Field Performance and Policy Implications of All-Electric Manufactured Homes in Hot Climates

Agatha Kazdan, Mazen Daher, Electric Power Research Institute (EPRI)
Jordan Dentz, Joy Liao, Systems Building Research Alliance (SBRA)

ABSTRACT

Manufactured housing is the largest source of unsubsidized affordable housing in the United States, yet it has historically lagged site-built housing in energy performance due to less stringent energy code requirements. This paper presents two years of field data from three all-electric manufactured home prototypes deployed in hot inland California climates. The homes were designed to achieve California Title 24-equivalent performance while operating on 100-amp electrical service and incorporating heat pumps, rooftop photovoltaics (PV), and enhanced building envelopes.

The study combines commissioning results, simulated-occupancy benchmarking, and occupied performance monitoring. Occupied performance is compared with Title 24 compliance models and a representative US Department of Housing and Urban Development- (HUD-) code baseline model using three metrics: long-term system cost (LSC), marginal greenhouse gas emissions, and resident utility costs. The three monitored homes exhibited substantially lower utility costs, long-term system costs, and greenhouse gas emissions than the representative HUD-code benchmark. Circuit-level analysis suggests that compliance models overpredicted annual energy consumption while underpredicting late-summer cooling demand.

Because only three occupied homes were monitored, the results should be interpreted as a field demonstration rather than statistically representative evidence. However, the technology packages were developed and reviewed with participation from leading manufactured-home producers, providing insight into scalable pathways for electrification and energy-efficiency improvements in this housing segment.

1. Introduction and Background

Manufactured homes are factory-built dwellings constructed under the federal Manufactured Home Construction and Safety Standards (HUD, 2024). In California, new manufactured homes are generally exempt from state energy code, Title 24 Part 6, despite the state's ambitious building decarbonization goals. Consequently, these homes tend to require more energy than a comparable site-built home for space conditioning, resulting in increased costs for those who can typically least afford it (Gabbe et al., 2025). According to the 2020 Residential Energy Consumption Survey data, the average energy use expenditures per square foot were $0.94 per square foot for single family homes in the US versus $1.27 per square foot for manufactured homes (though this may at least in part be explained by the fact that manufactured homes are smaller while containing the same end-uses). Bell-Pasht and Ungar (2022) investigated the potential for closer alignment of manufactured home standards with the International Energy Conservation Code (IECC) to alleviate energy burdens among manufactured home residents. They found that such a measure could reduce the percentage of energy burdened households residing in manufactured homes from 43% to 28%. The expected decrease was more pronounced for some demographics of interest, such as renters (46% to 30%) and low-income residents (71% to 41%). Talbot (2012) investigated specific design measures that would cost-effectively enhance the energy efficiency of manufactured homes. His analysis found that building shell measures and ductless HVAC systems would be particularly attractive measures for manufactured homes. Tang et al. (2024) explored the environmental benefits of subjecting manufactured home design to more stringent requirements in alignment with the Department of Energy's (U.S. Department of Energy, 2023) Zero Energy Ready Home (ZERH) program. They found that the net prospective benefit from ZERH-compliant design would amount to 680 kg eq CO_2 per year. Carley et al. (2023) looked beyond modeled benefits of more efficient designs in manufactured homes and explored the barriers to scalability of these practices, using the specific example of the Energiesprong model adopted in several European countries (Brown et al., 2018). They identified several challenges which hinder the adoption of energy conservation measures in manufactured homes, including structural challenges, production costs, and customer price sensitivity.

The present study developed, deployed, and monitored three all-electric manufactured-home prototypes in inland California climates. The homes were designed to demonstrate production-ready pathways to Title 24-level performance while remaining compatible with the 100-amp electrical service commonly found in manufactured-home communities.

A distinguishing feature of the project is that the prototype packages were developed in collaboration with the five highest-volume manufactured-home producers in the United States. Although the occupied monitoring sample consisted of only three homes, the design concepts themselves were vetted by organizations representing a substantial share of U.S. manufactured-home production. Accordingly, the paper focuses on lessons related to field performance, manufacturability, and implementation rather than statistical inference regarding the broader housing stock.

2. Study Design and Methods

2.1 Home Design

The demonstration included three homes: Home A (648 ft²) and Home B (648 ft²) are single-section homes, and Home C (1,050 ft²) is a multi-section home. Homes A and B use ductless mini-split heat pumps; Home C uses 120-volt packaged terminal heat pumps. All homes use heat pump water heaters and rooftop solar photovoltaics (PV). Two strategies were tested to manage 100-amp service constraints: smart electrical panels (Homes A and C) and an “economy of wattage” strategy relying on low-amperage appliances (Home B).

Table 1 summarizes the primary performance objectives established for the prototype homes. One important metric is the Energy Design Rating (EDR), a California Title 24 compliance metric that compares a home's modeled energy performance to a code-defined reference building. Lower EDR values indicate better energy performance, with an EDR of 100 representing a minimally compliant home and an EDR of 0 corresponding approximately to a net-zero-energy design under Title 24 assumptions. While EDR is not intended to predict actual occupied energy consumption, it provides a useful benchmark for comparing the relative efficiency of alternative home designs. In addition to achieving low EDR values, the project sought to demonstrate all-electric operation, compatibility with 100-amp electrical service, and technology packages that could be feasibly integrated into manufactured-home production.

Table 1. Performance targets relative to typical new HUD-code manufactured homes.

Performance Metric	Industry Standard	Research Goal
Energy Design Rating (EDR) and fuel type	EDR 80–100 typical for new HUD-code mixed-fuel homes	All-electric with EDR near 0 (goal) and sub-15 (targeted)
Energy performance (energy per square foot)	HUD Code practice	Meet Title 24 (2019) and align with DOE Efficient New Home intent; remain within 100 amps
Wall insulation (R-value)	R-11 to R-15	R-26 to R-29
Roof insulation (R-value)	R-20 to R-30	R-49
Envelope airtightness (ACH at 50 Pascals	No requirement; commonly 3–7	1–2
HVAC configuration	Typical HUD practice	Evaluate alternative heat pump configurations
Production friendliness	High	Factory-installed HVAC and PV where feasible

Technology packages were selected to meet project performance targets described in Table 1 through iterative design development and modeling to assess Title 24 performance and cost-effectiveness. Table 2 summarizes the prototype packages along with their locations based on California's climate zone definitions. All three homes were in Southern California Edison service territory.

Table 2. Prototype technology packages.

Home A (648 ft²)	Home B (648 ft²)	Home C (1,050 ft²)
Location: California Climate Zone 13	Location: California Climate Zone 10	Location: California Climate Zone 13
Advanced air sealing	Prescriptive air sealing	Aerosol spray air sealing
Mini-split heat pump (SEER 19; HSPF 10)	Mini-split heat pump (SEER 19; HSPF 10)	Packaged terminal heat pump (120V)
Heat pump water heater (HPWH)	HPWH (15-amp)	HPWH
PV 2.96 kW; solar-ready (site installed)	PV 3.07 kW; factory-installed shingles	PV 4.44 kW; solar-ready (site installed)
Smart panel load limiting	Standard panel; low-amperage appliances	Smart panel load limiting

2.2 Data Collection

Monitoring systems differed by home. Homes A and C used smart panels that provide breaker-level data in the cloud, while also relying on supplemental current transducers for data verification and redundancy. Home B used current transducers for selected circuits representing the largest loads (including HVAC, water heating, and the largest appliances). Smart inverter data showing solar production was available for all three homes. Furthermore, Advanced Metering Infrastructure (AMI) data was available through the local utility. As the smart panels allowed for more comprehensive monitoring of all circuits and end-uses compared to the selective monitoring implemented in Home B, the circuit monitoring section of this paper uses data from Homes A and C.

2.3 Testing the Homes

The monitoring study was conducted in two phases. The first year monitored unoccupied homes with simulated internal loads to establish an "as-delivered" baseline and to identify performance gaps. The second year monitored the homes under real occupancy to assess how organic behavior and real-world operation affect energy use, demand, and customer costs. This paper emphasizes the occupied phase while retaining key commissioning and simulated occupancy benchmarking results as supporting evidence.

2.4 Performance Metrics

Performance was evaluated using three metrics representing distinct stakeholder perspectives.

- Long-Term System Cost (LSC, formerly Time Dependent Valuation [TDV]) was used to assess performance relative to California Title 24 compliance objectives and to estimate the societal value of energy use and conservation.
- Marginal greenhouse gas (GHG) emissions factors published by the California Energy Commission were used to estimate operational carbon impacts.
- Resident utility costs were calculated using Southern California Edison's TOU-D-4-9PM tariff and reconciled with utility bills to evaluate customer affordability outcomes.

Together, these metrics provide perspectives on grid impacts, environmental performance, and household economics. Additional details regarding the calculation methodologies and California compliance framework are available in California Energy Commission documentation and prior project publications (Kazdan et al. 2024; Kazdan et al. 2025).

2.5 Benchmark Energy Models

Two benchmark sets of energy models were used in this study: First, a representative mixed-fuel HUD-code manufactured-home prototype from the DOE EnergyPlus prototype building library was used as a counterfactual baseline. The prototype represents prevailing manufactured-housing practice and includes natural-gas space and water heating. Comparisons against this baseline provide context for evaluating the relative affordability, emissions, and system impacts of the all-electric prototype designs. Second, Title 24 compliance models developed with Building Energy Optimization (BEopt) software during the design phase (Kazdan et al., 2024) were used to assess the performance of the homes against design targets.

3. Commissioning and Baseline Benchmarking (Simulated Occupancy Phase)

All three homes underwent commissioning and as-delivered assessment to verify installation quality and to understand transport and set-up impacts. Blower door testing performed after site installation showed all three homes exceeded the 3 ACH50 target. Blower door testing was conducted in the plant yard on the individual sections of Home C immediately before and after application of aerosol air sealant, resulting in a drop from 4.3 to 1.97 air changes per hour at 50 pascals (ACH50)(average of both home sections). Table 6 summarizes the field blower door results for all three homes (Homes A and B were not tested at the factory). The full set of commissioning tests conducted post-deployment are available to the reader in prior publication discussing the production phase of this project (Kazdan et al., 2024). Marriage line leakage, damage during installation and/or long range transportation may have contributed to envelope loosening in Home C. Given the emphasis that prior literature has placed on envelope robustness for manufactured home energy efficiency (Talbot, 2012), this pattern was important to document ahead of the two energy monitoring phases.

Table 6. Blower door test results after site installation.

Home	Square Footage (ft^2)	Building Volume (ft^3)	ACH50 (-50 Pa)
Home A	650	5,200	3.46
Home B	650	5,180	4.60
Home C	1,040	8,320	3.40

Commissioning identified several performance gaps between design intent and field deployment. Post-installation blower-door testing indicated that all three homes exceeded the project airtightness target of 1-2 ACH50. Simulated-occupancy benchmarking also showed that only one home met its modeled Title 24 target. These results suggest that model accuracy, transportation, site installation can materially influence realized performance in factory-built housing.

The commissioning results were documented before occupied monitoring began and provided important context for interpreting subsequent field-performance results. Detailed commissioning procedures and simulated-occupancy analyses are reported in prior publications (Kazdan et al. 2024; Kazdan et al. 2025). Measured EDR values are reported here solely as a comparative benchmark against modeled expectations intended to provide a consistent basis for comparing realized performance against the original Title 24 compliance assumptions. Table 7 illustrates the extent to which realized performance during the simulated-occupancy phase diverged from design expectations. Although all three homes were modeled to achieve similar EDR values and Title 24 compliance margins, only Home B achieved its compliance target during field testing.

Table 7. Simulated occupancy phase performance relative to modeled energy design ratio and Title 24 compliance targets

Site	Modeled EDR_e	Measured EDR_e	Compliance EDR_e	Compliant?
Home A	54	85.3	54.9	No
Home B	50.9	53.4	54.8	Yes
Home C	50.5	83.0	52.9	No

Homes A and C exhibited measured EDR values approximately 30 points higher than predicted, indicating materially higher energy consumption than anticipated under simulated occupancy conditions. It should be noted that Home A experienced significant HVAC malfunctioning which may have distorted its results to some extent. Still, the results for Home A are included to underline the challenges in deploying novel HVAC equipment in the manufactured housing sector.

These results suggest that field deployment and/or production effects, in addition to inherent modeling limitations (in particular, related to variable speed HVAC modeling assumptions), can erode performance gains estimated during the design phase. While the sample size is limited, the results underscore the importance of commissioning and quality assurance in manufactured housing, where transportation and site installation may significantly influence realized energy performance.

Notably, the elevated measured EDR values observed during simulated occupancy did not necessarily translate into poor occupied performance. For example, several HVAC and wiring defects were addressed prior and during occupancy highlighting the importance of evaluating both standardized benchmarking conditions and real-world operation.

4. Occupied Performance Results

The simulated-occupancy phase established an important baseline for interpreting occupied performance. Although commissioning identified envelope and heat pump performance deficiencies relative to design expectations, the occupied-monitoring phase provided an opportunity to evaluate whether these deficiencies translated into meaningful impacts on customer costs, emissions, and overall energy use under real-world operating conditions.

Despite the commissioning and simulated-occupancy performance gaps, all three homes generally outperformed the HUD-code baseline for all three metrics. Figure 1 compares annual customer energy costs under modeled and measured conditions. Measured costs were lower than those associated with the representative HUD-code baseline, even before accounting for photovoltaic (PV) generation. The addition of PV further reduced costs, although the magnitude of savings depended strongly on the compensation structure used for exported electricity. The contrast between Net Energy Metering (NEM) 2.0 and the Net Billing Tariff (NEM 3.0) highlights the growing importance of load matching and self-consumption in residential electrification strategies. One example is Home B, where annual energy costs fell from approximately $4.60 per square foot in the HUD-code baseline to $2.25 per square foot without solar. When solar was included, Home B's costs dropped further to approximately $0.49 per square foot under NEM 2.0 and $1.58 per square foot under NEM 3.0. Even under NEM 3.0, costs remained substantially below the HUD-code baseline, but the economics are materially different.

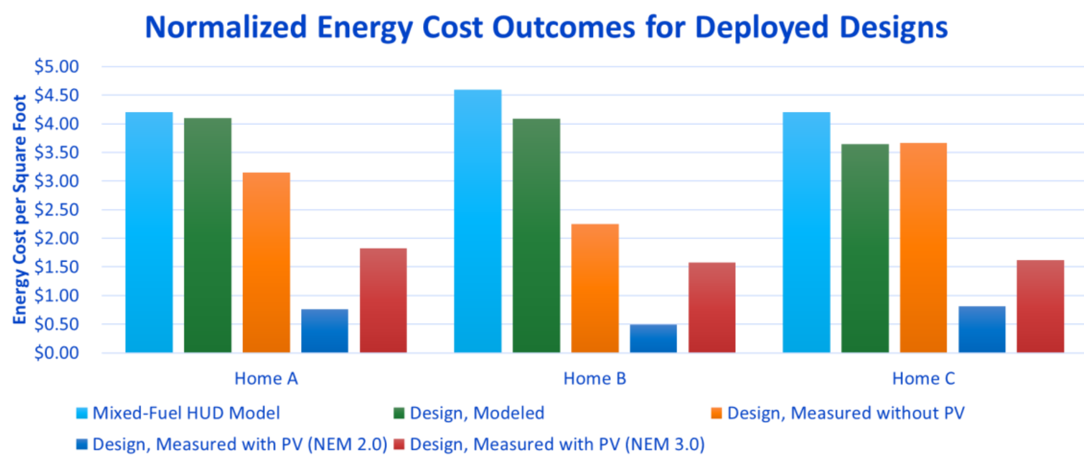

Figure 1. Observed customer energy costs normalized by floor area for different scenarios.

Figure 2 shows LSC outcomes under the same scenarios. Similar to resident costs, PV production appears to be a very significant driver of long-term system cost reductions, accounting for most of the total reduction for all three homes. In line with what was observed for utility costs, the measured performance of the homes tends to be better than the modeled performance.

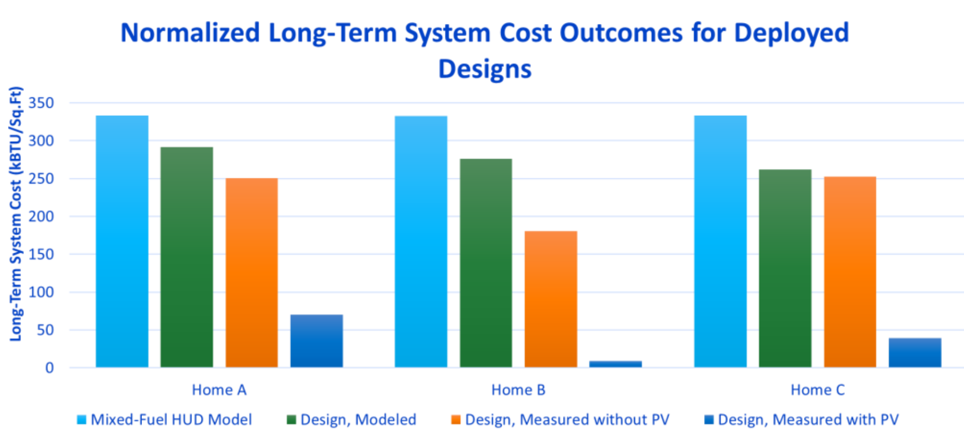

Figure 2. Observed long-term system costs normalized by floor area for different scenarios.

Figure 3 shows the emissions per square foot for each scenario for all three homes. A similar pattern emerges to that observed for the two other performance metrics. Measured emissions outcomes are generally consistent with modeled expectations. PV exports do not reduce emissions to the same extent that they reduce LSC. Under Title 24 assumptions for long run marginal emissions, grid imports of electricity are considered to incur no carbon emissions during periods of peak solar generation, particularly in spring and summer, due to the prevalence of utility scale solar in California. As a result, while PV drives substantial reductions in LSC (aligning with ZNE design principles), it does not reduce emissions as effectively.

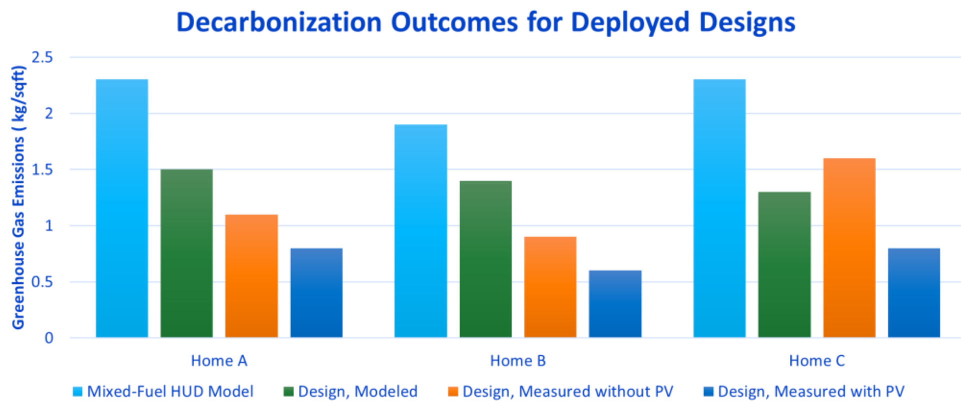

Figure 3. Observed greenhouse gas emissions normalized by floor area for different scenarios.

Circuit Level Analysis Results

End-use comparisons between modeled and measured performance revealed a consistent pattern across Homes A and C (Figures 4 through 6). It should be noted that these results are not weather normalized at the time of this writing. The Title 24 compliance models generally overpredicted annual electricity consumption while generally underpredicting HVAC energy use (though it should be noted that the data under study was not weather normalized). In both homes, measured domestic hot water and appliance loads were frequently lower than modeled assumptions, partially offsetting higher cooling consumption. Both homes had higher occupancies (3 vs 2 for Home A, 5 vs 3 for Home C) than what was modeled under Building America Simulation Protocols (Wilson and Horowitz, 2016).

Because occupant schedules and behaviors were not controlled during the occupied-monitoring period, the results do not identify causal behavioral mechanisms. However, the consistency of the observed directionality suggests that assumptions regarding internal gains, appliance use, and occupancy schedules may warrant further investigation for high-efficiency manufactured housing in hot climates.

HVAC energy use patterns are notable and warrant further discussion. As previously noted, the home’s occupied measured energy use tends to outperform benchmark models, with lower energy use, customer costs, system costs, and emissions. Yet, results described in a prior paper (Kazdan et al., 2025) showed higher HVAC energy use compared to the same benchmark models and a reliance on solar exports for cost reductions during the simulated occupancy phase of the deployment. However, a closer look at the circuit monitoring results reveals that HVAC energy use remained higher than the model, and that general performance gains observed in monitoring (compared to modeling) appear to stem from reduced energy consumption in other end-use categories. Lower occupant-driven loads offset elevated cooling consumption in these households.

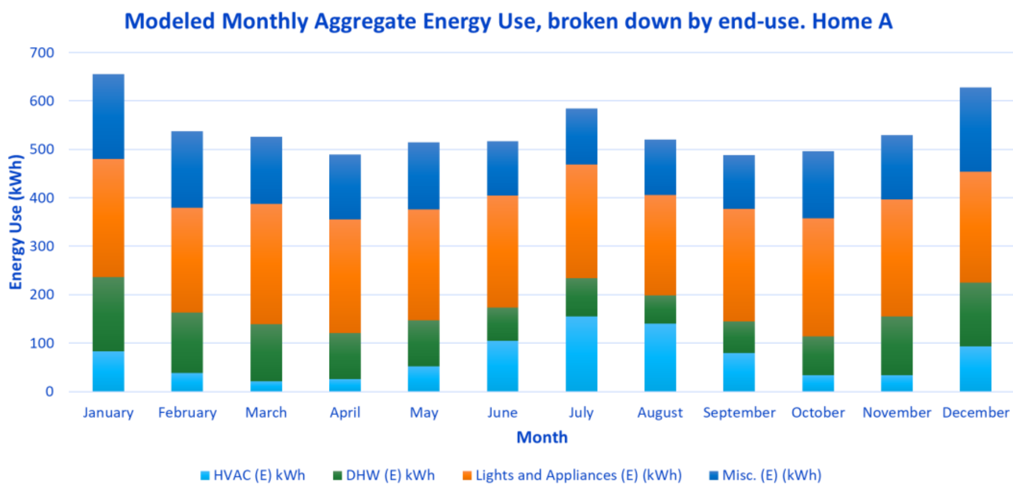

Figure 4. Modeled Monthly Aggregate Energy Use, broken down by end-use. Home A

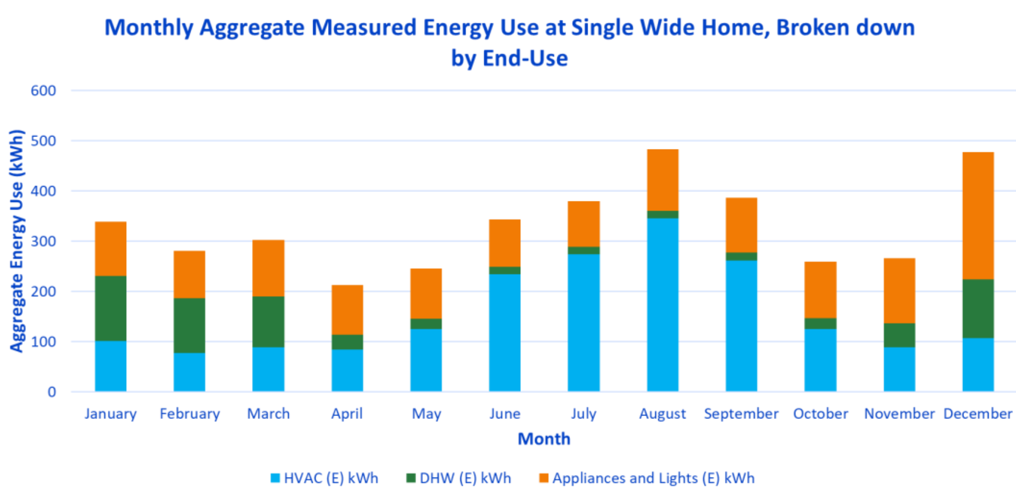

Figure 5. Measured Monthly Aggregate Energy Use, broken down by end-use. Home A

The modeled data consistently overestimates total energy use, predicting monthly totals between 500 and 700 kWh, whereas the actual measured use rarely exceeds 500 kWh.

Domestic Hot Water (DHW) and Appliances/Lights categories appear much larger and more static in the model; in reality, these uses fluctuated more month-to-month and generally amounted to lower totals than those that the model suggested. These differences in energy use may be attributed to individual behavioral patterns that are not clearly captured in generalized code compliance modeling. Therefore, compliance modeling software assumptions may have played a role in the discrepancies observed here.

Figure 5 shows the monthly aggregate energy use by end use for Home C, as predicted by the Title 24 Code Compliance Model previously developed for this project. Figure 6 shows the same end-use breakdown but based on measured data.

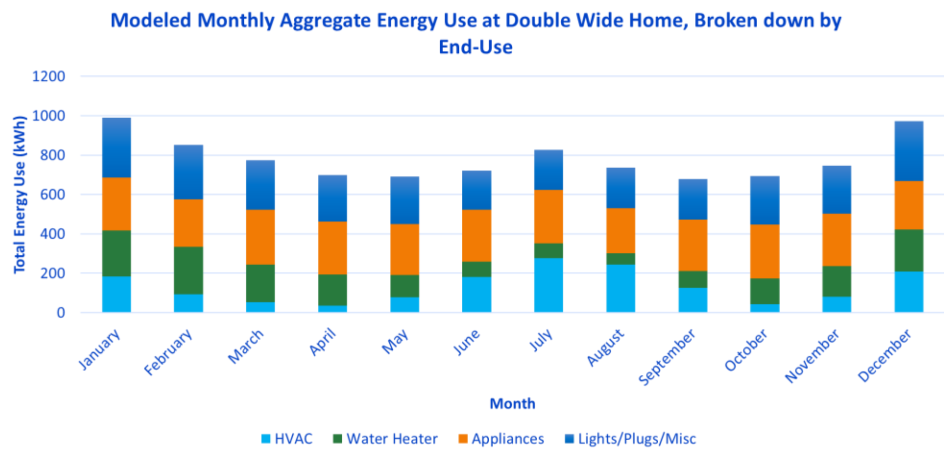

Figure 6. Modeled Monthly Aggregate Energy Use, broken down by end-use. Home C

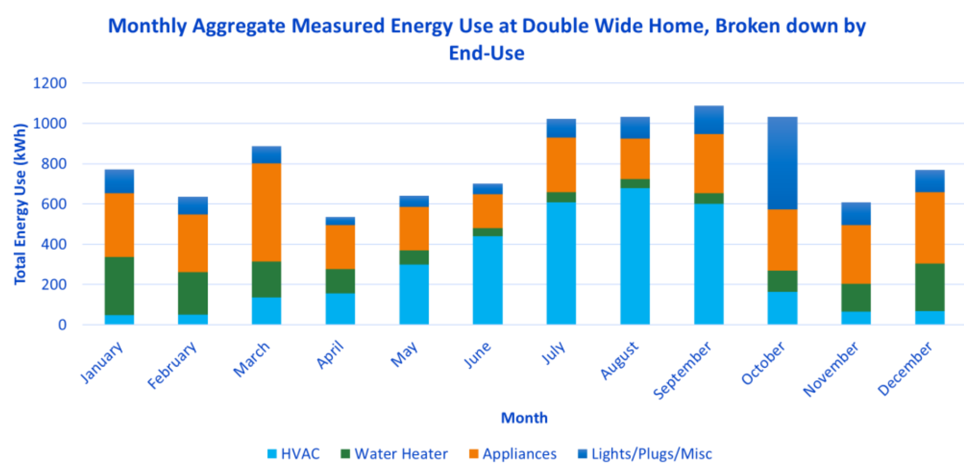

Figure 7. Measured Monthly Aggregate Energy Use, broken down by end-use. Home C

Directionally, analysis for Home C reveals a similar disconnect between modeled predictions and real-world performance to that observed in Home A. While the modeled data predicted relatively stable monthly totals fluctuating between roughly 700 and 1,000 kWh, the actual measured use shows higher volatility, peaking significantly above the model in the late summer. Specifically, HVAC consumption (light blue) shows substantial seasonal differences. While the model estimated moderate heating and cooling needs, measured performance data shows a substantial increase in energy use for cooling from June through September, with measured HVAC energy use being significantly larger than modeled HVAC energy use. However, winter HVAC use was lower than the model suggested.

As also seen in Home A, the Water Heater and Appliances categories appear larger and more consistent in the model than in practice. Measured energy use from those circuits was often lower than predicted. As discussed with respect to Home A, these differences in energy use may be attributed to individual behavioral patterns that are not properly captured in generalized code compliance modeling. However, while this field data is useful for assessing real world performance, a larger sample size is needed to draw more definitive conclusions as to the modeling deficiencies observed in this small-scale deployment.

End-use comparisons between modeled and measured monthly totals indicate a consistent pattern for Homes A and C in which the Title 24 compliance model overpredicted total consumption while underpredicting the intensity of cooling demand. In both homes, measured domestic hot water and general appliance loads were often lower than modeled assumptions, partially offsetting the elevated cooling demand. Because occupant behavior and schedules were not controlled during the occupied year, the results do not isolate behavioral causal mechanisms. The observed discrepancies should not be interpreted as evidence that Title 24 compliance models systematically overpredict energy use in manufactured housing. Rather, they suggest that total energy use is highly dependent on occupant behavior, internal gains, and end-use schedules. Additional field data from a larger sample of high-efficiency manufactured homes would be needed to determine whether the patterns observed here are broadly representative.

4. Discussion

Despite commissioning and simulated-occupancy performance gaps, all three homes generally outperformed the HUD-code baseline across all metrics. Annual energy costs under measured conditions remained below the baseline even without photovoltaic (PV) generation, and PV provided additional savings. However, the difference between NEM 2.0 and NEM 3.0 compensation structures demonstrates the increasing importance of load matching and self-consumption. Although savings were reduced under NEM 3.0, energy costs remained substantially below the baseline.

Across both code compliance metrics that were assessed (LSC and greenhouse gas emissions), all three homes showed substantial improvement when compared to a counterfactual HUD-code baseline. Reductions in LSC appear to be driven in large part by solar exports, whereas reductions in greenhouse gas emissions, which are less sensitive to solar exports (due to California's high renewable penetration), appear to be driven by electrification and improved efficiency. This difference can be inferred from Figures 2 and 3, which show the introduction of solar drastically reducing the LSC footprint of the homes, but having a less pronounced effect on the GHG footprint.

From a modeling perspective, the findings highlight potential systematic differences between compliance-model assumptions and real-world operation in this housing segment. In particular, the observed combination of higher-than-modeled cooling intensity and lower-than-modeled appliance and hot water loads suggests that internal gain schedules and end-use profiles used for code compliance may not always align with occupied performance for small, high-efficiency manufactured homes. While this does not imply that compliance models are inappropriate for regulatory use, it does suggest that additional field data can improve the representativeness of assumed schedules and behaviors for this housing segment, which has not historically been given substantial attention in code compliance modeling. Because the study monitored only three occupied homes, these observations should be viewed as hypotheses for future investigation rather than evidence of systematic bias in compliance-model assumption.

Finally, the project experience underscores that installation quality and workforce readiness influence realized performance. Even in factory-built contexts that offer control and repeatability, field deployment steps can introduce defects that affect envelope tightness, HVAC operation, and PV functionality. The occupied-year results indicate that overall performance can remain strong even with some observed defects, but scaling will require consistent commissioning, installer training, and clear responsibilities across factory and site trades. These implementation lessons align with broader findings from California demonstration efforts emphasizing the importance of workforce development and commissioning for high-performance, electrified housing.

This study has limitations that should be considered when interpreting the results. The sample includes three homes and a small number of households, which constrain representativeness across demographics and behavioral patterns. In addition, not all end-use circuits were metered in all homes, and PV telemetry gaps required limited supplementation with modeled estimates. Future work should expand the sample size across additional climates and occupant profiles and should include improved instrumentation for all major end uses to strengthen attribution of load drivers and to support more rigorous statistical assessment.

5. Policy Implications

Three discussion points emerge from this field demonstration.

First, the prototype designs achieved substantially lower utility costs, LSC, and greenhouse gas emissions than the representative HUD-code baseline while remaining compatible with 100-amp electrical service. This is significant because electrical-service upgrades can represent a major barrier to electrification in affordable housing.

Second, customer economics were highly sensitive to solar-export compensation. The transition from Net Energy Metering (NEM) 2.0 to the Net Billing Tariff (commonly referred to as NEM 3.0) materially reduced the value of exported electricity. Although the homes continued to outperform the HUD-code baseline under both compensation structures, the results suggest that future designs should prioritize efficiency, load management, and self-consumption rather than relying primarily on exported solar generation.

Third, the monitored homes consistently exhibited higher cooling consumption and lower appliance and domestic hot water consumption than predicted by compliance models. While the sample size is insufficient to support broad conclusions regarding model accuracy, the consistency of the observed pattern suggests opportunities for future investigation of occupancy schedules, internal gains, and end-use assumptions used in residential compliance modeling.

The occupied monitoring sample consisted of only three households and therefore does not support statistical inference regarding the broader manufactured-housing stock. The findings should instead be interpreted as evidence from a field demonstration of production-ready prototype designs. However, the technology packages evaluated in this study were developed in a real-world setting and reviewed through a Technical Advisory Committee representing the five highest-volume manufactured-home producers in the United States. As a result, while the monitored outcomes are not statistically representative, the design strategies themselves reflect approaches considered feasible by organizations representing a substantial share of U.S. manufactured-home production.

6. Conclusion

This paper evaluated the occupied-year field performance of three all-electric manufactured homes designed to meet California Title 24 performance targets while operating on 100-amp service in hot inland climates. The results show that measured utility costs and lifecycle societal metrics outperformed representative HUD-code baselines, supporting the premise that high-efficiency electrified manufactured housing can improve affordability and reduce emissions. The findings also demonstrate that energy tariff design and solar compensation structures closely correlated to resident bill outcomes and can alter perceived cost-effectiveness even when underlying energy performance is strong. Together, these findings illustrate the value of field demonstrations for refining modeling assumptions, informing code and program design, and accelerating equitable deployment of electrified manufactured housing.

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