Data-Driven Electrification and Retrofit Strategies for Vulnerable Manufactured Housing

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ABSTRACT

Manufactured housing represents one of the most energy-burdened and operationally complex segments of the U.S. residential building stock disproportionately occupied by low-income households. Despite growing interest in electrification and decarbonization, retrofit efforts in manufactured homes are frequently constrained by electrical service limitations, deferred maintenance, programmatic silos, and limited data on real-world system performance. This paper presents findings from an ongoing Building America–supported retrofit pilot at Audubon Estates, a manufactured housing community in Alexandria, Virginia. The project integrates high-resolution pre-retrofit monitoring, advanced diagnostics, and community-embedded engagement strategies to inform retrofit design, workforce development, and implementation sequencing.

Five occupied manufactured homes were evaluated using a two-stage assessment process combining traditional energy audits with enhanced diagnostics, including blower door testing, duct leakage measurement, LiDAR-based geometry modeling, and granular energy and indoor environmental monitoring. Parallel community engagement efforts employed bilingual outreach, trusted intermediary partnerships, and a compensated Community Advocate model to address participation barriers and logistical challenges. Early results from pre-retrofit assessments highlight recurring technical constraints, such as 60-amp service limits, oversized legacy HVAC systems, and degraded envelope components, as well as the critical role of trust-based engagement in sustaining participation. The paper concludes with lessons learned and recommendations for scaling equitable, data-driven retrofit programs in manufactured housing communities.

Introduction

Manufactured homes house more than 20 million residents nationwide. This segment of the building stock is disproportionately occupied by low-income, elderly, and fixed-income households (Bell-Pasht and Ungar 2022; Berkadia 2025) who frequently experience elevated energy burdens, compromised indoor air quality and aging heating and cooling systems.

While electrification and high-performance retrofits offer substantial opportunities for cost savings, health benefits, and emissions reductions, implementation in manufactured housing presents distinct technical, programmatic and community challenges. These include electrical service limitations, spatial constraints, deferred repairs, fragmented funding sources, and resident distrust of externally administered programs. Furthermore, participation in energy programs can be hindered by language barriers, limited knowledge of available technology, as well as access to technical information.

Data release date: March 2023
Revised data release date: March 2024

US Energy Information Administration - Residential Energy Consumption Survey (RECS)

Table CE1.1 Summary annual household site consumption and expenditures in the United States—totals and intensities, 2020

	# of housing units (million)	Site energy consumption[a]					Energy expenditures[a]				
	Total U.S.[b]	Total (trillion Btu)	Per household (million Btu)	Per household member (million Btu)	Per square foot (thousand Btu)	Comparison	Total (billion dollars)	Per household (dollars)	Per household member (dollars)	Per square foot (dollars)	Comparison
All homes	123.53	9,481	76.8	31.3	42.2		232.76	1,884	768	1.04	
Housing unit type											
Single-family detached	77.07	7,293	94.6	35.9	41.8		169.90	2,205	836	0.97	
Single-family attached	7.45	500	67.1	27.6	41.6		12.32	1,653	681	1.02	
Apartments in buildings with 2–4 units	9.34	500	53.5	22.2	54.7		13.14	1,406	585	1.44	
Apartments in buildings with 5 or more units	22.84	769	33.7	17.9	37.2		25.28	1,107	589	1.22	
Mobile homes	6.83	419	61.3	25.3	50.5	21%	12.12	1,773	731	1.46	51%
						All Mobile Homes have a 21% higher energy use					All Mobile Homes have a 51% higher energy cost
Ownership of housing unit											
Owned	82.92	7,501	90.5	35.9	41.6		177.03	2,135	847	0.98	
Single-family	73.22	6,950	94.9	37.0	41.2		161.09	2,200	857	0.96	
Apartments	4.32	218	50.6	25.8	42.5		6.37	1,474	754	1.24	
Mobile homes	5.38	333	61.8	26.5	49.4	17%	9.57	1,779	764	1.42	37%
						Owned Mobile Homes have a 17% higher energy use					Owned Mobile Homes have a 37% higher energy cost
Rented[e]	40.61	1,980	48.8	21.0	44.8		55.72	1,372	591	1.26	
Single-family	11.30	843	74.6	25.4	46.8		21.12	1,869	636	1.17	
Apartments	27.86	1,051	37.7	18.5	42.6		32.05	1,151	563	1.30	
Mobile homes	1.45	86	59.5	21.3	55.1	26%	2.54	1,752	627	1.62	48%
						Rented Mobile Homes have a 26% higher energy use					rented Mobile Homes have a 48% higher energy cost
2020 annual household income											
Less than $5,000	4.48	253	56.5	21.7	49.5		6.77	1,512	580	1.33	
$5,000 to $9,999	4.01	208	51.9	23.9	48.2		5.53	1,379	636	1.28	
$10,000 to $19,999	10.25	588	57.4	28.9	44.5		14.98	1,462	735	1.13	
$20,000 to $39,999	24.07	1,568	65.1	29.7	44.7		38.84	1,614	735	1.11	
$40,000 to $59,999	19.61	1,372	70.0	30.3	42.0		33.80	1,724	747	1.03	
$60,000 to $99,999	27.71	2,178	78.6	31.1	42.1		53.34	1,925	763	1.03	
$100,000 to $149,999	16.54	1,462	88.4	32.4	40.3		35.51	2,147	786	0.98	
$150,000 or more	16.86	1,852	109.8	37.6	40.1	19%	43.98	2,608	893	0.95	29%
						Lower income households have a 19% higher energy use					Lower income households have a 29% higher energy cost

Data source: U.S. Energy Information Administration, Office of Energy Demand and Integrated Statistics, Forms EIA-457A, D, E, F, & G of the *2020 Residential Energy Consumption Survey*
Notes: Because of rounding, data may not sum to totals. See RECS Terminology for definition of terms used in these tables.
Btu = British thermal units
[a] Consumption and expenditures for biomass (wood), coal, district steam, and solar thermal are excluded. Electricity consumption from on-site solar photovoltaic generation (that is, solar panels) is included.
[b] *Total U.S.* includes all primary occupied housing units in the 50 states and the District of Columbia. Vacant housing units, seasonal units, second homes, military houses, and group quarters are excluded.
[c] Housing units are classified using criteria created by the U.S. Census Bureau based on 2010 Census data. Urbanized areas are densely settled groupings of blocks or tracts with 50,000 or more people, while urban clusters have at least 2,500 but less than 50,000 people. All other areas are rural.
[d] The Building America program, sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), created these climate regions. We combined climate regions for this publication. The Subarctic region is included with data for *Very-cold/Cold*.
[e] *Rented* includes households that occupy their primary housing units without paying rent.
[f] *Total square footage* includes all basements, finished or conditioned (heated or cooled) areas of attics, and conditioned garage space that is attached to the home. Unconditioned and unfinished areas in attics and attached garages are excluded. The square footage of the home is based on respondent reports. Previous RECS cycles calculated square footage based on interviewer measurements. For households that did not report an exact square footage estimate, the square footage of the home was imputed based on a reported square footage range and/or characteristics of the home. See *2020 RECS Square Footage Methodology* for full details about data collection and processing.
[g] *Some other fuel* includes coal and district steam.
Q = Data withheld because either the relative standard error (RSE) was greater than 50% or fewer than 10 households in reporting sample.
N = No households in reporting sample.

Data from the 2024 Residential Energy Consumption Survey found national average manufactured housing energy use intensity of 50.5 kBtu/ft^2-yr compared to single-family site-built housing of 42.2 kBtu/ft^2-yr. Reducing manufactured housing EUI by 50% would yield 24 million metric tons annual avoided CO_2 emissions or $1.25B in annual utility bills.

Project Context and Objectives

This project, part of the U.S. Department of Energy's Building America Retrofit Solutions initiative, aims to transition manufactured homes, primarily occupied by lower-income and minority residents, to energy-efficient, low-carbon, high-performance solutions using a scalable, community-centered approach. It focuses on identifying, testing, and validating retrofit packages that reduce lifestyle carbon emissions while addressing local constraints such as fuel-switching restrictions, 60A electrical panels, safety and infrastructure vulnerabilities, and low voluntary program participation. Its primary objectives are to establish detailed pre-retrofit performance baselines using high-resolution monitoring and diagnostics, inform right-sized and climate appropriate retrofit designs for manufactured homes, identify workforce and contractor readiness challenges associated with electrification retrofits, test community-centered engagement strategies that reduce participation barriers and improve implementation outcomes, and generate lessons that can inform broader program and policy development.

The scope includes high-resolution pre- and post-retrofit diagnostics, development of practical technical solutions using commercially available technologies, refinement of incentive and program designs, and enhanced customer and community engagement, with the goal of producing models and guidance that can be deployed in manufactured housing communities nationwide.

The project is being implemented at Audubon Estates, a large manufactured housing community in Alexandria, Virginia (ASHRAE Climate Zone 4A).

Methodology

Unit Selection and Resident Context

Five (5) occupied manufactured homes were selected for pre-retrofit evaluation within the Audubon Estates community in Alexandria, Virginia. Units were identified by the property manager based on household need, with all participating households occupied by elderly residents on fixed incomes. Selection aligned with project goals to prioritize households experiencing high energy burdens and comfort challenges while enabling the project team to leverage supplemental repair and energy assistance programs. Figure 2 summarizes the integrated technical approach used in this study, including diagnostic assessment, retrofit implementation, workforce engagement, resident outreach, and data analysis activities.

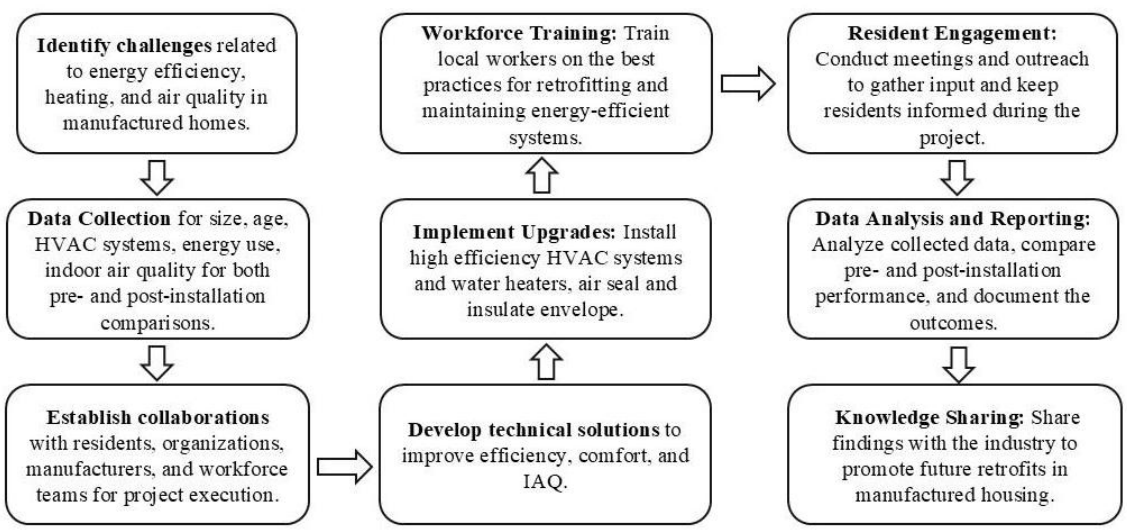


Figure 2. Integrated technical approach for the manufactured housing retrofit pilot, illustrating the sequencing of diagnostics, retrofit implementation, workforce engagement, resident outreach, and data analysis. *Source:* Haleh Moghaddasi, EXP Team 2025.

While additional units were available in the complex, securing resident trust and consent was a primary factor. Due to the recent immigration concerns, many residents expressed concern regarding sharing their personal data with a government affiliated program. Consequently, the five selected units represented the households that met all selection conditions and fully volunteered for participation.

Two-Stage Assessment Approach

The project employed a two-stage assessment methodology:

Stage 1 – Standard Energy Assessment: Consisted of building envelope inspections, mechanical and electrical system inventories, utility data reviews, and resident surveys addressing comfort concerns, appliance usage, and cooking preferences

Stage 2 – Enhanced Diagnostic Assessment. These diagnostics provided field-verified measurements of envelope leakage, duct performance, and system airflow characteristics necessary for accurate retrofit design.

- Blower door testing to quantify whole-house air leakage
- Duct leakage testing using a duct blaster
- Multi-point HVAC airflow and static pressure diagnostics
- Combustion Appliance Zone (CAZ) safety testing and carbon monoxide measurements
- LiDAR scanning to generate accurate three-dimensional building geometry models
- Electrical panel capacity review and National Electrical Code (NEC) load calculations

Modeling and Load Analysis

LiDAR scanning technology was used to develop a 3D model of each unit. These models were translated into building energy models using Trane TRACE 3D Plus. These models were further enhanced by field-verified envelope characteristics, measured infiltration rates, and the LiDAR-derived geometry. These HVAC systems were then calculated from cooling loads and adapted to support the high humidity loads in this hot-humid climate. We also selected the units based upon a lower airflow (evaporator size). This created a higher performing HVAC system for these smaller units with higher moisture concern spaces. Modeled peak cooling loads ranged from 1.4–2.0 tons, significantly lower than existing systems (2–3 tons), indicating consistent oversizing. The existing systems and rule of thumb sizing ranged from two to three tons despite home sizes near 1,100 ft^2, indicating opportunities for improved system sizing and improved moisture control in retrofit designs.

Monitoring and Instrumentation

A subset of homes was instrumented with high-resolution monitoring to capture real-time building performance data. Monitoring systems included circuit-level electrical monitoring; indoor air quality sensors measuring temperature, relative humidity, carbon dioxide (CO_2), and particulate matter (PM); HVAC airflow and enthalpy sensors to evaluate heating, cooling, and dehumidification performance; gas flow meters in select units; and outdoor weather stations measuring temperature, humidity, solar irradiance, wind speed, and precipitation. This monitoring strategy enabled detailed analysis of system performance, occupant interaction, and environmental conditions. Figure 3 presents the distributed data acquisition architecture, illustrating the relationship between the central communications hub and individual home-level monitoring nodes.

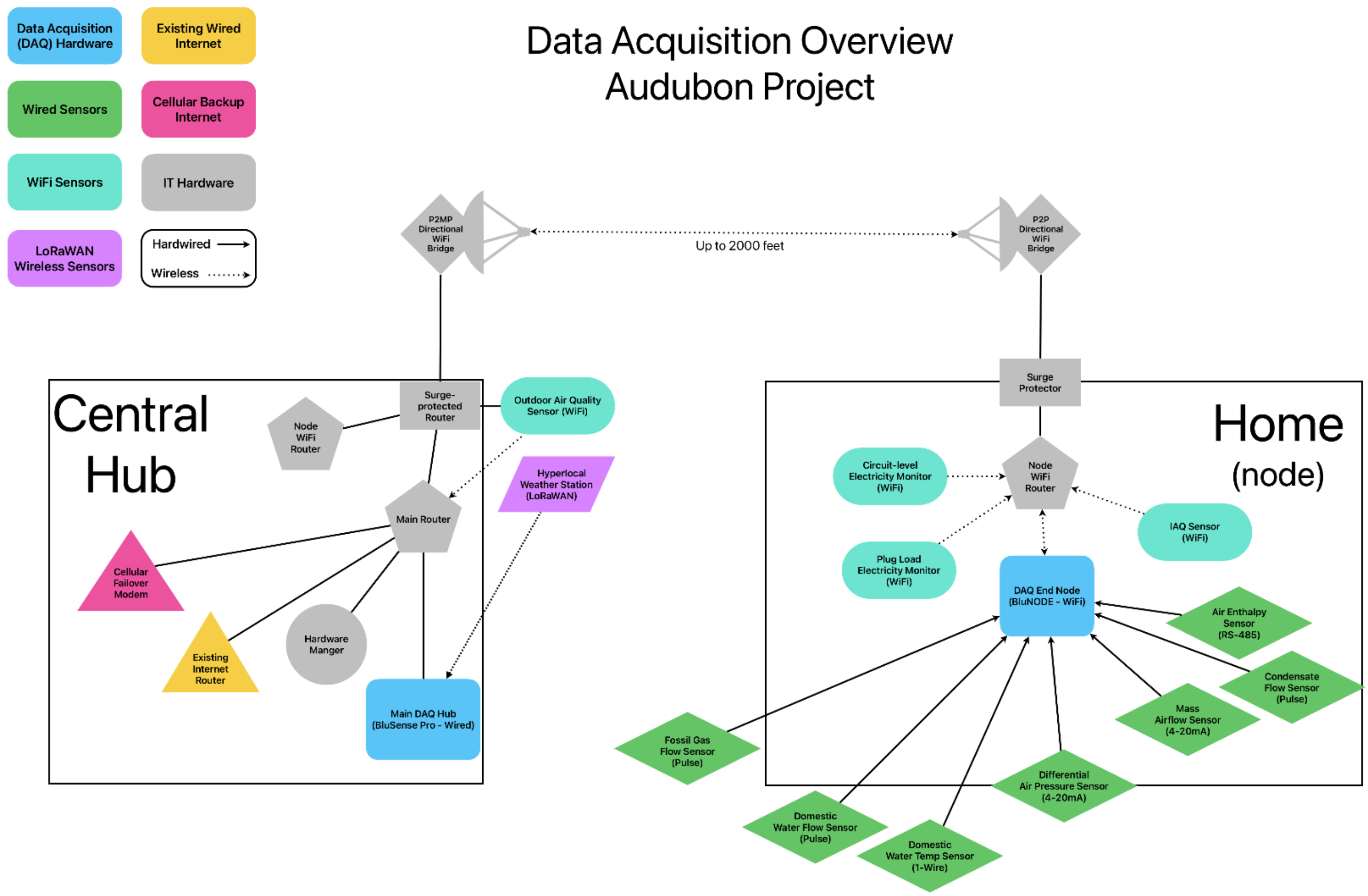


Figure 3. Data acquisition and communications architecture for the Audubon manufactured housing retrofit project, showing the central hub and home-level monitoring nodes. *Source:* Benjamin Knopp, EXP Team 2025.

Retrofit Design Integration

Findings from pre-retrofit diagnostics and monitoring directly informed the development of preliminary retrofit designs for participating homes. Diagnostic results, including measured infiltration rates, duct leakage, modeled heating and cooling loads, and electrical service constraints, were translated into right-sized HVAC configurations, envelope upgrade strategies, and electrification pathways that reflected site-specific limitations. Retrofit concepts emphasized commercially available technologies, minimized electrical service upgrades where possible, and prioritized measures with the highest potential for cost containment and performance improvement. Design development was intentionally scoped at a schematic level to support constructability review and implementation planning rather than final construction documentation. Design priorities focused on reducing building envelope leakage to minimize loads, right-sizing HVAC systems for optimal performance, and selecting equipment compatible with constrained ductwork while providing effective humidity control and airflow. Figure 4 illustrates the conceptual split heat pump system configuration used to translate pre-retrofit diagnostic findings into preliminary retrofit design strategies for manufactured housing.

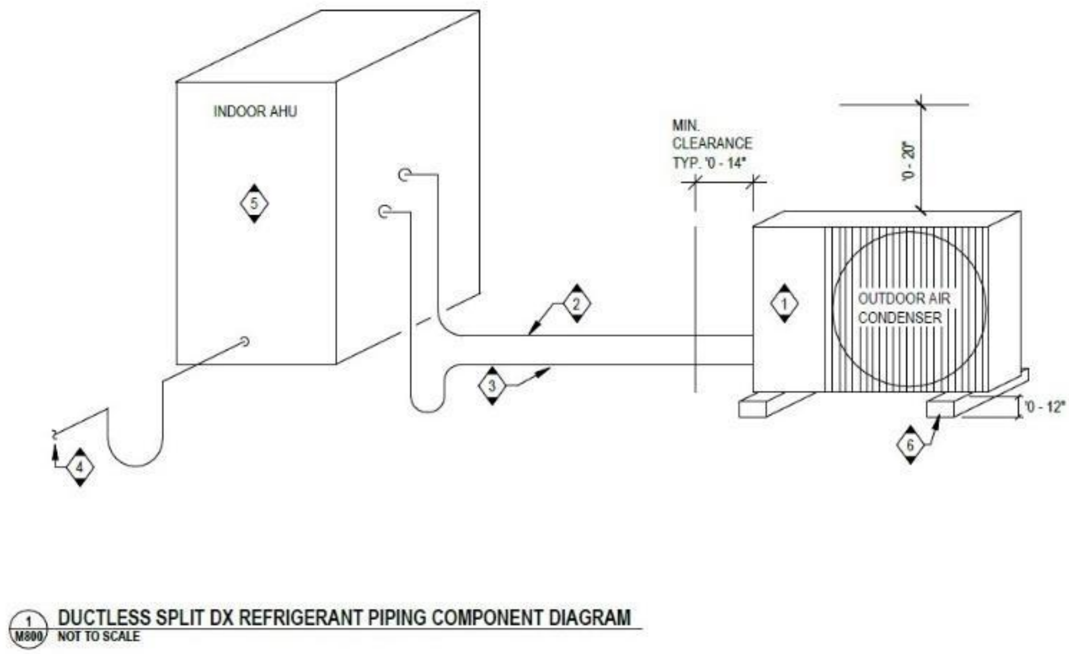


Figure 4. Conceptual split heat pump system configuration is used to translate diagnostic findings into retrofit design strategies for manufactured housing. *Source:* EXP Retrofit Design Team 2025.

Community Engagement Strategy

Engagement Framework

Recognizing that technical excellence alone is insufficient for successful implementation, the project integrated a robust community engagement strategy to build trust, reduce participation barriers, and maintain involvement throughout the study period. Engagement activities were coordinated in collaboration with the property manager, community partners, and participating households. Outreach materials were developed in both English and Spanish to support language accessibility, and project staff conducted in-person engagement during energy assessments and monitoring installation visits.

Community Advocate Model

A compensated Community Advocate model was developed to embed trusted residents within the project delivery process. Community advocates were recruited from within the neighborhood and trained to support engagement activities throughout the study.

Advocates functioned as trusted intermediaries between residents and technical staff and supported following activities:

- Translation and contextualization of technical information
- Appointment confirmation and coordination
- Residents engagement during surveys and follow-up activities
- Ongoing communication to prevent resident participation dropout
- Household readiness for contractor visits and monitoring installations
- Post-installation surveys and quality checks

This model addresses common participation barriers, including language access, scheduling constraints, and distrust of contractors or government-funded programs.

Workforce Development and Field Documentation

Electrification and energy efficiency retrofits in manufactured housing can present workforce and program delivery challenges that differ from site-built housing. These homes often include limited electrical capacity, constrained installation space, and structural conditions that affect retrofit sequencing. Manufactured housing communities may also face participation barriers such as language access needs and limited familiarity with retrofit technologies. In this context, workforce readiness and community engagement are closely linked to successful implementation. Prior research highlights the importance of workforce training grounded in field conditions and engagement strategies that leverage trusted intermediaries and locally based outreach (ACEEE 2023).

The workforce effort is currently in the Monitoring and Communications (M&C) installation phase, during which monitoring equipment and communications infrastructure are being deployed across participating homes. In this phase, monitoring equipment is installed to detect the performance of electric use, indoor air quality, and enthalpy (both temperature and relative humidity) at both the HVAC supply and return. Simultaneously, communications equipment is installed to wirelessly communicate data collected to a central onsite communications hub so the Project Team can remotely access monitoring data. This phase provides a valuable opportunity to observe contractor workflows and identify technical bottlenecks associated with electrification readiness and monitoring integration.

Field implementation is being documented using a structured Field Pulse Log, supplemented by post-installation debriefs with contractors. These tools capture installation conditions, electrical service constraints, spatial limitations, equipment placement and sequencing decisions, workflow disruptions, and observed skill or training needs. This approach provides systematic documentation of real-world bottlenecks in electrification and monitoring deployment without disrupting installation activities. These observations will inform the development of a two-part seminar that documents field-based lessons from monitoring and retrofit installation and is intended to support contractor development and workforce programs in the Northern Virginia Region.

Installation required more time than planned due to constrained spaces, electrical limitations, and coordination challenges. Workforce-related issues, particularly network configuration, were consistently observed.

Results

Study Site Demographics

The study was conducted at the Audubon Estate property, which consisted of five occupied residential units. A total of seven residents lived across the study units, with household sizes ranging from one to two occupants per unit (Table 1). Units 1, 2, and 5 were occupied by a single resident, while Units 3 and 4 each housed two residents. The study population consisted entirely of 100% elderly residents. This demographic characteristic is important for evaluating residential energy use and retrofit impacts, as elderly occupants may have different comfort requirements, occupancy patterns, and energy consumption behaviors compared to the general population (Chen et al., 2024).

The study population represented a diverse range of ethnic backgrounds. Two units were occupied by Hispanic residents, two units were occupied by residents identifying as White Non-Hispanic, and one unit included residents identifying as both White Non-Hispanic and Asian Pacific Islander. One unit was occupied by Black residents. Overall, the demographic composition reflected a mix of racial and ethnic groups within property.

Pre-Retrofit Energy Consumption

Pre-retrofit utility consumption data were collected and analyzed for five dwelling units over a recent 12-month period. Annual electricity consumption ranged from 5,188 to 6,543 kWh, while natural gas consumption ranged from 429 to 733 therms, indicating notable variation in end-use energy demand across units (Table 1).

Table 1: Pre-retrofit energy consumption Metric	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Total electricity (kWh)	5,188	6,238	5,446	6,543	6,082
Total gas (therms)	733	429	622	453	577
Average monthly electricity (kWh)	432.33	519.83	453.83	545.25	506.83
Average monthly gas (therms)	61.08	35.75	51.83	37.75	48.08
Total annual energy cost ($)	2,060.74	1,768.75	2,560.13	1,988.17	1,916.32
Electricity cost ($/kWh)	0.1689	0.1703	0.1480	0.1949	0.1592
Gas cost ($/therm)	1.6160	1.6463	2.8204	1.5744	1.6430
Total energy use (MMBtu)	91.00	64.18	80.78	67.62	78.45

Overall, Units 1 and 2 exhibited contrasting energy-use profiles. Unit 1 had the lowest electricity consumption (5,188 kWh) but the highest gas consumption (733 therms), resulting in the highest total site energy use at 91.0 MMBtu. In contrast, Unit 2 had the lowest overall energy use (64.2 MMBtu), driven by relatively high electricity consumption (6,238 kWh) but the lowest gas use (429 therms).

Units 3 through 5 showed intermediate and less extreme patterns, with total energy consumption ranging from 67.6 to 80.8 MMBtu. Unit 3 recorded 5,446 kWh and 622 therms (80.8 MMBtu), Unit 4 recorded the highest electricity use (6,543 kWh) with 453 therms (67.6 MMBtu), and Unit 5 used 6,082 kWh and 577 therms (78.5 MMBtu). These differences suggest variation in heating demand and occupant-driven usage patterns across similar dwellings.

Annual energy costs ranged from $1,768.75 (Unit 2) to $2,560.13 (Unit 3). While Unit 1 had the highest total energy consumption, its cost ($2,060.74) was lower than Unit 3, reflecting differences in utility rates between electricity and natural gas. Unit 5 participated in a levelized billing program for natural gas, with an average monthly gas cost of approximately $79.

Across all units, average annual consumption was 5,899 kWh of electricity and 563 therms of natural gas, corresponding to an average total energy use of 76.4 MMBtu per unit and average annual energy cost of approximately $2,059. Natural gas represented the dominant contributor to site energy use in most units, highlighting heating demand as the primary end-use driver in the pre-retrofit condition. These baseline results provide a reference for evaluating post-retrofit energy savings and identifying units with higher relative heating loads.

These pre-retrofit results establish the baseline energy performance against which post-retrofit energy savings and cost reductions will be evaluated.

Post-Retrofit Modeled Energy Savings

Energy Modeling: Approach and Assumptions Tool

The energy savings analysis was developed using a detailed hourly building energy simulation framework consistent with DOE Building America modeling practices. The model was structured as a residential hourly load calculation tool (8760-hour simulation) based on EnergyPlus/eQUEST-style formulations, combining envelope heat transfer, infiltration, internal gains, and HVAC system performance.

Baseline Conditions (Energy Use and Cost Profile)

For energy modeling, the baseline energy conditions are characterized by natural gas driven end use structure. Natural gas accounts for 74% of total site energy consumption, while electricity represents the remaining 26%. Despite the lower share of total energy use, electricity accounts for a disproportionate share of total energy cost. Electricity represents 48% of total utility cost at a modeled rate of $0.169/kWh, while natural gas represents 52% of total cost at $1.886/therm. This distribution reflects differences in both system efficiency and unit energy pricing.

1. **Modeled Energy Breakdown (Before vs. After Retrofit)**

Table 2 compares the modeled annual end-use energy distribution for the baseline and post-retrofit conditions. The baseline reflects a gas-dominant system configuration, while the retrofit case reflects full electrification of major end uses combined with envelope improvements.

Table 2. Modeled energy breakdown (Before vs. After retrofit)

End use	Baseline (% energy)	Retrofit (% energy)
Space heating	40% (Gas)	20% (Heat pump)
Water heating	20% (Gas)	8% (Heat pump water heater)
Space cooling	12% (Electric)	10% (Heat pump)
Lighting & appliances	20%	15%
Cooking	8% (Gas)	5% (Electric resistance)
Envelope loss residual	-	10%
Total	100%	68%

The modeled end-use breakdown shows a substantial shift in energy use patterns following electrification and efficiency improvements. In the baseline condition, space heating (40%) and water heating (20%) dominate total energy consumption, reflecting a high dependence on natural gas systems. Cooling, lighting and appliances, and cooking account for the remaining 40% of total energy use (Table 2).

In the post-retrofit condition, gas-fired end uses are replaced with high-efficiency electric systems, including a heat pump for space and water heating, and an electric resistance cooking unit. This transition results in a redistribution of end-use shares, with space heating reduced to 20% and water heating reduced to 8%. Lighting and appliance energy decreases to 15%, while cooking declines to 5%. A residual envelope loss category accounts for 10% of post-retrofit energy use.

Overall, the retrofit scenario reduces total site energy use to approximately 68% of the baseline end-use total. This reduction is primarily driven by the elimination of combustion-based space and water heating systems and the associated efficiency gains from electrification. Natural gas consumption is reduced from 74% of baseline energy use to approximately 5-10% in the post-retrofit condition, representing a reduction of more than 90%.

2. **Peak Demand Analysis**

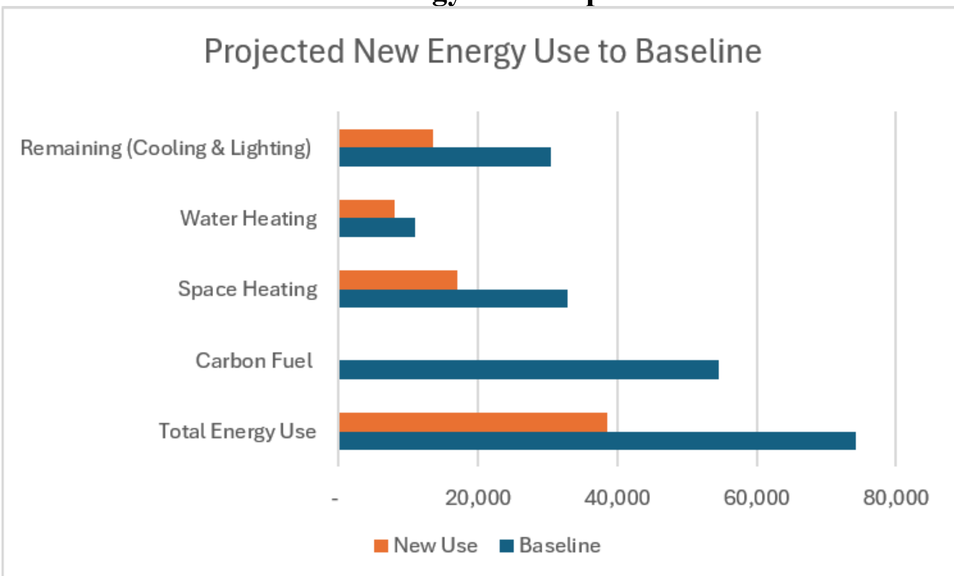
Table 3 summarizes modeled peak heating, cooling, and electric demand for the baseline and retrofit conditions.

Table 3. Peak demand comparison (baseline vs. retrofit)

Metric	Baseline	Retrofit
Peak heating load	30 kBtu/hr	18 kBtu/hr
Peak cooling load	18 kBtu/hr	14 kBtu/hr
Peak electric demand	4.5 kW	5.5 kW

Peak heating load decreases from 30 kBtu/hr in baseline condition to 18 kBtu/hr in the retrofit condition, while peak cooling load decreases from 18 kBtu/hr to 14 kBtu/hr. In contrast, peak electric demand increases from 4.5 kW to 5.5 kW in the retrofit case. This increase is associated with the electrification of heating and water heating systems, which shift thermal loads from gas to electricity, resulting in higher electrical demand despite overall reductions in site energy use.

3. **Modeled Annual End-Use Energy Consumption**



Key Findings and Challenges

The pre-retrofit evaluation and early implementation activities highlighted an interrelated set of technical, programmatic and community challenges affecting the feasibility and timing of electrification upgrades within the Audubon Estates manufactured housing community. These challenges include building infrastructure limitations, policy and programmatic constraints, logistical barriers to monitoring and retrofit installation and resident engagement dynamics among participating households. Collectively these findings highlight the barriers to electrification and necessitate the need for systematic and coordinated technical, policy and community-based solutions.

Technical Constraints

Across the five evaluated homes, technical constraints consistently limited the feasibility and sequencing of electrification and high-performance upgrades. Although several homes contained 100A interior electrical panels, the community's original development as a recreational vehicle park resulted in 60A outdoor electrical service configurations that restricted the deployment of heat pump HVAC systems, electric water heating, and induction cooking technologies. In multiple cases, inconsistencies between meter ratings, breaker capacities, and panel configurations further complicated National Electrical Code (NEC) compliance and increased retrofit complexity (U.S. HUD 2024). These findings suggest that electrical infrastructure readiness must be evaluated during the earliest phases of retrofit planning to avoid redesigns, cost escalation, and implementation delays.

Advanced diagnostic testing and energy modeling also revealed substantial HVAC oversizing and envelope performance deficiencies. Energy modeling indicated peak cooling loads ranging from approximately 1.4 to 2.0 tons, yet installed systems often exceeded these electrical constraints requirements by a factor of two or more. Oversized equipment contributed to short cycling, inadequate humidity control, and elevated energy use. Envelope diagnostics revealed elevated air leakage with blower door results exceeding 3,000-4,800 CFM50 as well as degraded floor insulation, particularly in vented crawlspaces, which exacerbated comfort and moisture issues. These conditions contribute to comfort challenges, moisture risks, and increased heating and cooling loads (ENERGY STAR 2021).

The analysis further demonstrated that deferred maintenance and structural repair needs were also concerning factors across participating households. Issues identified during energy assessments included roof leaks, damaged subfloor sections, ceilings and walls, deteriorated ductwork, and plumbing leaks. In some cases, these structural issues posed safety risks. For instance, in one case, the water heater closet collapsed with a disconnected flue pipe, highlighting the need for addressing structural and safety measures before implementing energy upgrades. Space constraints significantly influenced heat pump water heater (HPWH) selection, with split-system configurations often required in constrained layouts.

Airflow measurement presented another important technical challenge. Airflow monitoring was more straightforward for packaged systems because ducted airflow pathways could be instrumented directly. In contrast, outdoor split-system units operated in open-air configurations without dedicated duct structures, significantly complicating airflow capture and measurement procedures. Filtration and long-term maintenance considerations emerged as additional operational considerations during retrofit planning. To improve indoor air quality and reduce maintenance frequency, the project team evaluated the use of oversized MERV 13 filtration systems and deep media filter cabinets. Higher-efficiency filtration strategies were expected to reduce replacement frequency compared with conventional low-cost filters while also helping maintain HVAC performance and long-term system efficiency. Filtration and long-term maintenance considerations emerged, with higher-efficiency filters improving indoor air quality but increasing long-term cost burdens for residents. Crawlspaces beneath several homes contained debris that restricted access for duct sealing, insulation, and monitoring installation, increasing labor requirements.

Programmatic and Logistical Barriers

Beyond unit-level technical issues, the project identified systemic programmatic barriers that affected implementation timelines and scope. One of the most significant barriers was the restriction on fuel switching within certain utility efficiency programs, which limited the ability to transition from gas to electric appliances even when electrification offered long-term cost and emissions benefits. Funding prerequisite repairs was challenging, as needs identified in initial assessments often exceeded energy efficiency program scopes. The project team pursued multiple external funding sources and partnerships, but differing eligibility criteria and program limitations delayed retrofit implementation.

Pre-retrofit health, safety, and structural conditions needed considerable repair before any electrification upgrade could be implemented in the study site. Excluding electrical service upgrade work, the completed repairs totaled $8,024.77 and included subfloor repairs ($4,098.73), window paneling repairs ($1,250.25), flea treatment ($1,200.00), plumbing repairs ($610.90), ceiling repairs ($550.12), and electrical inspection services ($314.77). These additional costs represented a significant project burden that would not typically be covered through standard energy efficiency funding mechanisms. Electrical service upgrades emerged as a critical bottleneck. Addressing existing service limitations requires extended coordination among utilities, property management, and contractors. In some cases, electrical service upgrades with an estimated cost ranging from $7,000-$10,000 per home added financial constraints to low-income households.

Implementing electrification measures in retrofit situations and particularly within aging infrastructure at times need additional field coordination and technical oversight. Some significant challenges included multiple site visits due to access limitation, iterative design adjustments, navigating monitoring equipment configuration and installation complexities. Additional coordination challenges affected monitoring deployment.
Workforce-related challenges, including network configuration gaps and manufactured housing such as specific installation constraints, directly contributed to extended installation times and rework.

The project also identified installation challenges that impacted post retrofit timelines, labor requirement and system installation at study sites. A key challenge was limited space and access within existing water heater closets, where the HPWH's height (72 inches) left minimal clearance for installation. Tight space, combined with restricted door openings, required additional labor for equipment positioning in the closet and raised concerns about future maintenance work, particularly for T&P valves that were partially obstructed. Equipment logistics and procurement delays also impacted installation timelines.

These challenges increased labor hours, required additional site visits, and introduced schedule uncertainty during both monitoring installation and retrofit preparation phases. As a result, workforce readiness emerged as a first-cost and schedule risk factor, not merely a training consideration, with direct implications for installed cost control in manufactured housing retrofit programs. The greatest logistical barrier was coordination with the local electric utility. Upon sharing the scope of the project with the utility, the utility notified the team they would need to upgrade the electric service at each household. The initial timeline was within 16 weeks of notification, however, due to severe weather, IT systems changes, and communication lapse, the first electric service upgrades only stated approximately 34 weeks from initial scoping assessment.

Resident Engagement-Related Insights

Some of the participating households were elderly residents living on fixed incomes, and several households included Spanish-speaking residents, requiring bilingual communication and a culturally inclusive approach.

Community engagement outcomes were closely linked to participation and data quality. Consistent, in-person engagement improved resident responsiveness and reduced missed appointments, particularly among elderly households. Visual and step-by-step materials proved more effective than text-heavy explanations in communicating retrofit activities and setting expectations with an anticipated timeline.

The Community Advocate model played a central role in sustaining participation by serving as a trusted intermediary between residents and the project team. Advocates supported scheduling, clarified technical activities in culturally and linguistically appropriate ways, and helped identify household concerns that could affect retrofit readiness. This approach reduced participation drop-off risk and improved the completeness of diagnostic data collected.

Implications For Scaling and Policy

While this pilot was conducted in ASHRAE Climate Zone 4A, the identified constraints, including electrical service limitations, oversized legacy HVAC systems, crawlspace access challenges, and deferral repair needs, are structural characteristics common across manufactured housing communities nationwide. These conditions are not climate-specific and have been documented in manufactured housing across multiple regions, indicating that the findings and implementation lessons from this project are broadly transferable beyond the Virginia context. Findings from this pilot underscore the need for integrated program design that aligns technical requirements, funding mechanisms, workforce readiness, and community trust.

Technical Diagnostics and Data Collection

Traditional retrofit programs often rely on available utility data or energy modeling, which fails to account for the gap in theoretical energy savings and operational efficiency in old, manufactured homes.

This project demonstrated the value of enhanced diagnostic methods, including blower door testing, duct leakage testing, airflow measurements, and LiDAR based building scans, that identified substantial envelope leakage and system inefficiencies that are not fully identifiable from utility data. The monitoring strategy also incorporated sub-metered electricity data and indoor air quality sensors to capture real-world operational performance.

HVAC Sizing and System Performance

In several households, duct leakage, high airflow rates, or oversized equipment were identified as concerning factors contributing to system inefficiency and potential resident comfort issues. Our selections were focused on variable airflow sized lower for smaller mobile homes ductwork, and higher dehumidification to address moisture issues.

Measured load data and advanced diagnostics are essential for right-sizing HVAC systems and avoiding performance penalties associated with oversizing.

Electrical Infrastructure Readiness

Electrification infrastructure limitations emerged as a significant barrier to electrification. Although these homes had 100A interior electrical panels, the property's original design as an RV park led to these homes with a 60A outdoor service disconnect.

Early assessment of electrical infrastructure should be a prerequisite for electrification programs in manufactured housing to prevent downstream delays, cost escalation and scope changes.

Deferral Repairs and Housing Conditions

Many of the participating homes required structural repairs before electrification measures could be implemented. Some of the key issues identified include damaged subfloor, crawlspace debris blocking access for ductwork, and plumbing leaks. While these issues were not part of our projects, ignoring them would have diminished our performance.

Flexible funding mechanisms that address deferral repairs alongside energy measures are critical to enabling comprehensive upgrades.

Community Engagement and Participation

Maintaining resident participation requires sustained communication and coordination with community advocates. Language barriers, scheduling constraints, and resident concerns required trusted intermediaries to help explain the project and maintain engagement (ACEEE 2023).

Embedding community-based roles within technical programs improves participation, data quality, and supports implementation efficiency.

Together, these lessons point to the need for policy frameworks that treat manufactured housing retrofits as integrated health, safety, and energy interventions rather than isolated efficiency measures.

Conclusions

This project demonstrates that high-performance, low-carbon retrofits in manufactured housing require a combination of advanced technical diagnostics, early infrastructure, and sustained community engagement. The study site included five (5) resident occupied units and a total of seven elderly residents, highlighting the importance of accounting for vulnerable populations with potentially higher sensitivity to comfort, indoor air quality and energy burden.

Baseline analysis showed substantial variation in household energy use, with natural gas serving as the dominant contributor to site energy consumption and space and water heating accounting for approximately 60% of modeled baseline energy use. Energy modeling results indicate that electrification combined with envelope improvements reduces total site energy use to approximately 68% of baseline while reducing natural gas consumption by more than 90%.

Enhanced diagnostic methods, including blower door testing, duct leakage testing, airflow measurements, and LiDAR based building modeling provided detailed insight into building envelope and system performance. These measurements identified significant air leakage, duct system inefficiencies, and airflow imbalances that would not have been captured through utility data alone. Field diagnostics identified significant envelope leakage (3,000–4,800 CFM50), HVAC oversizing, and degraded insulation, reinforcing the value of measured building performance data for correct system sizing. Implementation was also constrained by deferred maintenance and limited electrical service capacity (60A outdoor disconnects), which required resolution prior to retrofit deployment. The findings underscore the importance of field-based measurements to support accurate system sizing and avoid performance losses associated with oversized or improperly calibrated equipment (Pigg et al. 2023).

Modeling results indicate that electrification paired with envelope improvements reduced total site energy use to ~68% of baseline and cut natural gas consumption by more than 90%. Peak heating loads fell from 30 to 18 kBtu/hr, reflecting both heat pump efficiency and reduced building loads following envelope improvements, while peak cooling loads also declined (18 to 14 kBtu/hr). Heat pump technology also substantially reduced end-use heating and water heating demand, with modeled heating energy dropping from 40,000 to 17,000 kBtu and water heating from 20,000 to 8,000 kBtu.

If these modifications are done systematically and programmatically with incentive support from many participants (owners, utilities, local groups, state and federal programs) the benefit can be tremendous and economically feasible with a less than 10-year simple payback.

Structural and infrastructure constraints, including limited electrical service capacity (60A exterior disconnects), deferred health and safety repairs, and crawlspace access limitations, had to be addressed prior to retrofit implementation and often required additional funding support. These findings underscore the importance of flexible program designs that integrate energy upgrades with essential pre-retrofit repair needs.

Community engagement was critical to successful implementation. Coordination with community advocates helped overcome language barriers, maintain resident participation, and support high-quality data collection through trusted, on-the-ground engagement.

By combining technical rigor with community-embedded implementation approaches, the pilot establishes a replicable framework for equitable retrofit delivery in manufactured housing communities. Ongoing monitoring and post-retrofit analysis will further refine best practices and support the development of scalable programs that advance energy affordability, resilience, and decarbonization goals nationwide.

Acknowledgements

This work was developed based upon funding from the Alliance for Sustainable Energy, LLC, Managing and Operating Contractor for the National Laboratory of the Rockies, formerly the National Renewable Energy Laboratory for the U.S. Department of Energy. The authors also acknowledge the contributions of project partners, community organizations, and participating residents, Rebuilding Together-Arlington/Fairfax/Falls Church.

AI-assisted Tools: Disclosures and Responsibility

AI-assisted tools used: Microsoft Copilot.

Used for: drafting assistance, formatting, citation research, and editorial refinement.

Extent: light drafting and editing support.

Human review: The authors reviewed and verified all content, analysis, calculations, and citations and take full responsibility for the accuracy of the work.

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