area (square feet) depends on the number of panels required for the desired power.
- If plumbing vents, chimneys, or other roof penetrations/equipment will interfere with the solar array, relocate these, as practical, before retrofit panels are installed.
- Install conduit for future electrical wiring (from the photovoltaic array to the inverter location) or piping (for solar thermal systems) through the roof and into the attic (at least) before installing retrofit panels.
- Before the retrofit panel installation, confirm that the new loads including the solar array do not exceed the load-bearing capacity of the roof structure. The contractor should document structural inspection results and design loads; a conventional photovoltaic system typically adds approximately 6 lbs/ft^2 of dead load.
- Solar arrays are commonly mounted on rails (or racks) supported by posts (or roof mounts). Each roof mount generally must be screwed to a roof truss or rafter (except for standing-seam metal roofs where mounting clamps can be attached to the seams, or except where direct attachment to sheathing is permitted). The longer screws required for the retrofit panel thickness might be difficult to align with framing. Internal wood blocking at trusses/rafters (between or attached, “sistered,” to trusses/rafters) might be optimal for some applications to securely attach lag screws or through-bolts (Shelly 2011; Dwyer et al. 2011); blocking could be installed during retrofit panel installation if an accurate solar array layout was available.

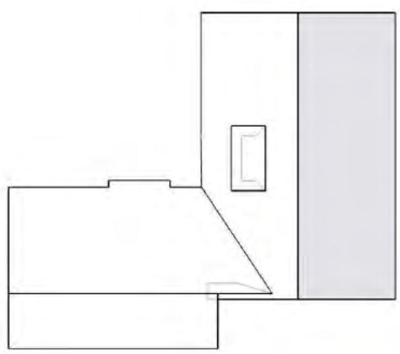
Appendix C: EagleView Reports

The project teams ordered roof reports from EagleView Technologies, Inc., that were generated using satellite technology. Portions of the reports are presented here.

EAGLEVIEW TECHNOLOGIES

Premium Report
March 30, 2016

Michigan:



In this 3D model, facets appear as semi-transparent to reveal overhangs.

TABLE OF CONTENTS

MEASUREMENTS

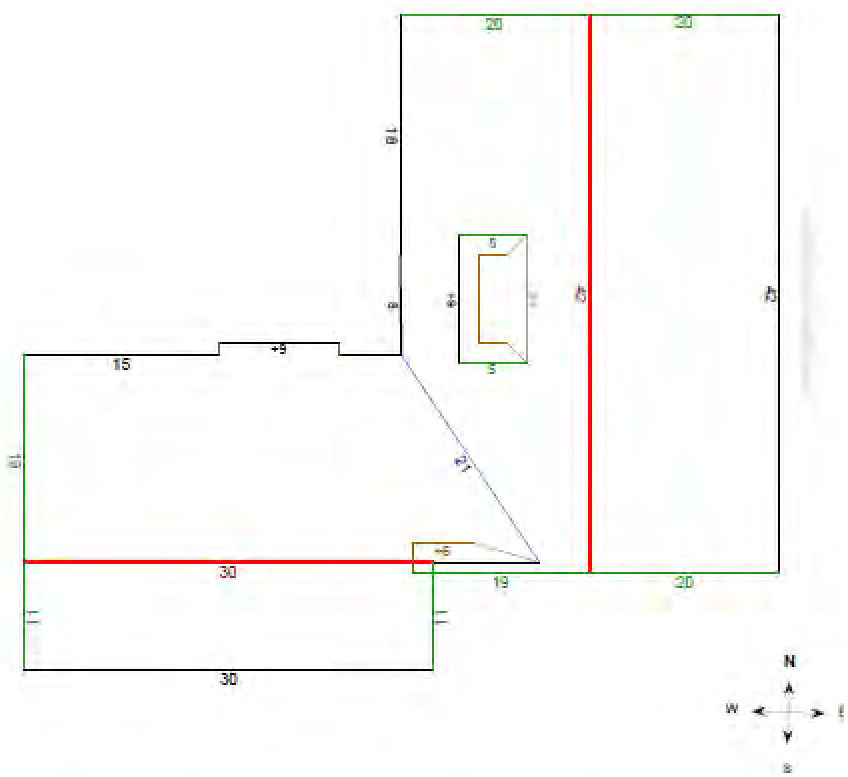
Total Roof Area =2,569 sq ft
Total Roof Facets =5
Predominant Pitch =12/12
Number of Stories >1
Total Ridges/Hips =73 ft
Total Valleys =22 ft
Total Rakes =133 ft
Total Eaves =144 ft

LENGTH DIAGRAM

Total Line Lengths:
Ridges = 73 ft
Hips = 0 ft

Valleys = 22 ft
Rakes = 133 ft
Eaves = 144 ft

Flashing = 9 ft
Step flashing = 25 ft
Parapets = 0 ft



Note: This diagram contains segment lengths (rounded to the nearest whole number) over 5 feet. In some cases, segment labels have been removed for readability. Plus signs preface some numbers to avoid confusion when rotated (e.g. +6 and +9).

North Side

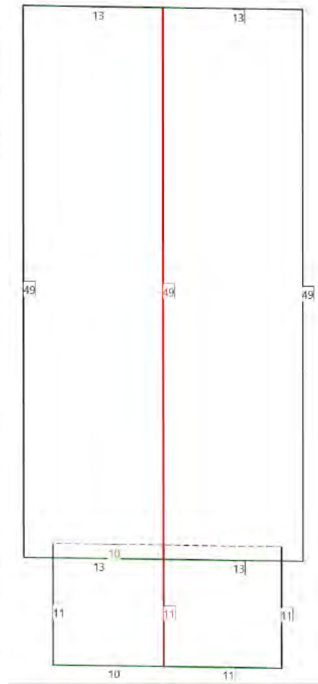
South Side

East Side

West Side

Georgia

Note: the roof report picked up the front porch roof but did not pick up the one-story shed roof in the back of the house because of tree coverage.



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