

Advanced Energy-Efficient and Fire-Resistive Envelope Systems Utilizing Vacuum Insulation for Manufactured Homes

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ABSTRACT

The goal of this project is to design, develop, and demonstrate three prototype manufactured homes with dramatically improved energy performance and fire resistance by implementing high-performance envelope and heating, ventilation and air conditioning (HVAC) technologies. Manufactured homes, that are built according to the United States Department of Housing and Urban Development (HUD) specification, currently lag behind site-built homes in energy efficiency.

In this project, the prototype manufactured homes will contain envelope technologies that will integrate vacuum insulation panels (VIPs) and state-of-the-art air sealing methods. VIPs offer thermal resistance that is 6-10x of common building insulation materials for a given thickness. Thus, VIP-based envelopes can achieve high energy efficiency levels within a relatively small thickness and increase the usable space in dimensionally-constrained manufactured homes. Further, VIPs possess excellent fire resistance properties. Improved fire resistance is a critical need for manufactured homes located in wildfire-prone regions.

This article describes the current state of the project and progress made so far in the design of the manufactured homes, development of a measurement and verification (M&V) plan for the prototype manufactured homes, performance evaluation of VIP-based envelope assemblies and initial EnergyPlus modeling of the prototype homes for estimates of energy savings. Calibrated EnergyPlus modeling will be utilized to evaluate the cost-effectiveness of the different energy efficiency measures proposed to be implemented in this project. Furthermore, the estimated energy savings will be extrapolated to demonstrate the potential for emission reductions with broad adoption.

Introduction

This project was funded under the California Energy Commission's (CEC's) Grant Funding Opportunity GFO-19-307 for single family manufactured homes (GFO-19-307 2020). The goal is to develop prototype manufactured homes with dramatically improved energy performance and fire resistance by implementing energy-efficient envelopes and HVAC technologies with advanced manufacturing methods, while charting a path to cost-effectiveness. Cost-effectiveness will be evaluated by modeling progressively higher efficiency measures and comparing the increased implementation costs with reduced energy bills. The project supports California's goals of applying advanced window and building envelope systems in manufactured homes to reduce HVAC energy use and decarbonization of the building sector.

The specific purpose is to demonstrate single family, all-electric manufactured homes that can meet the California Code of Regulations Title 24 2019 residential building energy

efficiency standards (CEC 2019) and transform manufactured home construction practices. This project will use VIPs and state-of-the-art air sealing technologies to meet the stated envelope targets of GFO-19-307, i.e. wall R-value of 26-29 hr-ft²-°F/Btu or R26-29, roof R-value of R49, and air change rate of ≤ 1 ACH50 (air changes per hour at 50 Pa pressure differential).

In comparison, HUD-compliant manufactured homes typically have R11 wall insulation and R19 in the ceiling, with an envelope air tightness in the range of 7-9 ACH50. California lies in HUD climate Zone 2, requiring an overall heat transfer coefficient (U) of 0.096 Btu/h-ft²-°F. Above-code ENERGY STAR certified manufactured homes have a requirement of an overall envelope U-factor of ≤0.08 Btu/h-ft²-°F or equivalently, R11 for walls and R33 for the roof.

Figure 1 shows a VIP and a visual comparison of the nominal thermal performance of a VIP with regular insulation materials. This project will develop VIP-based envelope systems to achieve R26+ and R49 for walls and roofs, respectively. VIPs can deliver 6-10X the R-value per inch relative to current rigid foam insulation materials widely used in buildings.

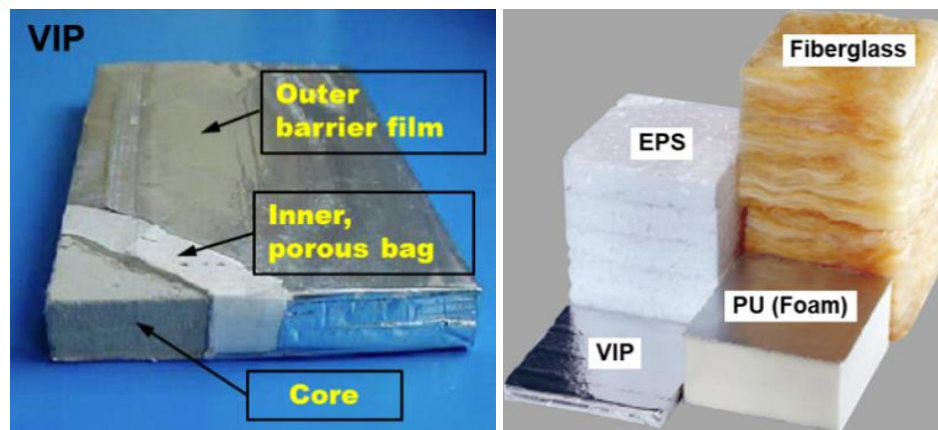


Figure 1. Vacuum insulation panel and comparison with regular insulation of equivalent thermal resistance. Sources: ECBCS 2005, ECBCS/IEA Annex 39, Vacuum Insulation Panels (Subtask A); <http://anjestroy.com/services/arenda>.

VIPs contain a nano or microporous core material that is formed to the desired shape, evacuated to very low pressures (0.1-10 mbar) and sealed inside barrier film bags; see **Error! Reference source not found.** The evacuation of the core provides the ultra-low thermal conductivity (or very high R/inch). VIPs made of fumed silica and fiberglass, two most commonly used core materials, have been reported to achieve nominal thermal conductivities of 0.0024-0.005 W/mK (Kalnæs and Jelle 2014). These conductivities translate to R29-60/inch. Full-scale foam-VIP composites have been developed in a factory environment and experimentally verified to achieve about R13/inch (Biswas et al. 2018). Recent advances in materials and manufacturing technologies have reduced the cost of VIPs. The projected cost at mass production is in the same range as foam insulations (especially on a \$/ft²/R-value basis). The building envelope systems in this project will incorporate VIPs and will also use advanced air sealing technologies like fluid applied air and water resistive barriers. This improves the air tightness and moisture durability of manufactured homes and reduces the air infiltration to about 1 ACH50, providing greater control of indoor comfort and air quality.

In addition to their excellent insulative properties, VIPs are highly fire-resistant. A recent study on fire resistance of multi-layered drywall systems showed the ability of fumed silica VIPs to significantly delay the penetration of heat through the test walls when compared to the other

insulation configurations (Kontogeorgos et al. 2016). The test results showed VIPs could delay time-to-failure by 68% compared to a baseline wall. In comparison, foam and mineral wool insulation delayed the time-to-failure by only 2-19%. Improved fire resistance is a critical need for manufactured homes located in wildfire prone regions such as California.

Beyond the planned envelope upgrades, manufacturing partner Dvele implements high-efficiency equipment and energy recovery ventilators in their homes. The equipment include air source heat pumps, heat pump water heater or high-efficiency resistance heaters, induction cooktop and all-electric appliances.

Scope of Work

The following technical tasks are planned within this project:

1. Design Specifications of Prototype Manufactured Homes: The goal of this task is to develop the designs of three prototype manufactured homes for field demonstrations. The designs will include specifications of the envelope upgrades, including VIPs and air-tightness measures, needed to meet the energy usage targets.
2. Fabrication And Testing of Envelope Prototypes: This task will develop and evaluate the VIP-based envelope prototypes following typical standard test methods combined with numerical modeling, and to verify resistance rating of prototype envelope systems. In addition, fire resistance rating tests following ASTM E119 (ASTM 2021) will be done to verify 2-hour fire ratings of the envelope assemblies.
3. Development And Demonstration of Prototype Manufactured Homes: The goals of this task are to fabricate at least three manufactured homes with advanced envelope features, install the manufactured homes for field testing, perform measurement and verification (M&V) of the upgraded manufactured homes, and estimate and verify the energy savings of the improved homes using simulations and field test data.

Additional tasks will evaluate the potential energy and emission-related benefits if the proposed technology were to reach broad adoption. The team will create a plan to determine the steps that will lead to the manufacturing of technologies developed in the project or to the commercialization of the projects results. Finally, the project team will make the knowledge gained from this project available to the public and key decision makers and share lessons learned and experimental results.

Manufactured Homes Design and Construction

The following two model home designs are under consideration for the prototype homes:

1. Angora: A 750 ft² HUD style manufactured home as shown in Figure 2
2. Roberts: An 800 ft² manufactured home as shown in Figure 3.

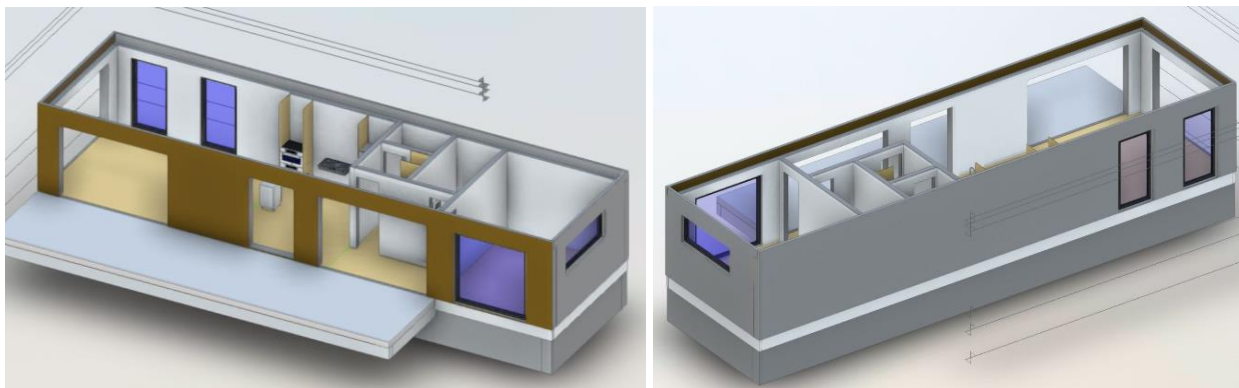


Figure 2. Angora model

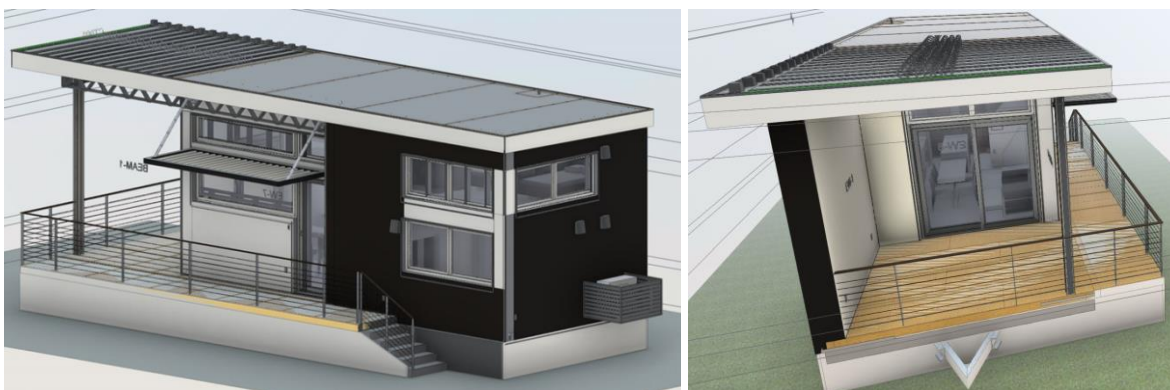


Figure 3. Roberts model

In addition to the high-efficiency envelope and HVAC equipment being considered, the manufacturing partner Dvele is incorporating several upgrades to their factory to improve production efficiency and reduce construction costs. These upgrades are partly funded by the Department of Energy under a project titled “Transformative Efficiency and Automation in Modular Homes” (TEAMH 2020). As part of these upgrades, Dvele has commissioned multiple truss and panel machines that can prepare the light gauge steel (LGS) members for construction in automated manner. These truss and panel machines can produce LGS structural members in required numbers with the exact dimensions and ready for assembly, including holes drilled/punched for assembly. Figures 4-6 show the LGS machines and sample assemblies created using the LGS structural members



Figure 4. LGS machines.



Figure 5. Top: Feedstock for an LGS machine. Bottom: LGS machines creating structural members with different cross-sections.



Figure 6. Truss and wall assemblies created using the LGS structural members prepared with the LGS machines.

Measurement & Verification Plan

The objectives of the M&V tests are geared towards measuring the actual energy performance of manufactured homes that will be developed with VIPs as part of the building envelope in order to provide confidence in the EnergyPlus model results. The EnergyPlus models are intended to be used for developing energy savings and cost effectiveness estimates. The M&V test results will also help determine whether the VIP envelopes achieve the desired wall and roof R-value targets. The tests will be performed in two phases, involving tests under unoccupied conditions (Phase I) and actual/simulated occupancy conditions (Phase II). For the long term monitoring, at least one home each will have simulated occupancy and real occupancy.

The three VIP homes will be tested, in addition to one base case test of a standard Dvele home (Phase I testing only) that will be funded by the National Renewable Energy Laboratory. The specific measurement objectives include:

1. Phase I: Short term testing
 - a. Determination of leakage in the building envelope through the performance of a Blower Door Test
 - b. Determination of leakage from ducts through the performance of a Duct Blaster Test
 - c. Measurement of heating loads as a function of weather conditions through performance of short-term co-heating Tests
 - d. Disaggregation of the effective heat loss coefficient (HLC) of VIP-enhanced wall and roof assemblies from other components of envelope thermal conductance, air infiltration, solar gains, and energy storage through a combination of test and analytical methods.
2. Phase II: Long term monitoring
 - a. Total annual electricity use.
 - b. Indoor and outdoor heat pump unit electricity use
 - c. Interior temperature, relative humidity (RH) and heat flux through envelope components
 - d. Outdoor temperature, RH, and wind speed and direction
 - e. Energy and cost savings for the VIP upgrades through calibrated modeling

The duct blaster test, blower door test and the co-heating tests will comply with relevant ASTM standards. If possible, the Phase I tests will be conducted over a two-week period when weather conditions are cool, stable and thermal mass effects can be minimized. Specific short-term test duration requirements will be established as part of the baseline test activities funded by NREL. The Phase II tests will be conducted over the course of 9-12 months at the different manufactured home sites.

Figure 7 shows an example layout of sensors and heaters in a 2-story model home for the short term tests. In this example, the red circles are the space heaters, with an orange circle for the space heater in any upstairs space. The blue triangles represent the angular range of the space heaters. The green circles represent the locations of the thermocouples. Long term monitoring will use much of the same equipment as the co-heat test monitoring, with the addition of a smart thermostat, sensors for HVAC operation and monitoring and measurement of total electricity use. The HVAC system operation will be programmed to run using typical set points in the simulated occupancy homes. Additional simulated occupancy details are in development, for example, adding humidifiers to simulate occupant loads.

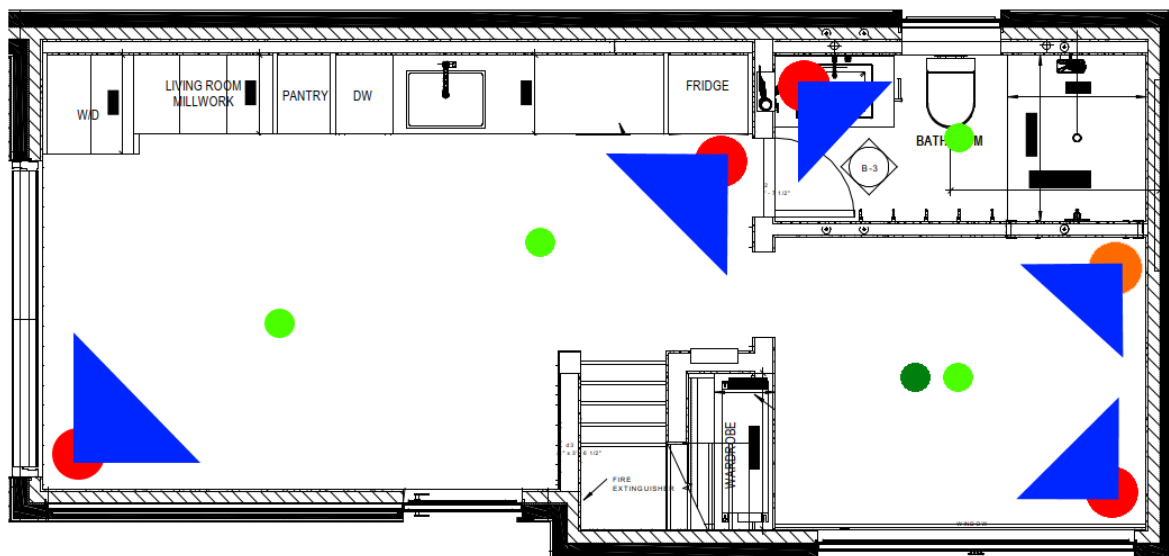


Figure 7. Example thermocouple and space heater layout in a model home of about 800 ft² of conditioned space.

Performance Evaluation of VIP Assemblies

In this project, VIPs with fumed silica core are being used. In addition to the field M&V, laboratory evaluations of VIP assemblies are being performed to assist in the final design of the envelope systems to meet the desired R-value targets. First, the VIPs will be tested in heat flow meters (HFM) following the ASTM C518 test method (ASTM C518 2012). The HFM tests are being performed to test the center-of-panel thermal conductivity and R-value of the VIPs. The first set of VIPs of dimensions 600 mm x 600 mm x 25 mm were measured to have a nominal conductivity of 0.0045 W/m-K, which translate to R32/inch.

In addition, assemblies of about 4 x 4 sq. ft. will be tested in Lawrence Berkeley National Laboratory's Infrared Thermography Laboratory (IRLab). In the IRLab, quantitative IR

thermography is used to measure the surface temperature distribution and local heat transfer through building envelope systems using small heat flux sensors, which can be used to validate computer modeling, and thus derive the overall conductance or U-value of the test specimen.

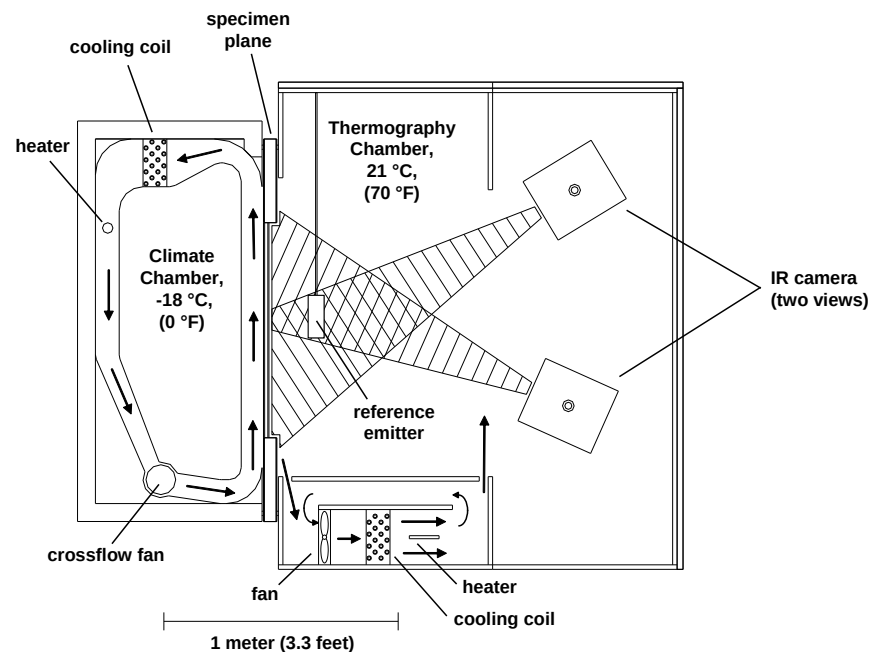


Figure 8. Top: IR thermography schematic setup. Bottom: IRLab quantitative thermographic apparatus, with a window test specimen.

Figure 8 shows the IR Thermography apparatus. The apparatus consists of a cold box capable of achieving a standard outdoor temperature of -18°C (0°F) and lower. The cold box also contains a fan, capable of achieving a standard convective heat transfer coefficient of $30 \text{ W/m}^2\text{K}$. The warm side of the apparatus has a small fan that provides uniform airflow over the specimen, simulating natural convection. Walls of the warm side are insulated and are located in a

controlled laboratory environment, providing uniform background temperature. High quality IR camera and calibration system enables the measurement of surface temperatures within 0.5°C (1°F) absolute accuracy. These temperature fields are used to validate computer models and allow the back-calculation of thermal resistance in a standard controlled environment. In addition to temperature fields, the IR thermography apparatus can be used to directly measure U and R values through the use of surface heat flux meters.

Figure 9 shows a schematic of an approximately 4 x 4 sq. ft. VIP test assembly that will be tested in the IRLab. The assembly contains four VIPs separated by furring strips and heat flux sensors for local heat flux measurements. Furring strips will be used to support the installation of the VIPs on the exterior sheathing of the actual manufactured homes and allow locations for mechanical fasteners for the outer-most siding, similar to Chan et al. (2019).

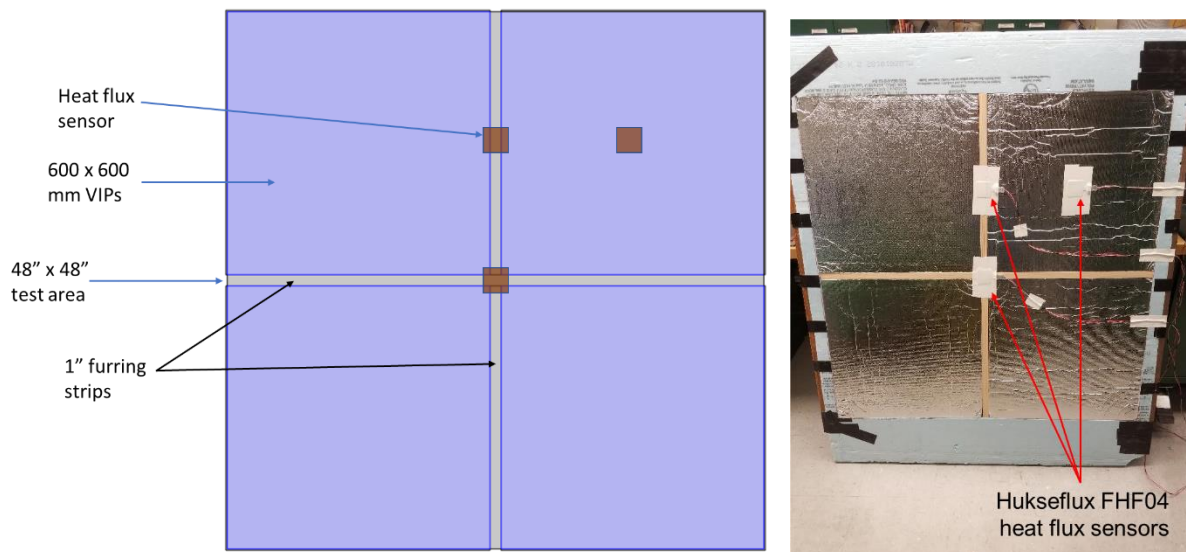


Figure 9. VIP assembly for testing in the IRLab.

The results of the HFM and IRLab tests will be used to develop and calibrate THERM and COMSOL models of VIP systems to estimate the overall R-value of final design of the manufactured homes' exterior building envelopes.

Initial EnergyPlus Models and Results

Initial models of the Angora model home have been created. The model assumes that the exterior walls are constructed with 3.5 inch LGS and the roofs are constructed with 12 inch LGS members. The exterior wall cavities contain R15 rockwool insulation and the roof cavities contain dense-packed cellulose insulation (R3.75/inch). The envelope air leakage was assumed to be 3 ACH50 for the baseline model which is an upgrade over HUD-compliant homes. A first set of parametric simulations was performed by adding R10-R25 in exterior continuous insulation (CI) to the walls and R15-R30 exterior CI to the roofs. The intent was to evaluate the impact of increasing wall and roof R-values on the heating and cooling loads, and at what level of exterior insulation the savings would start diminishing. Simulations were performed for climate zones represented by Los Angeles, CA and South Lake Tahoe, CA, which fall under ASHRAE climate zones 3 and 6, respectively.

Figure 10 shows an E+ rendering of the Angora model home. Figures 11 and 12 show the calculated cooling and heating loads as functions of the overall roof and wall R-values in South Lake Tahoe and Los Angeles, respectively. Based on these initial simulations, the cooling and heating loads were more sensitive to the changes in the wall R-values compared to the roof R-values. These simulations will be updated to capture the characteristics of the as-built homes.

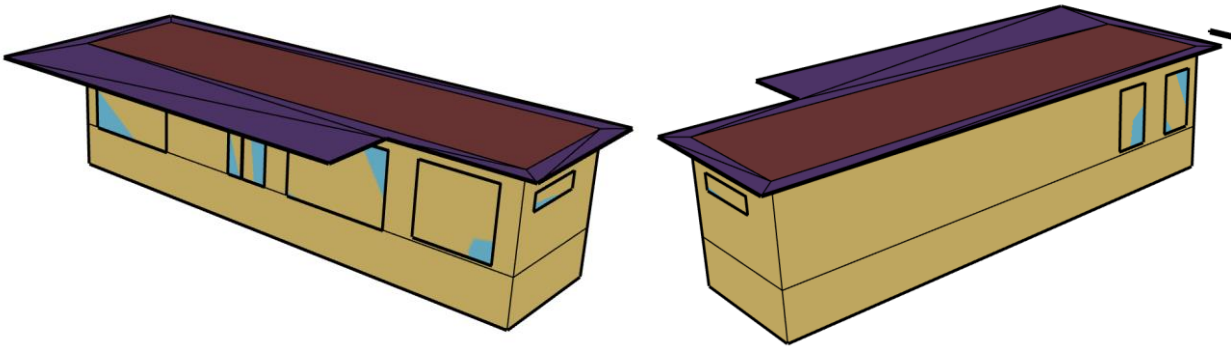


Figure 10. EnergyPlus renderings of the Angora model.

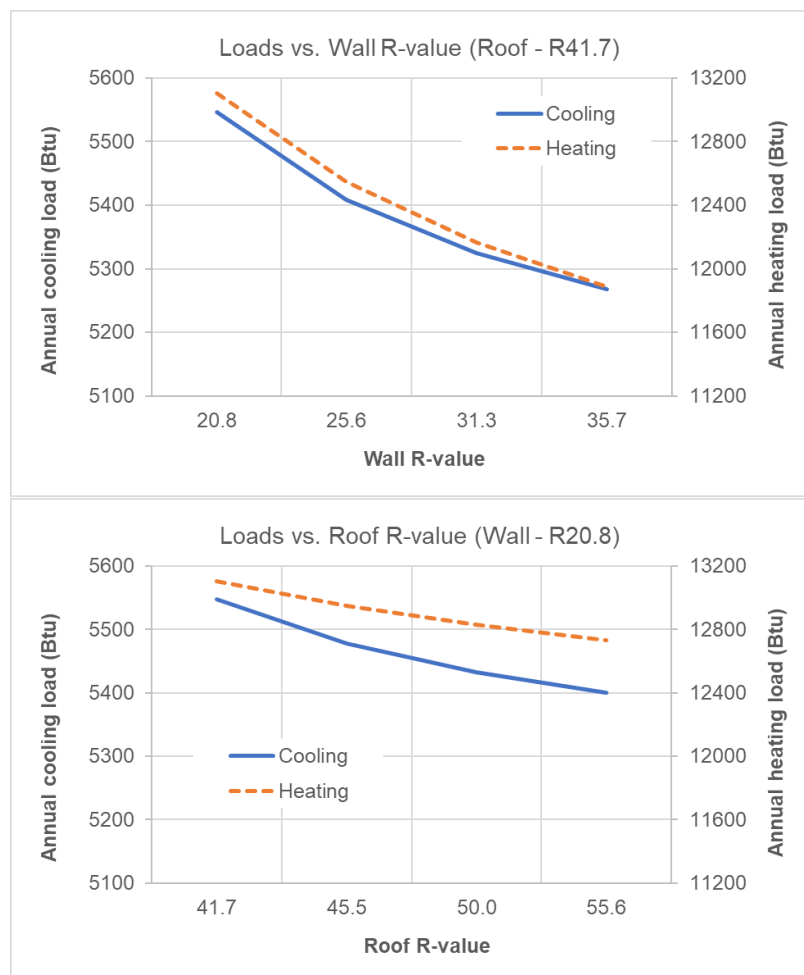


Figure 11. Cooling and heating loads as functions of wall R-values (top) and roof R-values (bottom) in South Lake Tahoe. The baseline wall and roof R-values were R20.8 and R41.7, respectively.

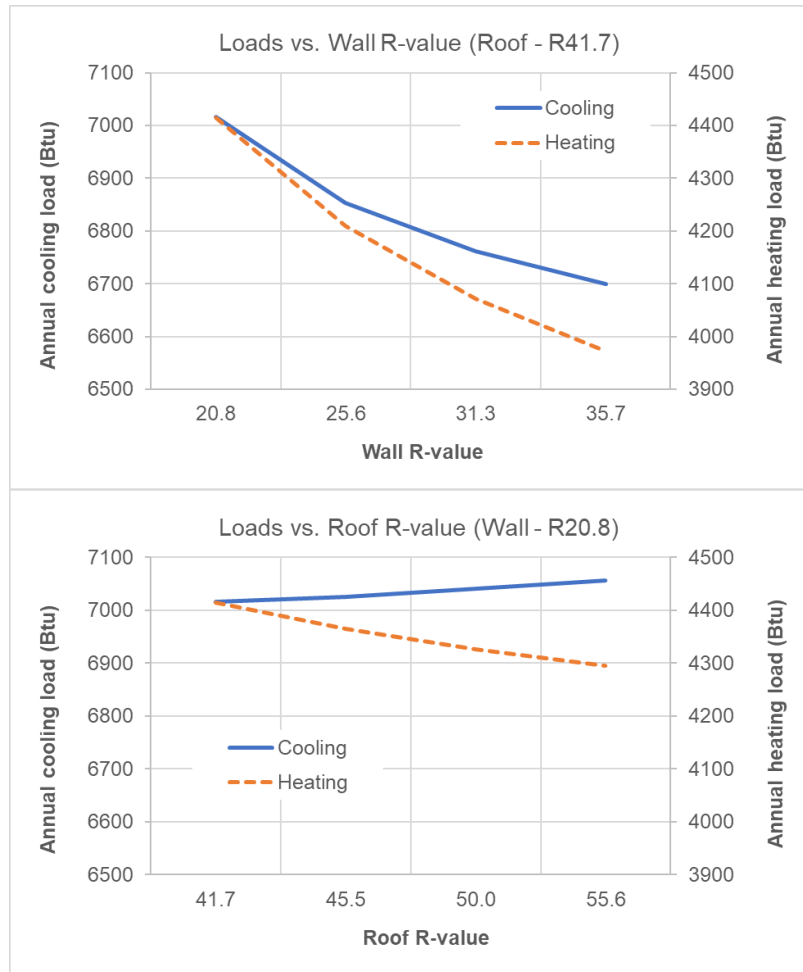


Figure 12. Cooling and heating loads as functions of wall R-values (top) and roof R-values (bottom) in Los Angeles. The baseline wall and roof R-values were R20.8 and R41.7, respectively.

Estimated Benefits

Preliminary energy savings calculations were performed with BEopt.¹ The results are shown in table 1. For the baseline case, the envelope characteristics were based on climate zone 2 specifications of the HUD code. The upgraded envelope characteristics were based on the targets set in the GFO-19-307 (GFO-19-307 2020). Cost savings are based on a rate of \$0.1698/kWh listed in GFO-19-307.

Table 1. Comparison of envelope characteristics and energy performance

	HUD baseline	Envelope upgrade
Wall R-value	9.3	29.3
Roof R-value	16.3	50.4
Air change rate (ACH5)	9	1

¹ <https://www.nrel.gov/buildings/beopt.html>

Average annual electricity usage	2,024 kWh	1,042 kWh
Electricity usage per square foot	1.56 kWh/ft ²	0.80 kWh/ft ²
% Savings	-	49%
Savings/square foot	-	0.76 kWh/ft ²
Annual bill savings	-	\$167
CO ₂ e avoided/year (lbs.)		494

Summary and Next Steps

The major impact of this project will be to introduce technologies that can transform the construction practices and energy performance of manufactured homes. The project team is in the process of designing and evaluating envelope systems containing VIPs for the prototype manufactured homes. The team will manufacture and commission the prototype homes during summer and fall of 2022. The EnergyPlus models will be updated and calibrated using the short- and long-term performance measurements of the prototype homes. Finally, calibrated EnergyPlus modeling and cost analysis will be used to define the energy savings potential and cost effectiveness of the different measures to be implemented in the prototype manufactured homes.

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