Scalable Decarbonization Strategies for Manufactured Homes

Agatha Kazdan, Mazen Daher and Maggie Sheng, Electric Power Research Institute (EPRI)

Joy Liao and Jorden Dentz, System Building Research Alliance (SBRA)

ABSTRACT

Manufactured housing is the largest source of unsubsidized affordable housing in the nation. While smaller and more affordable on a first cost basis than their site-built single-family counterparts, on a per square foot basis they typically use larger amounts of energy to heat and cool due to less energy efficient envelope standards, higher surface to volume ratio, and smaller overall size, increasing their carbon footprint and utility costs per square foot for those who typically can least afford it. As part of a multi-year study and to further understand the opportunities best suited for this building sector, three low-cost, all-electric, zero net energy (ZNE) manufactured home prototypes were produced and deployed in two inland California communities. Innovations include factory-installed HVAC and solar PV, smart electric panels, 120v heat pumps for space conditioning and heat pump water heaters, advanced insulation, framing and air sealing, fire resilience measures and low-amperage appliances and lighting. With the homes now operational in the field, production processes and ongoing performance are being evaluated to determine opportunities to further commercialize, reduce costs and ensure optimal performance of key enabling electrification and energy efficiency technologies at all stages of production associated with this building segment. This paper will present key results and lessons learned. Such empirical evidence is vitally important to inform ongoing program and policy discussions concerning this segment and ultimately to maximize the availability of affordable housing solutions that effectively meet this country's decarbonization and net zero targets.

Introduction

Manufactured housing constitutes approximately 10% of new housing starts and is a critical source of affordable housing in the United States today.[1] In 2022, the average national purchase price for a manufactured home was $108,000, [2] compared to $392,000 for the construction (not including land) of a site-built single-family home.[3] These homes, however, tend to use larger amounts to heat and cool on a per square foot basis, increasing their carbon footprint and costs for those who can typically least afford it.[4] The median household income for a manufactured

[1] Ryan, Doug. Lance George. Kimberly Vermeer. Manufactured Housing. National Low Income Housing Coalition. 2023.
[2] US Census Bureau. Manufactured Housing Survey. 2022.
[3] Celucci, Nick. Rachel Abraham. "How Much Does It Cost to Build a Home in the US in 2024?" Forbes. December 23, 2023.
[4] Energy Information Administration. Residential Energy Consumption Survey. 2020.

home household was $35,000 with forty-seven percent of households reporting energy insecurity compared with twenty-two percent of single family detached.[5]

This paper details the findings from a research effort to design, install and test all-electric, zero net energy (ZNE) manufactured homes that align with the State of California's 2045 goal of carbon neutrality and Title 24 energy code, while remaining cost-effective to purchase and operate. These homes were designed to leverage the efficiencies of factory production to drive down the costs and make more broadly accessible promising decarbonization technologies, like advanced framing, insulation and air sealing strategies, energy efficient heat pumps and appliances, building controls, and solar PV technologies.

Figure 1: Prototype home construction on the plant production line. EPRI. 2022.

Background

[5] American Council for an Energy Efficient Economy. Manufactured Housing Topic Brief. 2023.

The manufactured housing sector offers the potential to control construction and equipment install quality and broaden accessibility of decarbonization and resilience technologies. Nevertheless, the sector remains under the jurisdiction of a federal standard set out by United States Department of Housing and Urban Development (HUD), which has not received a notable update to its energy or fire safety standards, since the 1990s. [6] The Electric Power Research Institute (EPRI) partnered with market players within this sector to cost-effectively develop three prototype all-electric, ZNE homes that could exceed the HUD and current industry standard and meet increased fire and energy standards, including those set out by California's Title 24 energy code and DOE's Zero Energy Ready Home (ZERH) Standards. Partners included Clayton Homes (the largest fabricator of manufactured homes in the United States), System Building Research Alliance (the program administrator of federal programs aimed at the manufactured housing sector including ENERGY STAR and Zero Energy Ready *for Manufactured Homes* Programs) and Augusta Communities (a California-based nonprofit manufactured home park owner and operator). To address a common electrification design constraint, these homes evaluated different scalable strategies to optimize household power distribution and limit power draw to stay within a 100-amp electrical service panel limit. Note, this constraint can be found not only in most California manufactured home parks but nation-wide especially in regions that have been traditionally dual fuel. Additionally, in response to the rising occurrence of wildfires in California, the homes were outfitted with enhanced fire resilience strategies on the building enclosure, which serves as the first line of defense between the occupant and its environment.

Technology Overview

The team used as its guiding research question: "What is the least cost and scalable pathway for manufactured homes to be all-electric high efficiency ZNE?" At the same time, the team evaluated where it could incorporate emerging electrification and load flexibility technologies and strategically engage industry, program, and policy makers to effectively advance decarbonization within this sector. Table 1 provides an overview of the building research goals relative to the industry standard. Note that the Energy Design Rating (EDR) is a scoring metric that determines a building's compliance with California's Title 24 ZNE definition.

Table 1: Performance Targets

Performance Metric	Industry Standard	Research Goal
Energy Design Rating (EDR) and Title 24	80 to 100 typical for new HUD-code, mixed-fuel homes	0 or sub 15 EDR, all-electric
Energy performance (energy/sf)	HUD Standards	Title 24 (2019), DOE ZERH, must NOT exceed 100 amps
R-value of walls	R-11 to R-15	R-26 to R-29
R-value of roof	R-20 to R-30	R-49
ACH50	No requirement, commonly 5-8 ACH50	1 to 2 ACH50

[6] Walton, Robert. "DOE's manufactured home efficiency rule disappoints conservation advocates, manufacturers." Utility Dive. 2022.

HVAC energy use	HUD Standards	Different heat pump configurations
Costs	~$100-150/SF (2022) $50-75/SF (2019)	$150-175/SF (2022) <$100/SF (2019)
Fire protection	Various flame spread requirements per the HUD Code	Two-hour rating/Wildland-Urban Interface (WUI) standard; tempered glazing, backdraft dampers
Production friendliness	High	Factory installed HVAC and solar PV

The project team and technical advisory comprised of the top five US fabricators of manufactured housing chose to adopt the technology packages in Table 2 based on a series of modeling activities with additional vetting on "production readiness" from major manufactured home fabricators and key technology vendors. For renewables integration, the homes demonstrate two approaches: 1) "Solar Ready," where the plants installed electrical conduit and junction boxes and reinforce the roof to support the future solar PV system requiring theoretically fewer manhours on site to complete; and 2) full factory-installed solar using solar PV shingles (pictured in Figure 2) where the plants installed the entire system with the on site installers only handling inverter commissioning and interconnection. The solar PV shingle manufacturer was engaged and willing to honor warranty integrity through transport, unlike traditional panel manufacturers who are concerned with transport at high wind speeds of their mounted panels. A trade-off of the full factory install over the "solar-ready" approach however, was the higher cost per installed watt ($6.90) of solar shingles compared to standard silicon modules ($2.86 in the US in January 2024[7]), which are now a mature industry with many 400 watts+ panels on the market. The project team, however, selected the Suntegra solar shingle product because it was the one viable option to enable a factory-installed solar PV array that met the ZNE manufactured home requirements. While more efficient, standard roof-mounted silicon modules do not lend themselves to transport at high windspeeds and their manufacturers were unwilling to honor their product warranty integrity through transport. Suntegra not only honored its warranty for the application, but provided guidance and involvement in the successful deployment of the product in the factory. Other factors that dragged down the full factory install economics include having to hire a third party to handle on-site work, including interconnections and inspections and to handle permitting requirements with the state agency overseeing manufactured home improvements, the California Department of Housing and Community Development.

Table 2: Prototype Technology Packages

Home A (648 SF)	Home B (648 SF)	Home C (1,050 SF)
Prescriptive air sealing	Advanced air sealing	Aerosol spray air sealing
Mini-split HP SEER 19, HSPF 10	Mini-split HP SEER 19, HSPF 10	Package terminal HP 120V

[7] Walker, Emily. Vikram Agarwal. "Solar panel cost in 2024: It may be lower than you think." EnergySage. January 31, 2024. Data based on EnergySage Marketplace, a national clearinghouse for soliciting solar PV bids.

<table>
<tr><td>HPWH</td><td>HPWH (15-amp)</td><td>HPWH</td></tr>
<tr><td>Solar PV: 2.96 KW
Solar-ready (site installed)</td><td>Solar PV: 3.07 kW
Factory-installed shingles</td><td>Solar PV: 4.44 kW
Solar-ready (site installed)</td></tr>
<tr><td>Smart panel for load limiting</td><td>Standard panel, low amperage appliances</td><td>Smart panel for load limiting</td></tr>
<tr><td colspan="3">• Ceiling: R-40; Walls: R-21; Floor: R-21;
Belly: R-22; RESNET Grade I installation
• Fire resilient materials and Wildlands Urban Interface (WUI) spec: class ‘A’ fiberglass shingles, pop vents with wire mesh screens, fiber cement siding, and tempered glass windows and other fire-resistant materials like fiber cement
• Indoor Air Plus requirements
• 2x6” Framing
• Radiant Barrier
• Cool Roof Shingles</td></tr>
</table>

Figure 2: Solar PV shingle installation in plant yard. EPRI. 2022.

Modeling

A series of modeling activities supported the decision-making of the final adopted technology packages. These modeling activities include life cycle cost analysis, EDR compliance analysis and panel capacity analysis. The life cycle cost analysis was performed using BEopt, a specialized modeling software for residential buildings which can run parametric models to determine the technology bundles that would result in the lowest life cycle costs. Using optimization mode, BEopt was able to analyze and compare technology selections one by one and provide the optimal selection of technologies with maximum cost savings. Additionally, a consultation with leading national fabricators and technology vendors ensured the production readiness of the final specifications adopted in the homes. For example, transport constraints related to the added bulk and weight led to certain building envelope measures for added resilience and efficiency to be eliminated from the final scope.

EDR represents both an energy use index and metrics for compliance with Title 24. It functions on a scale of zero to 100, where zero represents a building that has ZNE consumption based on the proposed design, and 100 represents a building compliant with 2006 International Energy Conservation Code (IECC). The lower the EDR index, the more energy efficient the home. The EDR has three components: efficiency EDR (EDRe), demand flexibility EDR including PV, and total EDR (EDRt). The efficiency EDR is based on the energy efficiency features of the home such as envelope, air conditioning, water heating, ventilation, as well as lighting, plug loads and appliances. Demand flexibility EDR includes the PV system, battery storage system, precooling and other demand response technologies. The total EDR combines both EDRs by subtracting demand flexibility EDR from efficiency EDR:

$$Total\,EDR = Efficiency\,EDR - Demand\,Flexibility\,EDR$$

To comply, EDRe of the proposed design needs to be lower than EDRe of Title 24 standard design, and EDRt of the proposed design needs to be lower than EDRt of Title 24 standard design. The compliance of the selected technology bundles was modeled and verified in EnergyPro. EnergyPro is a CEC-approved modeling software to demonstrate performance compliance with the single-family residential provision 2022 Title 24.[8] The software provided results of EDR of each prototype home, summarized in Table 3. While compliant, several of the envelope measures had to be compromised due to their added weight and bulk through transport, resulting in higher than targeted EDRe results.

Table 3. EDR Results Using EnergyPro

	Home A	**Home B**	**Home C**
EDRe	53.6	52.9	52.1
Title 24 EDRe	54.9	54.8	52.9
EDRt	20.5	20.7	17.3
Title 24 EDRt	27.6	27.6	27.6
Title 24 Compliant?	Yes	Yes	Yes

To stay within the 100-amp electrical service panel limit, two homes employed “smart panels” to prioritize selected systems when ampacity limits were reached (Figure 3), while the third

[8] 2022 Energy Code Compliance Software. California Energy Commission. 2021.

employed an economy of wattages, using low amperage appliances like a combined condensing washer and dryer, 240V 15A heat pump water heater as well as advanced air sealing to drive down demand. As shown in Figure 4, the panel capacity analysis was used to verify that the technology bundles did not exceed the 100-amp panel electric service threshold. The analysis was performed by the home manufacturer according to the National Electric Code. Ductless mini split heat pumps, packaged terminal heat pumps, and heat pump water heaters were selected over standard split HVAC and storage tank hot water systems to demonstrate full factory install and energy performance gains. Efficient domestic hot water distribution design, ENERGY STAR appliances and light emitting diode (LED) lighting were also incorporated to reduce overall electric baseload.

Figure 3: Smart Panel Installation in Home A

CALCULATION FOR ELECTRICAL FEEDER LOAD
(Optional Method - NEC Section 220-30)

Home Size 648 Square Feet

	INPUT		WATTS
Total Floor Area =	648	Square Feet	1,944
Small Appliance Circuits =	3		4,500
Laundry Circuits =	0		0
Optional Garage Circuits =	0		0
Exhaust Fans =	3		600
Garbage Disposals =	0		0
Dishwashers =	0		0
Electric Clothes Dryers =	1		1,200
Furnace Blower Motors =	0		0
Electric Water Heaters =	1		3,600
Electric Ranges (nameplate) =	1		11,500
Electric Ovens (nameplate)=	0		0
Electric Cooktops (nameplate)=	0		0
Oven with Microwave =	0		0
Microwave Oven on Sep Circuit	1		1,580
Optional Trash Compactor =	0		0
Optional Evaporative Coolers =	0		0
Miscellaneous =	240V15A EV Charger		1,536
		Sub Total Watts =	26,460
		First 10,000 Watts @ 100% =	**10,000**
		Balance @ 40% =	**6,584**

	INPUT		WATTS
Mini-split	1		7,200
		Net AC or Furn. Watts =	**7,200**
		Total Watts =	**23,784**
		Total Amps =	**99.1**
		Main Panel Size Required =	**100**
Per Note 3 to Table 310-16 →		**Hot Conductor Size Required =**	**2**

Figure 4: Panel Capacity Analysis for Home

Production

The demonstration homes' production processes highlighted challenges with some of the advanced decarbonization strategies. For example, commercially available heat pump capacities are oversized for manufactured home loads, which tend to be smaller than site-built homes; high performance manufactured homes such as the demonstration homes have even smaller loads. Some of the technologies increased production time. Rigid board foam sheets, as shown in Figure 5, for example, had to be trimmed on the assembly line to match wall dimensions, which along with air sealing, added more than twenty-four hours of labor to the production line.

Figure 5: Installation of foam sheathing at plant. EPRI. 2022

Of the three prototype manufactured homes, plant management appreciated the high performing technologies but noted that the upfront cost might hinder adoption. Manufactured housing production is significantly different than the site-built housing construction process. Introducing the changes demonstrated in these homes has cascading impacts on product design, inventory tracking and staging, training, labor needs, and marketing/sales. Unless the technology is cost-effective and can smoothly be incorporated into the processes, it is difficult to convince the industry to adopt it. Some critical technical considerations are listed below:

- **Design flexibility.** Most manufactured homes are either single-section or double-section (two sections joined together). New technologies must work with both home types. This poses limitations for plant-installed ductless mini-splits and aerosol air sealant technology. Refrigerant lines cannot be connected in the plant between two home sections. One solution is to have two outdoor units, one on each section, but this increases equipment costs. Another solution is a ducted system with a single indoor air handler. Much like a traditional manufactured home, a crossover duct would be installed in the field to connect two trunk ducts. Applying aerosol sealant in double-section homes is also challenging. It requires additional labor and material to temporarily seal the open mate walls while the aerosol sealant is applied. For wildfire resilience, initial two-hour fire rated assemblies were deemed infeasible for factory and transport due to added time, weight and cost of the solution. In its place, the project adhered to Wildlands Urban Interface (WUI) requirement and provisioned additional fire resilient exterior cladding materials. The metal mesh covering air supply, however, had to be compromised to meet pressure differential required by packaged terminal heat pump installation guidelines.

- **Skills.** Ease and speed of production is critical to maintaining the factory profitability. New skills might require additional investment in staff training and tools. The complexity and difficulty of an installation procedure may also increase the risk of system failure due to plant error. Plant-installed solar, smart panels, and aerosol air sealant all require specialized technical expertise. Outside contractors can be brought into the plant to complete the installation, at added cost. For plants to train staff in these tasks, these technologies would have to be used on a regular basis – at least weekly, ideally daily. Otherwise, production staff turnover will erode the training investment and not be cost-effective. For certain technologies, special licensures are required: charging refrigerant lines requires an EPA 608 certification; solar panels (or solar shingle) installation requires licensure documentation of the solar installer.

- **Transport.** Completed homes are often shipped hundreds of miles. Foam sheathing is known for increased risk in nail popping due to vibration and wind during transportation. Hence, home manufacturers tend to avoid continuous foam envelope insulation. Adding vertical blocking can reduce this issue but requires additional labor and perhaps space accommodation in the plant.

- **HUD Code.** Given that much of the HUD Code was last updated in the 1990s, it cannot anticipate some of the new technologies available today. The wall-mounted packaged heat pump and hybrid heat pump water heater both required alternative construction letters and a time-consuming documentation and approval process. While these are one-time events that were resolved during this project, other new technologies could face similar obstacles.

Commissioning

All three homes underwent a series of commissioning tests and as-delivered assessments to verify the installation quality and the impact of transport and set-up processes. Table 5 summarizes the procedures and results from all the tests conducted post installation at the three homes. As shown in Table 6, all three homes exceeded the 3 ACH50 goal during blower door testing upon their site installation. Home A, which was sealed using a method that builds upon traditional sealing practices by dedicating more effort to ceiling electrical boxes and ceiling openings, exhibits the least leakage. Home C, the double-wide sealed using an aerosol air sealant not typically applied to manufactured homes, exhibits substantially more leakage, as does Home B, where advanced air sealing was installed whereby caulking and gaskets are installed between the walls and floors, electrical, pipe and duct penetrations and door and window seals. The results suggest that additional consideration needs to be made when sealing manufactured homes at the plant. Since manufactured homes need to be transported after sealing, there also may be a need to further study envelope damage from transportation, and in the case of the double wide home, imperfect sealing during the connection of the two separately built halves. Figure 6 depicts the blower door testing performed on Home C in the yard, where the air leakage rate was within the target range (below 2 ACH50), but conducted on individual halves of the double-wide by the aerosol air sealant applicant, Figure 7 depicts the blower door test performed in the field, where the air leakage consistently exceeded the performance target.

Table 5: Overview of Commissioning Tests and Results

Test	Equipment/procedure	Overall Result
Envelope leakage	Blower Door test with digital manometer; pressurization and depressurization.	Higher than expected ACH50 rates for all homes, Increase in envelope leakage between plant and on-site test, likely attributable to transportation damage.
Ventilation fan flow rates	Exhaust fan flow box with digital manometer	All homes appear to comply with ASHRAE 62.2-2010 requirement of 45 CFM for two-to-three-bedroom dwellings with a square footage less than 1500 square feet.
Bath exhaust fan flow rates	Exhaust fan flow box with digital manometer	Homes A and B exhibited lower than designed flow rates.
DHW distribution efficiency test	Electronic thermometer and flow bag for compliance with ZERH hot water distribution requirements	All operational hot water outlets appear to perform in accordance with ZERH hot water distribution requirements.
Functional testing of all HVAC equipment	Operational check for heating and cooling contingent on ambient conditions during time of test.	All tests were successful
Power measurements	Multimeter used to as a second measurement to confirm logger power measurements.	Tests completed on select circuits in Home C to confirm reliability of Smart Panels.

Table 6: Blower Door Test Results

	Square Footage	**Bldg. Volume (Cu. Ft)**	**Air leakage @ -50 Pascals (CFM)**	**ACH -50 Pascals**	**ACH Natural (no induced air flow)**	**Air leakage @ +50 Pascals (CFM)**	**ACH +50**
Home A	650	5,200	300	3.46	0.081	410	4.73

Home B	650	5,180	406	4.60	---	486	5.67
Home C	1040	8,320	472	3.40	0.052	780	5.62

Figure 6: Blower door test at plant yard. EPRI. 2022.

Figure 7: Blower door test at the site. EPRI. 2023.

Homes A and B do not comply with the specifications outlined prior to construction, namely the requirement that the single bathroom flow rate be greater than 50 CFM. Home A's bathroom exhaust fan had a flow rate of 31 CFM, and Home B's bathroom fan had a flow rate of 24 CFM. In the team's experience, such an issue can be resolved by eliminating kinks from the duct and increasing duct diameter. In prior work, those changes have resulted in an increase of 18 to 23 CFM, but experimentation may be needed to ascertain the benefit of these measures in the homes at hand.

Performance Monitoring

The objective of performance monitoring is to verify Title 24 ZNE performance and EDR over 18 months during unoccupied/simulated load and occupied testing periods. In addition, monitoring of maximum amperage draws has generated a lot of interest among industry partners. As of the time of writing, unoccupied testing is underway. Homes B and C have shown good agreement. Flaws in the methodology and/or implementation are being investigated in Home A. Homes A and B are being monitored through both smart panel and external current transducers, with measurement methods showing good agreement. As of the time of writing, there have been no alerts of panel overloading at any of the sites.

Conclusions and Recommendations

In conclusion, to be scalable within the manufactured housing sector, new measures must lend themselves to standardized designs, processes, and workforce skills. Those that add additional time, weight, cost, manufacturing complexity, supply chain complications, service needs or warranty risk to the production, transport and set-up processes may encounter resistance or fail to be adopted. Development of the Title 24 zero net energy manufactured homes described in this paper exposed the need for additional training and coordination to reduce cost and performance uncertainty, especially for the electrification and air sealing measures explored in these homes.

The voluntary above-code programs ENERGY STAR and Zero Energy Ready Home have proven an effective model for encouraging producers to exceed the minimum HUD Code performance standard. For example, major manufacturer Clayton Homes, responsible for over half the volume in the country and the fabricator for this project, formally announced that it will adopt the ZERH program standard and will include heat pump water heaters in its baseline home models, leading by example in the adoption of a key electrification technology. Mini-split heat pumps and solar PV also have the potential to be included in standard production with further development.

Even beyond the ZERH program, there remain opportunities for policy makers to further advance decarbonization in the manufactured home sector through supporting all-electric homes, renewable generation tactics, zero net energy goals, energy design rating performance targets, and peak shifting.

References

1. American Council for an Energy Efficient Economy. Manufactured Housing Topic Brief. 2023. < https://www.aceee.org/topic-brief/2023/08/topic-briefs-upgrading-manufactured-homes>

2. Celucci, Nick. Rachel Abraham. "How Much Does It Cost to Build a Home in the US in 2024?" Forbes. December 23, 2023. < https://www.forbes.com/home-improvement/contractor/cost-to-build-a-house/>

3. United States Census Bureau. Manufactured Housing Survey. 2019 and 2023.

4. United States Energy Information Administration. Residential Energy Consumption Survey. 2020.

5. Ryan, Doug. Lance George. Kimberly Vermeer. Manufactured Housing. National Low Income Housing Coalition. 2023. < https://nlihc.org/sites/default/files/AG-2024/6-5_Manufactured-Housing.pdf>

6. Walker, Emily. Vikram Agarwal. "Solar panel cost in 2024: It may be lower than you think." EnergySage. January 31, 2024. < https://www.energysage.com/local-data/solar-panel-cost/>

7. Walton, Robert. "DOE's manufactured home efficiency rule disappoints conservation advocates, manufacturers." Utility Dive. 2022. < https://www.utilitydive.com/news/doe-manufactured-home-efficiency-rule-energy/624118/>

8. 2022 Energy Code Compliance Software. California Energy Commission. 2021. < https://www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards/2022-building-energy-efficiency-1>