Balancing Act: Seeking Equilibrium Between Cost and Performance in Housing Affordability

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Sustainable building certification programs and energy modeling have transformed the way design professionals approach the design and construction of high-performance housing. While the impact of these tools has generally been positive, the value of implementation can be more difficult to assess when working in market sectors like affordable single-family[1] housing. In this context, where the cost-benefit question is always front and center, design teams need more detailed information to understand which elements of green certification standards have the greatest impacts with the least added construction costs and to advise their clients accordingly. Implementation requires responsible translation of modeled performance data into realistic expectations for actual operating cost, and common sustainability "best practices" must be reconsidered and recalibrated to variations in building scale and site context.

The research study profiled here has been designed to provide the perspective needed to find the balance point between front-end construction costs of improved performance and back-end performance consequences by studying the predicted and actual energy usage of homes built to specific beyond-code standards: Passive House Institute US (PHIUS) and Department of Energy's Zero Energy Ready Homes (ZERH). The study is built on a small, detached, single-family prototype home developed for the context of the mixed-humid climate of Alabama. By constructing two identical prototype homes on the same street, with similar orientation, but with differing energy-related assemblies and details, the authors can evaluate the initial cost of construction associated with achieving these two performance standards against the actual energy use in each home.

In addition to gaining insights on the costs and benefits of building to beyond-code energy standards, the study also seeks to illustrate the differences between model-predicted energy use and actual energy consumption with the goal of helping housing provider partners understand how to use modelling as a resource when evaluating alternative construction approaches.

THE PROJECT

This study is part of Front Porch Initiative, Auburn University Rural Studio's larger research initiative pursuing a holistic approach to housing affordability. Each project offers the opportunity to study issues of efficiency, resilience, wellness, and community building. In this particular project, a partnership with Auburn Opelika Habitat for Humanity (AOHFH) afforded a unique opportunity for a focused research project on energy performance. With a close proximity to Auburn University's main campus, the partnership with AOHFH allowed Front Porch Initiative to harness additional student and faculty assets.

The project consists of two homes constructed on the same street in Opelika, Alabama, approximately twenty minutes from campus. The home design chosen for this study was based on Buster's House,[2] a home prototype developed in a previous design-build studio. Auburn Opelika Habitat for Humanity felt that this two-bedroom, 900-square-foot prototype filled a gap in their offerings to eligible families. Furthermore, the home met the 800-square-foot minimum area required by local zoning regulations while also fitting within the setbacks of irregularly-shaped parcels in AOHFH's portfolio. This allowed AOHFH to leverage non-conforming lots that they had previously found challenging to build on while simultaneously providing more opportunities for homeownership to their clients.

Each home was the focus of a design-build studio taught in the architecture program at Auburn University. The first house, referred to as House 66, was designed and constructed in the

Figure 1. Completed houses. House 66, left. House 68, right. Image credit Matt Hall.

spring and summer semesters of 2018; the second house, House 68, in the spring and summer of 2019.[3]

The energy study process consists of four stages. First, for each house, the students, faculty, and energy consultants developed an energy model, working through multiple iterations of key details to optimize assemblies and ensure each design met the respective standard. The final chosen design was modeled in WUFI to ensure compliance with each performance standard. Second, blower door tests were conducted at critical milestones during construction, allowing for corrections to air sealing. Third, each home sought applicable third-party certifications.[4] And, finally, monitoring equipment was installed in each home at the completion of construction.

RESEARCH DESIGN

Frequently, housing "affordability" is addressed by simply reducing up-front construction costs. As such, one of the primary barriers to delivering high-performance homes in the affordable market is the additional up-front cost that these performance "upgrades" require. This research theorizes that targeted increases in construction costs can actually enhance affordability when they are considered as but a single variable in the total cost of homeownership. However, in order to eliminate any risk to Auburn Opelika Habitat for Humanity created by an increase in initial construction costs to meet the desired beyond-code performance outcomes, all "extra" costs to build the homes to beyond-code standards were covered through grants and contracts secured by Auburn University.

The primary research objective is to develop an understanding of how the energy performance of small, single-family detached homes could be optimized within an affordable cost-to-construct and cost-to-operate framework. To pursue this question, the faculty-led team elected to build the first home to the most rigorous certification standard: Passive House Institute U.S. (PHIUS). This initial choice to build to the highest performance standard first is a key element of the research design: this established optimized energy performance as the benchmark for the project and focused the assembly design, engineering, and construction efforts on finding the most affordable way to reach this performance expectation.

Insights gained from the construction of House 66 were subsequently brought to bear on House 68, which aimed to reduce the construction cost while holding closely to the performance standards set by House 66. House 68 was constructed to the Zero Energy Ready Home (ZERH) standard developed by the U.S. Department of Energy. The desired outcomes of the ZERH standards are similar to the more prescriptive PHIUS requirements but allow more flexibility in the approach to detailing construction systems due to its more descriptive nature. This is a key factor when considering construction approaches across markets and procurement strategies.

Construction costs were tracked and documented, and energy monitoring began once each home was occupied by the homeowner family. With the permission of the homeowners, the research team installed monitoring equipment in each home that provides detailed, circuit-level information on energy use as well as indoor temperature and humidity conditions throughout the house. Side-by-side monitoring of the two homes began in February of 2020 and will continue into 2022.

KEY ASSEMBLIES

Based on the experience of building House 66 to the PHIUS standard, three key construction assemblies were identified as critical opportunities in simplifying constructability and reducing construction cost to House 68 without creating a significant negative impact on building performance. These assemblies are illustrated comparatively in Figure 2.

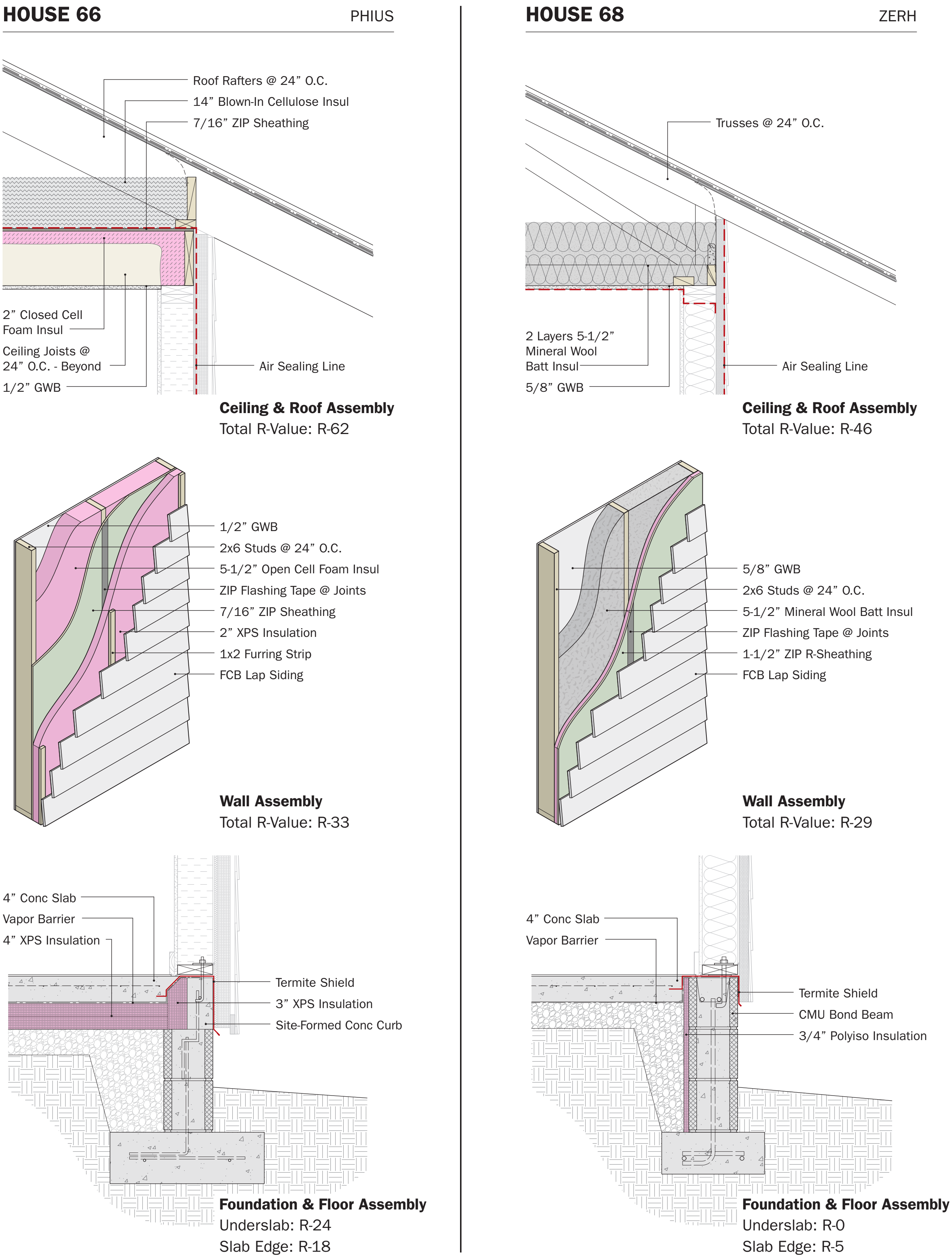


Figure 2. Comparison of Key Assemblies. Image credit Auburn University.

APPROACH TO UNDER-SLAB AND SLAB EDGE INSULATION / THERMAL BREAKS

PHIUS standards place significant emphasis on limiting energy transfer through the foundation. The amount of under-slab insulation (4” of extruded polystyrene) and the insulation required to isolate the slab edge from the foundation wall (2” of extruded polystyrene) on House 66 made for a time- and labor-intensive detail at the top of the foundation wall. The necessity of a physical termite barrier associated with the use of under-slab foam products in the “very heavy” termite infestation zone further complicated the assembly.

Given the relative mildness of Climate Zone 3 winters, it was hypothesized that under-slab insulation at House 68 could be eliminated, and the thickness of the slab edge insulation reduced (to ¾”of polyisocyanurate), while still maintaining a thermal break. The efficacy of slab edge and under-slab insulation in Climate Zone 3 is ambiguous, so this study sets up an opportunity to gather a clearer perspective on the actual performance of these two distinct strategies.

APPROACH TO WALL INSULATION, WINDOWS, AND EXTERIOR DOORS

House 66 utilized open cell spray foam in the 2x6 wall stud cavity. ZIP sheathing,[5] the primary air barrier, was coupled with 2” of extruded polystyrene (XPS) outboard of the sheathing. This provided the necessary thermal break while simultaneously achieving the R-value required to meet the PHIUS target. Vertical furring and fiber cement lap siding followed. While this approach ultimately created a well-sealed and well-insulated wall assembly, it did so via several complex steps. It required the installation of several additional layers of the assembly and special detailing around the window frames and door openings to accommodate the depth of the continuous insulation. In response to these concerns, House 68 utilized ZIP-R sheathing,[5] which allowed for the installation of the sheathing and thermal break in one step.

Special attention was paid to the fenestration at each home, as it tends to be the most expensive and poorest-performing element of the wall system. PHIUS certification is tied to using PHIUS-listed products, and sourcing PHIUS-listed windows is often challenging from a supply and budget perspective. House 66 incorporates PHIUS-listed, triple-glazed vinyl windows and upgraded exterior doors. When designing House 68, predictive energy modeling indicated that the ZERH goal could be achieved with locally-supplied, double-glazed windows at a much lower cost.

APPROACH TO AIR SEALING AND INSULATION AT THE CEILING PLANE

Concerns over meeting the rigorous PHIUS air sealing target on House 66 led to stick framing the ceiling joists and enclosing the ceiling with ZIP sheathing, followed by installation of a site-framed roof. This provided an air-tight lid on the house and a ceiling joist cavity to contain ductwork, plumbing lines, and light fixtures within the sealed envelope. The house was then insulated at the ceiling plane, with 2” of closed-cell foam on the underside of the sheathing and an additional 14” of blown-in cellulose in the ventilated attic. While this approach allowed for a very straightforward approach to air sealing, it also involved a significant amount of additional framing material and on-site labor.

House 68 shifted to a simpler approach utilizing prefabricated roof trusses. The gypsum board at the ceiling acts as the topside air barrier. It was determined this approach was more in keeping with a typical Habitat for Humanity build and provided the opportunity to explore the management of air leakage with this more straightforward approach. The gypsum board ceiling was installed first, prior to enclosing the walls. Next, the joint between the gypsum board and the top plate was sealed to ensure an airtight perimeter. All other penetrations through the ceiling plane, such as light fixtures, were carefully sealed as well. While this approach required less framing material and labor, the break in the gypsum board installation sequencing meant the installer had to make two trips, increasing cost on that element of the project.

RESULTS (TO DATE)

To generate comparable data for the study, the research team documented construction costs for key elements, sought third-party verification of performance via a HERS Index score, and installed circuit-level energy monitoring equipment in each home.

The left graph of Figure 3 illustrates how the changes to key assemblies translated to construction costs. As with all Habitat for Humanity projects, while some key work is subcontracted to licensed and/or skilled tradespersons, the majority of the on-site work is performed by volunteers (in this case, students, faculty, and community volunteers). Consequently, the project cost histories do not provide a complete picture of the labor costs. However, cost data presented here reflect the same approach regarding volunteer versus subcontracted labor on both homes. The costs tallied here are isolated to the elements of the building design that relate most directly to performance:[6]

- Active systems (ductless mini-split, ERV, water heater, etc.)
- GWB at perimeter of envelope
- Fenestration (windows and exterior doors)
- Insulation
- Framing
- Foundation

The cost difference between the two homes comes to about $10,600, with the largest increase incurred by the costs of the foundation system, insulation, windows, and exterior doors at House 66.

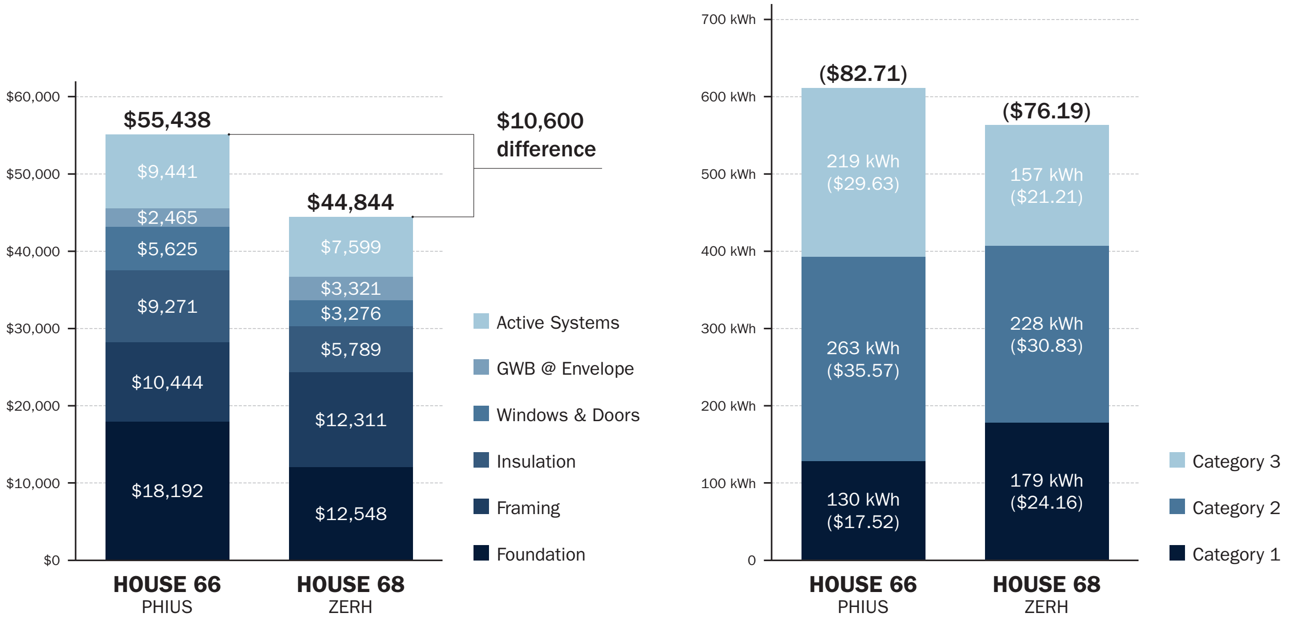


Figure 3. Comparative costs. Construction of key elements, left. Total average monthly energy use, right. Image credit Auburn University.

The research team measured the cumulative effect of the interventions by comparing air tightness and HERS scores. Upon completion of construction, a final blower door test confirmed air tightness results of 0.37 ACH50 at House 66 and 1.76 ACH50 at House 68.[7] A more comprehensive measure of performance, the HERS Index score considers assemblies, air tightness, and equipment efficiencies. House 66 achieved a final HERS score of 38, while House 68 achieved a final score of 40.

The research team is now collecting ongoing energy consumption data in each home to determine how alternative approaches to the key assemblies translate into energy use. Side-by-side monitoring began in February 2020, yielding 23 months of comparative data as of the publication date for this paper.[8] To compare the energy use of the two homes more closely, with different families as occupants, the modeled and monitored data is grouped into three categories:

- **Category 1**: This category of energy use relates most directly to the envelope-driven elements of the house. It includes the energy consumed to heat and cool the home and operate the active ventilation system and the dehumidifier. Additionally, interior temperature and humidity are monitored to understand differences in the interior conditions tied to the associated energy use in this category.
- **Category 2**: This category of energy use includes lighting, large appliances, and water heating. These costs are impacted by the efficiency of the equipment specified but are also impacted by variable occupancy patterns and appliance use.
- **Category 3**: This category of energy use includes all the user-connected appliances and fixtures. These “plug loads” are predominately occupant-driven. While they can have a significant impact on the total percentage of overall energy consumed—particularly in a high-efficiency house—they have little relation to the way the home was designed or constructed.

Regarding the questions of how the cost-reduction strategies impact operating costs, and how this relates to affordability, the data collected thus far is beginning to provide some answers. The right graph of Figure 3 illustrates how the average operational costs of the three categories of energy use add up for each home.[9]

The costs to heat and cool both homes (Category 1 energy use) is less than $25 per month ($300/year), compared to just over $67 per month ($804/year) for an average home in Alabama.[10] That energy cost savings of $42 per month can offset approximately $10,080 in up-front investments in performance. Establishing such an ambitious goal for operating cost savings is critical to our goal of redefining “affordability” as inclusive of the total cost of homeownership.

Savings due to energy efficiency are most often calculated as an annual cost reduction. However, as most homeowners develop and manage their household budget on a monthly basis, it can be more useful to consider monthly energy savings instead. By transferring monthly energy savings from an expense to an investment—represented by the mortgage payment in the homeowner’s monthly budget — a straightforward cost/benefit analysis can now be considered. For example, in a traditional 30-year fixed-rate mortgage, every dollar of monthly mortgage payment finances roughly $200 of construction. Therefore, if a homeowner reduces their energy expenses by $25 per month, they can then invest that same $25 in their mortgage payment, affording an additional $5,000 in energy efficient construction with no increase in their total monthly outlay. AOHFH typically utilizes a 20-year zero-percent interest loan; consequently, every dollar added to the mortgage payment finances $240 of construction. Additionally, such upgrades can increase the appraised value of the home, better protecting the investment of both lender and homeowner.

The $10,600 cost premium on key elements to achieve PHIUS for House 66 (versus ZERH for House 68) translates to about $44 per month more in mortgage costs under AOHFH's model. As illustrated in Figure 3, based on data collected to date, the envelope and systems upgrades on House 66 do not result in a net savings per month on Category 1 energy costs. Even though House 66 returns a savings in the colder months, the alterations to the key details on House 68 appear to translate to an effective approach to balancing ambitious performance and affordable construction costs.

The top graph on Figure 4 shows how the energy use for heating, cooling, and active ventilation systems tracks over the 23 months of side-by-side use data collected so far.[11] A few unexpected variables have impacted overall energy use, such as the stay-at-home order associated with the COVID-19 pandemic and a faulty dehumidifier at House 68.[12] The lower graph on Figure 4 compares energy consumption of dehumidifier alone between House 66 and House 68. After dehumidifier data was removed from Category 1, actual HVAC energy use reconverged with the modeled predictions.

An unanticipated finding of the modeled-versus-actual-use comparison was that of its use as a tool for monitoring systems maintenance needs. A faulty humidistat on the dehumidifier at House 68 malfunctioned in May 2020 and again in June 2021, causing a spike in energy use, as illustrated in the lower graph on Figure 4. Upon noticing that the dehumidifier in House 68 was consuming ten times more energy than the corresponding equipment in House 66, the research team determined that the

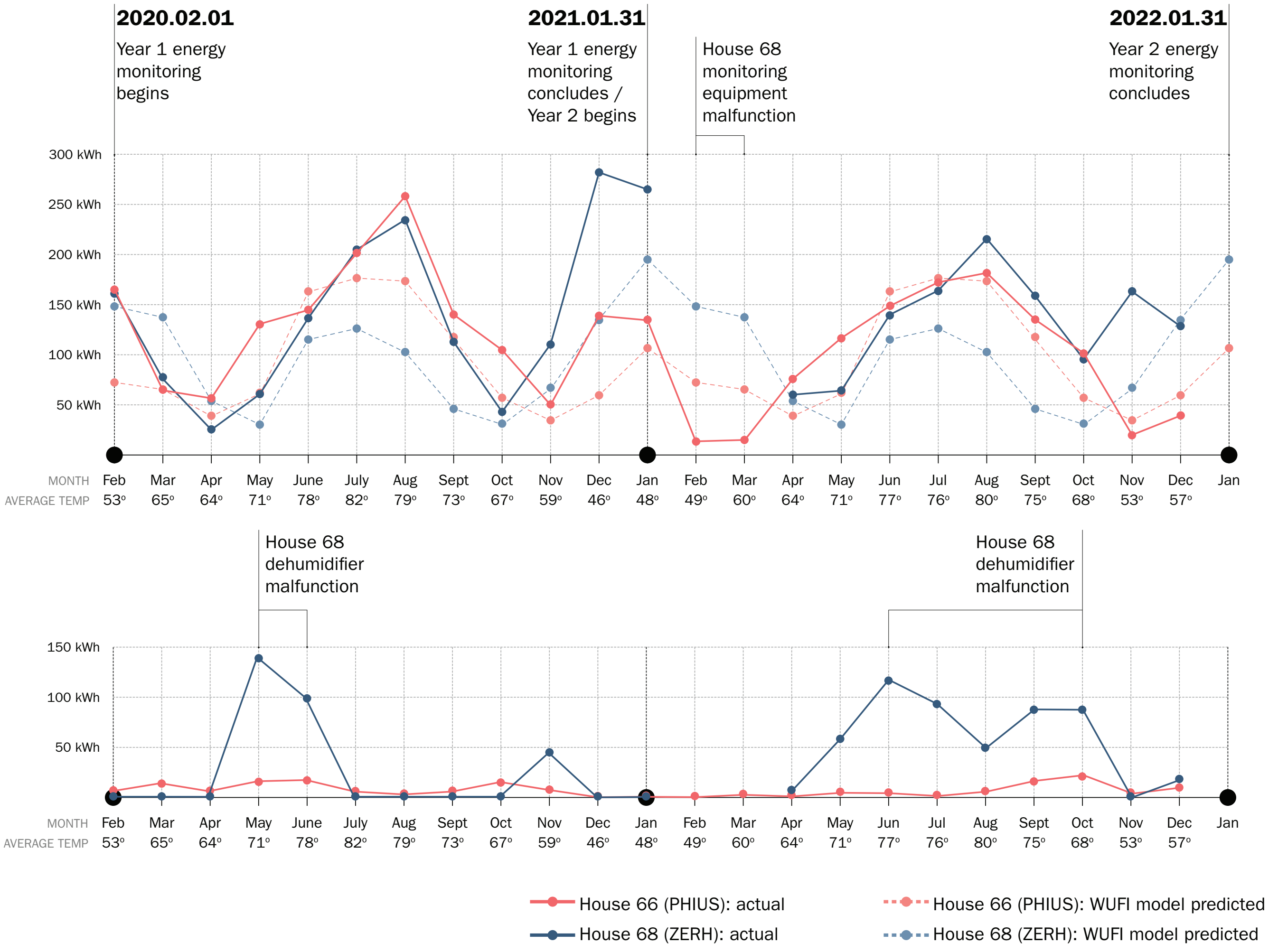
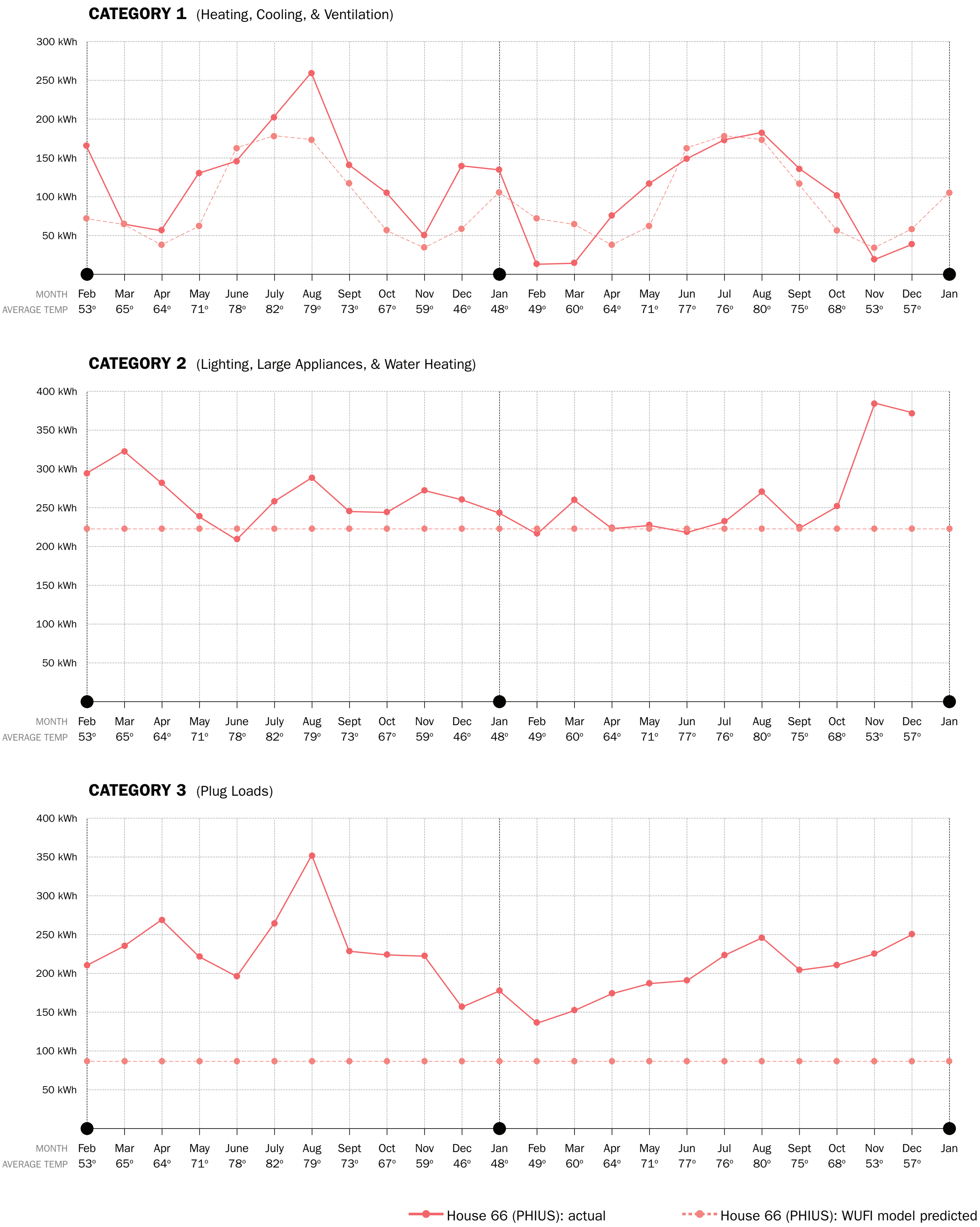


Figure 4. Comparison of modeled and actual HVAC energy use, top. Comparison of actual dehumidifier energy use, bottom. Image credit Auburn University.


CATEGORY 1 (Heating, Cooling, & Ventilation)

CATEGORY 2 (Lighting, Large Appliances, & Water Heating)

CATEGORY 3 (Plug Loads)

Figure 5. Comparison of modeled and actual energy use in Categories 1,2, and 3 at House 66. Image credit Auburn University.

humidistat had malfunctioned and repaired it. Were it not for the energy monitoring, the malfunctioning equipment would likely have gone unnoticed and unrepaired.

Regarding the comparison of model-predicted energy use to actual use, the data for House 66 illustrates that the actual energy consumption for heating and cooling (Category 1) is generally tracking closely with the modeled energy use, as illustrated in Figure 5. The average deviation between predicted and actual use is 20.7 kWh per month (22% higher). Category 2 (lighting, appliances, and water heating) also shows moderate deviation between actual and predicted costs. However, the actual energy consumption for Category 3, which consists of occupant-driven plug loads, greatly exceeds the modeled projections (149% higher). While the design and construction of the building envelope has minimal effect on Category 3 energy use, this category becomes increasingly crucial to address as energy consumption is minimized in Categories 1 and 2.

NEXT STEPS

The research team will continue to monitor energy use on the two homes through the summer of 2022.[13] The team has begun monitoring energy use in a third AOHFH home—based on the affiliate's standard design and built to meet the locally-adopted energy code (2015 IECC)—to provide a baseline for comparison to the energy use in House 66 and House 68.

Additionally, the research team is conducting focused investigations into the performance of specific elements of the key assemblies identified above. The first of these investigations includes an analysis of the different under-slab and slab-edge insulation approaches in House 66 and House 68. The team is collecting temperature data at key points in the wall and slab edges with the goal of understanding heat flows across the wall and floor assemblies. Sensors mounted at the midpoint of wall and on the floor nearest the exterior wall register indoor surface temperatures, while infrared camera readings provide surface temperatures at the exterior. From the difference between the two temperatures, one can infer the assembly's resistance to heat transfer. These types of investigations into specific aspects of the building envelope supplement areas where even a detailed energy model provides limited information as to the efficacy of alternative construction scenarios.

Concrete, field-validated evidence of the operating cost benefits associated with up-front investments in energy performance—and the costs of implementing them—is critical to both Auburn University's efforts to refine and advance the research and outreach to assist not-for-profit housing providers and advocates. The findings from this study will be folded into future cycles of design/build/evaluate work by faculty and students in the context of the design/build studio, incrementally advancing a comprehensive understanding of how to improve building performance affordably. The perspective and knowledge gained from this work will also inform the advice and technical assistance provided by the Front Porch Initiative; enhancing evidence of the opportunities of embracing a definition of "affordable" inclusive of the total cost of homeownership.

ENDNOTES

1. While the research team acknowledges that higher-density housing is inherently less resource-intensive and more sustainable and affordable, single-family structures are the predominant form of housing utilized by the not-for-profit housing advocates active in the rural and suburban areas of the Southeastern U.S.
2. Buster's House was designed and built by a team of Auburn University 5th-year architecture students at Rural Studio in 2017. The student design team for Buster's House included Olivia Backer, Carley Chastain, Ben Malaier, and Janine Mwenja. The Buster's House prototype is based on this design.
3. The student team for House 66 included: Spring Studio- Lauren Ballard, Meghan Bernhardt, Fox Carlson, Emma Clark, Katherine Ferguson, Jed Grant, Haley Hendrick, Jeff Jeong, Mary Ma, Kate Mazade, Ashley Mims, Walker Reeves, Rowland Sauls, Jordan Staples, and Matthew Wigard. Summer Seminar- Heath Barton, Emma Clark, Noah Dobosh, Melissa Ensley, John Going, Mason Handey, Dee Katoch, Mack Mahoney, Ashley Wiley, Joshua Williams, and Valencia Wilson.

   The student team for House 68 included: Spring Studio – Clare Bruce, Justin David, Ozzy Delatorre, Adam Fehr, Jonathan Grace, Emily Hiester, Dongting Huan, Reeed Klimoski, Mingtao Liu, and Emma Porter. Summer Seminar – Erik Aguilar, Carol Allison, Craig Baker, Elizabeth Bowman, Caty Bowman, Zack Burrogh, McClean Gonzalez, Davis Johnson, Emme Mora, Karmon Sullivan, and Nieman Ugbesia.

   The faculty team for House 66 & 68 included Professors David Hinson and Mackenzie Stagg (Architecture) and Professor Mike Hosey (Building Science). The consultant team included David Bitter, CPHC; Bruce Kitchell, PHIUS+ Rater; and Alexander Bell, energy modeler. The team also recieved generous assistance from Mark Grantham, Executive Director of Auburn Opelika Habitat for Humanity; Jaqueline Dixon, Contractor of Record; Rob Howard of Mitsubishi Electric Heating & Cooling; Alex Cary and Warner Chang from the Institute of Business and Home Safety (IBHS); and Eric Oas of Oasis Heating and Air.
4. House 66 was the first building to achieve PHIUS certification in Alabama (2020). House 68 was designed and constructed to the standards of the Zero Ready Home program but was not certified due to a problem with third-party verification of the slab edge insulation.
5. ZIP sheathing is a structural wall sheathing with integral water-resistive barrier. When panel joints are taped, the system serves as an air barrier. ZIP-R laminates a layer of rigid polyisocyanurate to the interior face, providing continuous insulation outboard of the studs.
6. Costs of project components that do not translate to differences in performance, such as those associated with sitework, landscaping, interior millwork, etc., are excluded from this analysis.
7. By comparison, the maximum air leakage allowed by PHUS is 0.6 ACH50. The maximum air leakage allowed by 2021 International Energy Conservation Code (2021 IECC) for Climate Zone 3 is 3 ACH50.
8. A Site Sage system installed in each home provides energy consumption data on each circuit within the home. Circuits were organized to align with the major categories of the WUFI model: heating & cooling, auxiliary fans, the ERV system, major appliances, lighting, and miscellaneous loads.

   Side-by-side monitoring began in February of 2020 and will continue into 2022. The data reported here reflects results through December 2021.
9. The local electric service provider charges $0.135 per kWh.
10. Source for this figure is the U.S. Energy Information Administration report on "2018 Average Monthly Bill – Residential" https://www.eia.gov/electricity/sales_revenue_price/pdf/table5_a.pdf?kbid=118190 . This report identifies the average monthly energy use for a home in Alabama as 1,201 kWh. At $0.135/kWh for the local electric provider, this equates to $162/month and $1,945/year. The USEIA estimates that 41.5% of energy use in U.S. homes is associated with heating and cooling.
11. Figure 4 shows a gap in data for House 68 where the monitoring equipment malfunctioned and did not upload, resulting in a loss of data. This time period has been removed from the average energy use data for both houses as shown in Figure 3.
12. The COVID shutdown meant that both homes were occupied nearly 24 hours/day April-July, impacting all categories of energy use. The humidistat on the dehumidifier in House 68 malfunctioned in May and June of 2020, and again beginning in June 2021 through October 2021, resulting in errant data for this piece of equipment.
13. Data collection is facilitated by Elizabeth Farrell Garcia, Assistant Research Professor, and Anthony Spafford, graduate research assistant.