PonderHouse: A Ponder-Based Mass Timber Home That Helps our National Forests and Provides Sustainable, Resilient Housing

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ABSTRACT

The current urgency to thin fire-prone national forests provides a ready feedstock for cities that need to provide energy-efficient, sustainable, and resilient housing. Ponderosa pine is the most common and dominant tree species in the Rocky Mountains. Thus, cross-laminated timber (CLT) based on ponderosa pine can become the go-to envelope solution to help builders, cities, and the United States Forest Service achieve their housing and sustainability goals. CLT's inherent airtightness, combined with ample thermal mass and high insulation levels, could provide a resilient and sustainable home with minimal HVAC needs. However, most architects and contractors are not familiar with CLT, and there are no open-source blueprints to empower people and developers to build mass timber homes. This paper presents detailed drawings and energy analysis for a flexible housing unit design that aims to maximize current CLT dimensions and performance characteristics while meeting passive house standards. The result is PonderHouse, a ponderosa-based CLT home for different family sizes. This presentation will cover the details and outline the broad benefits: compared to other manufactured home options in Denver, CO, Atlanta, GA, and Medford, OR, our results show that the electrified PonderHouse can achieve lower electric usage than other modern manufactured home options , all while reducing energy bills by 30% and CO_2 emissions by about 50%. PonderHouse can also maintain indoor air temperatures above 60°F for four times longer (24 hours) during a winter power outage.

Introduction

Manufactured housing comprises about 10% of the new single-family housing stock in the United States (United States Census Bureau 2025). Communities across the United States face an intersecting crisis of rising housing costs, increasing natural disaster risk, and a rapidly growing need for resilient, low-carbon construction. Housing affordability across the United States has sharply declined, with conventional single-family homes priced far beyond what many residents can afford (Zhao 2025). Concurrent to the housing challenge, in areas like Southwest Colorado, aggressive forest thinning is urgently needed to reduce wildfire intensity and prevent fires from climbing exponentially, yet there is currently a four-billion-dollar backlog in treatment for overgrown forests (Colorado State Forest Service 2020). These challenges highlight the urgent need for holistic solutions that leverage forest products into new housing solutions that are not only affordable, but also durable, energy efficient, and resilient to disruptions such as extreme weather caused power outages. Developing housing systems that can maintain safe indoor conditions, minimize long-term energy costs, and provide long service life is especially critical for low-income communities, who are often the most overlooked yet the most vulnerable to energy insecurity and climate-related hazards. Addressing housing affordability while utilizing locally available forest resources presents a unique opportunity to rethink how residential design, forest management, and material selection can work together to create safer, more sustainable, and resilient communities.

Ponderosa pine is one of the most prevalent tree species in Colorado, and due to its large volume, it requires significant thinning efforts to mitigate wildfire risk and improve forest health (Colorado State Forest Service 2025). Ponderosa pine can be utilized in low-rise CLT structures although additional investigation is required to evaluate broader performance implications (Bhandari et al 2021). In addition to its abundance, ponderosa pine possesses favorable characteristics for mass timber manufacturing, including good dimensional stability and high bending strength and stiffness for residential applications. Leveraging this abundant species in cross-laminated timber (CLT) production offers a pathway to supply a renewable material for housing while also reducing hazardous forest overgrowth. Historically ponderosa pine has not been associated with building products or mass timber. However, recent efforts by Timber Age Systems Inc have developed ponderosa-based CLT panels for the residential market.

CLT has gained attention for its structural performance, carbon storage capabilities and compatibility with modular and prefabricated construction methods. Prior research has analyzed the structural and environmental performance of CLT panels and current research examines the energy implications of CLT buildings. For example, Salonvaara et al (2024), found that CLT construction in commercial buildings can reduce HVAC energy use and cooling demand compared to conventional systems. While these findings are useful, most existing research centers on commercial or multi-story applications rather than single-family residential housing. In parallel, high-performance residential design frameworks, such as Passive House, emphasize enhanced insulation strategies, greater air tightness, and use of thermal mass to reduce energy demand. Here, CLT could provide additional mass to increase passive house thermal resilience. Mach et al (2025), evaluated a residential single-family home built to passive house standards and saw a substantial reduction in GHG emissions. However, there is still a lack of clarity about how these principles can be incorporated into scalable CLT residential housing.

Despite increasing interest in CLT and high-performance residential design, substantial research gaps remain. Most existing studies focus on commercial or multi-story applications, with relatively little attention given to affordable single-family housing, operating costs, and resilience to power outages during extreme weather events. At the same time, many manufactured homeowners, housing providers, and community developers must decide whether to continue operating older manufactured homes, invest in retrofit improvements, replace older homes with newer energy-efficient manufactured homes, or pursue alternative high-performance housing solutions. However, there is limited research comparing these options using consistent metrics for energy performance, utility costs, emissions, and resilience.

To address this gap, this paper analyzes potential retrofit and electrification scenarios for Pre-HUD manufactured homes across three climate zones in the US: (1) retrofitting using weatherization assistance program, (2) replacing with a new ENERGY STAR manufactured home, (3) replacing with a new DOE Zero Energy Ready manufactured home, and (4) replacing with a ponderosa pine cross-laminated timber home. The results provide a comparison of energy use, operating costs, emissions, and resilience outcomes to support housing decisions for homeowners, developers, and affordable housing providers.

Methodology

This study evaluates operational energy performance, utility costs, peak loads, carbon emissions, and resilience potential for a range of housing options available to manufactured home residents and affordable housing providers. The analysis compares housing upgrade scenarios a homeowner, state or utility program could face: (1) retrofit a pre-HUD manufactured home, (2) buy a new ENERGY STAR manufactured home, (3) buy a DOE Zero Energy Ready manufactured home, and (4) buy a CLT home. These scenarios represent common options for homeowners seeking to improve housing performance, affordability, and resiliency. All housing upgrade scenarios are simulated across three representative International Energy Conservation Code climate zones to evaluate performance under varying heating and cooling conditions. The designs are compared based on total energy consumption, average daily energy use, peak heating and cooling loads, annual energy costs, operational carbon emissions, and resiliency performance during simulated power outage conditions.

All analyzed homes represent affordable housing solutions for manufacturing housing:

- Pre-HUD Manufactured Home. This housing scenario represents an existing manufactured home constructed prior to the implementation of federal manufactured home standards (HUD 1976). We chose Pre-HUD because there are around 1-1.5M houses in this category that need urgent repairs or replacement (Hamberg 2025). The model is based on homes currently being monitored as part of a parallel community-scale retrofit and electrification study involving approximately 30 manufactured homes in Colorado (Munz 2025). These homes are typically smaller (500-900ft^2) than modern manufactured homes and are characterized by limited insulation, significant air leakage, single-pane windows, and aging mechanical systems. Window sizes, orientation, infiltration rates, and HVAC efficiency are based on field observations from the monitored homes.
- Retrofitted Manufactured Home. This housing scenario represents a pre-HUD manufactured home that has undergone a comprehensive weatherization and electrification retrofit based on actual electrification project (Tabares-Velasco 2026). The retrofit package includes envelope improvements, air sealing measures, upgraded windows, and high-efficiency appliances and mechanical systems. The purpose of this scenario is to evaluate the potential benefits of improving an existing manufactured home rather than replacing it. Retrofit measures and performance characteristics are based on improvements currently being implemented and evaluated within the parallel community retrofit study (Munz 2025).
- ENERGY STAR Manufactured Home. This scenario represents a newly constructed manufactured home meeting the requirements of the ENERGY STAR Certified Homes Program (ENERGY STAR 2026). Compared to older manufactured homes, ENERGY STAR homes incorporate improved insulation levels, tighter building envelopes, higher-performance windows, and more efficient HVAC equipment. This housing option represents a commonly available replacement option for homeowners seeking improved energy performance while remaining in the manufactured home market.
- DOE Zero Energy Ready Manufactured Home. This scenario represents a newly built manufactured home meeting the U.S. Department of Energy Efficient New Homes

Manufactured Homes National Program requirements. These homes achieve higher performance than ENERGY STAR homes due to slightly higher requirements for insulation, air tightness, and mechanical systems. This option represents one of the highest-performing manufactured housing options currently available and provides a benchmark for evaluating whether the proposed PonderHouse offers additional benefits beyond the CLT housing construction.

- PonderHouse. The proposed CLT home is designed to maximize usage of Timber Age 5'x10' CLT panels with little modification and to ensure minimal material waste, timely manufacturing, and enhance replicability for implementation on a community scale. Timber Age™ Modular Building System (TAMBS) envelope incorporates low-carbon materials and a design inspired by the Passive House principles while utilizing all-electric appliances and mechanical systems. The wall and roof assemblies have similar construction based on 3-ply, three-inch-thick CLT panels, air barrier, wooden I-joist framing 24'' apart filled with dense pack cellulose insulation, and weather barrier. The resulting assembly achieves approximately R-68 thermal resistance while maintaining the thermal mass benefits of the CLT structure. Previous TAMBS-built homes have achieved an air infiltration rate of 0.6 air changes per hour (ACH) or less, so this value was selected for the use in the energy simulations. Figure 1 presents the first-floor plan of the PonderHouse design, a 1,305 ft^2, two-bedroom, two-story residential design, that can easily be modified to become a 3 or four-bedroom home.

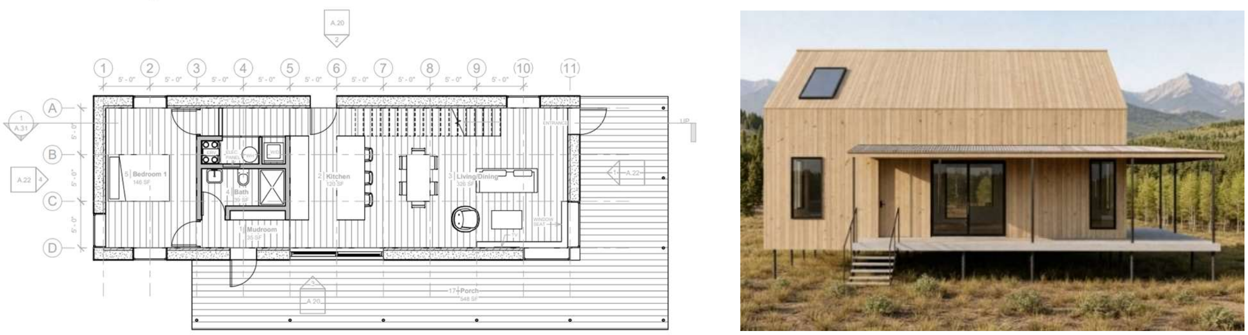


Figure 1. First-floor plan of the PonderHouse prototype (two-bedroom, two-story design) and 3D rendering. Only the first floor is shown for clarity. *Source*: Timber Age Systems 2024.

Table 1a summarizes the main housing characteristics, and Table 1b summarizes the appliance and equipment specifications for the analyzed housing scenarios. The analyzed housing scenarios were selected to represent realistic housing options available to manufactured home residents and new home buyers. The pre-HUD manufactured home has a conditioned floor area of 900 ft^2, reflecting the size of many older manufactured homes currently found in manufactured home communities. The retrofitted manufactured home, ENERGY STAR manufactured home, DOE Zero Energy Ready manufactured home, and PonderHouse each have a conditioned floor area of approximately 1,300 ft^2, which is representative of current manufactured housing. This approach reflects the practical decision faced by many homeowners and new home buyers: whether to continue living in an existing home, invest in retrofit improvements, or replace their home with a newer and larger housing option.

Table 1a. Fixed Home Scenario Geometry and Ventilation Specifications

Home Model & conditioned space	Infiltration (ACH50)	Windows	Window Area (F / B / L / R%)	Mechanical Ventilation
Pre-HUD MH 1970 (900 ft^2)	18	Single Pane, Metal Frame	15 / 2 / 5 / 10	Exhaust
Pre-HUD MH Retrofit (1,300 ft^2)	15	Low-E, Double Pane, Insulated	15 / 10 / 5 / 10	Exhaust
ENERGY STAR MH (1,300 ft^2)	4	Low-E, Double Pane, Insulated	24 / 15 / 0 / 0	Exhaust
DOE Zero Energy Ready MH (1,300 ft^2)	3	Low-E, Double Pane, Insulated, Argon	24 / 15 / 0 / 0	Exhaust
PonderHouse (1,300 ft^2)	0.6	Low-E, Triple Pane, Insulated	20 / 10 / 20 /40	Heat Recovery Ventilation: SRV – 95%

Table 1b. Fixed Home Internal Scenario Specifications

Home Model	Lights	Hot Water Fixtures[1]	Heating & Cooling	Kitchen[2]	Laundry[3]
MH Pre-HUD1970	100% CFL[4]	1.25	Gas Furnace: 60% AFUE Window A/C: 8.4 CEER	R: Top freezer, EF:6.9 S: Gas DW: 318 kWh/yr	CW: IMEF 1.41 CD: CEF 3.10
Pre-HUD MH Retrofit	100% LED	1.00	20.9 SEER2, 8.9 HSPF2 ASHP[5]	R: Top freezer, EF:14.1 S: Electric DW: 307 kWh/yr	CW: IMEF 1.57 CD: CEF 3.73
ENERGY STAR MH	100% LED	1.0	14.5 SEER2, 9.25 HSPF2 ASHP	R: Bottom freezer, EF:21.3 S: Electric DW: 237 kWh/yr	CW: IMEF 2.95 CD: CEF 3.3
DOE Zero Energy Ready MH	100% LED	1.0	14.3 SEER2, 7.5 HSPF2 ASHP	R: Bottom freezer, EF:21.3 S: Electric DW: 237 kWh/yr	CW: IMEF 2.95 CD: CEF 3.3
Ponder House	100%	0.50	29.3 SEER2, 14 HSPF MSHP	R: Bottom freezer, EF: 20.1	CW: IMEF 3.1 CD: CEF 10

[1] Fraction of the national average hot water consumption
[2] R: Refrigerator, S: Stove, DW: Dishwasher
[3] CW: Clothes washer, CD: Clothes dryer
[4] Compact fluorescent lighting
[5] ASHP: Air Source Heat Pump

Home Model	Lights	Hot Water Fixtures[1]	Heating & Cooling	Kitchen[2]	Laundry[3]
	High-EF LED			S: Elec, Induction, High-EF DW: 200 kWh/yr	

To assess climate-dependent performance, each housing configuration is simulated across the three HUD climate zones: Denver, Colorado (cold); Medford, Oregon (mixed); and Atlanta, Georgia (warm). These locations were selected to represent a wide range of heating and cooling dominated conditions and to evaluate how envelope improvements influence performance across different climate zones. Climate-specific insulation levels, mechanical systems, and envelope characteristics were assigned according to representative regional construction practices and code requirements. In addition, each home is modeled using consistent occupancy schedules and internal gains so that differences in performance are driven primarily by the building envelope, system characteristics, and climate.

Table 2 summarizes the envelope properties, utility rates, and water heating systems assigned to each housing scenario across the three climate zones.

Table 2. Climate Specific Envelope and Water Heating Specifications

Location and heating and cooling degrees	Model	Electric/ Gas rate ratio[6]	Wall R-value	Roof R-value	Crawl R-value	Water Heater Type and efficiency (50 gal)
Denver, CO (70°F, 76°F)[7]	Pre-HUD[8]	1.868	7	11	13	0.57 UEF (Nat. Gas)
	Pre-HUD Retrofit[9]		11	22	21	0.93 UEF (Electric)
	ENERGY STAR		21	38	30	0.93 UEF (Electric)
	DOE Net Zero Ready		21	38	38	Heat Pump
	PonderHouse[10]		60	60	68	Heat Pump
Atlanta, GA (70°F, 76°F)	ENERGY STAR	3.19	13	30	19	0.93 UEF (Electric)
	DOE Net Zero Ready		13	33	33	Heat Pump
Medford, OR (70°F, 76°F)	ENERGY STAR	3.05	13	38	19	0.93 UEF (Electric)
	DOE Net Zero Ready		21	38	38	Heat Pump

[6] Electricity rates ($/kWh) were converted to $/therm using 1 therm = 29.3 kWh. The utility cost ratio is calculated as gas cost per therm divided by electricity cost per therm. Applies to all home scenarios in each location

[7] Heating setpoint, Cooling setpoint

[8] Same specifications for the Pre-HUD model in Atlanta, GA and Medford, OR except the water heater is a 0.93 UEF (Electric) water heater.

[9] Same specifications for the Pre-HUD model in Atlanta, GA and Medford, OR

[10] PonderHouse specifications are the same for all climates

To estimate annual utility costs, regionally representative electricity and natural gas rates were applied for each location. Electricity and natural gas prices were obtained from publicly available residential utility tariffs for the primary utilities serving each region. The utility rates are as follows:

- Denver (Xcel Energy 2026):
  - Electricity: $0.13/kWh | Natural Gas: $2.046/therm
- Atlanta (Georgia Power 2026; Georgia Natural Gas 2026)
  - Electricity: $0.12/kWh | Natural Gas: $1.20/therm
- Medford (Pacific Power 2026; Avista Utilities 2026)
  - Electricity: $0.15/kWh | Natural Gas: $1.50/therm

These rates were used to calculate the gas-to-electricity utility cost ratios shown in Table 2 and to estimate annual utility expenses for each housing scenario.

Energy Modeling Approach. This study uses BEopt 3.1.1 for all energy simulations. Model inputs were assigned according to the parameters defined in Tables 1 and 2. Heating, cooling, and water heating systems, along with their associated capacities, were selected to reflect technologies typical of each housing type and construction era while also accounting for the predominant fuel types used in each region (RECS 2009). For example, natural gas water heating systems were modeled for the Denver scenarios, reflecting the prevalence of natural gas infrastructure in cold-climate regions, while electric water heating systems were used in the Atlanta and Medford models, consistent with typical residential equipment in those regions. Mechanical system types and efficiencies were similarly selected to represent realistic equipment associated with both the construction era and regional practices.

The PonderHouse CLT envelope is simulated using a custom OpenStudio/EnergyPlus measure developed for this study that replaces the conventional wood-frame wall, roof, and floor constructions with layered Timber Age TAMBS mass timber panel assemblies, as described in the PonderHouse Design section. This measure defines the CLT structural components and associated insulation assemblies within the EnergyPlus simulation engine while maintaining compatibility with the BEopt workflow. The assembly maintains an overall R-68 thermal resistance using, 12” thick, continuous exterior insulation. This approach allows the CLT envelope to be modeled within the same simulation framework used for the other housing scenarios while accurately representing the thermal and structural characteristics of the mass timber construction.

For each scenario and location, annual site energy consumption, average daily energy use, and associated annual utility costs were calculated. In addition, operational CO_2 emissions were obtained directly from BEopt, which estimates emissions based on modeled electricity and natural gas consumption. Electricity emissions factors are region specific and derived from the Cambium 2021 long-run marginal emissions rates dataset, while natural gas emissions are calculated based on standard emissions factors within the BEopt analysis framework. These metrics were used to compare the performance of the housing scenarios across climates and to evaluate differences in energy efficiency, operating costs, and resilience characteristics.

Resilience Model Approach. The thermal resilience of each home simulates a power outage in winter, January, and summer, July that lasts for a two-day period, over the weekend. The power outage is represented in BEopt by modifying heating thermostat setpoint (from 70°F to 45°F in winter and from 76°F to 100°F in summer) and disabling all internal electrical loads to approximate the loss of grid power and active HVAC operation.

Results

Energy Consumption. Figure 2 shows the annual site electricity (dark blue) and natural gas (light blue) consumption for each home type across Denver, Atlanta, and Medford. The Pre-HUD manufactured home is the only scenario that uses natural gas, while the retrofit, ENERGY STAR, DOE Net Zero Ready, and PonderHouse scenarios are fully electrified. Although the retrofit eliminates natural gas consumption, it exhibits the highest annual electricity consumption in all three climates. This is due to increases in reliance on electric space conditioning, water heating, and appliances. Electricity then progressively decreases through the ENERGY STAR and DOE Net Zero Ready homes as envelope performance and equipment efficiencies improve.

The PonderHouse demonstrates the lowest annual electricity consumption in each climate despite having a conditioned floor area identical to the other modern manufactured home cases. Relative to the retrofit scenario, annual electricity usage is reduced by approximately 54%, 45%, and 49% in Denver, Atlanta, and Medford, respectively. Because occupancy schedules, internal gains, and operating assumptions are held constant across all scenarios, these reductions are primarily attributable to improvements in envelope performance, air tightness, ventilation effectiveness, and equipment efficiency. The consistency of results across cold, mixed, and warm climates demonstrates that combining electrification with a high-performance building envelope is necessary to achieve substantial reductions in overall energy demand.

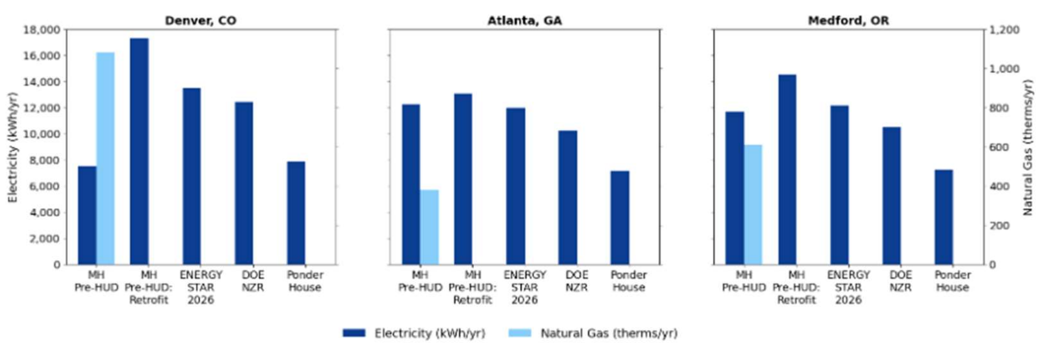
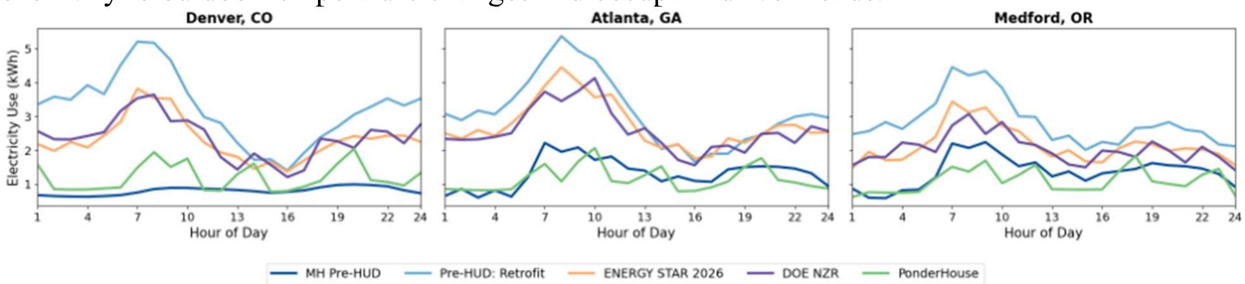


Figure 2. Annual site electric (dark blue) and gas (light blue) use for all analyzed homes in Denver, Atlanta and Medford.

Figures 3a – 3b show the total average hourly electric usage profile, over a typical 24 hour period, for Denver, Atlanta, and Medford, for summer (a) and winter (b) In all three climates, electricity demand exhibits a pronounced morning peak which is associated with space heating, water heating, and increased occupant activity at the beginning of the day. The retrofit scenario consistently shows the largest peak electricity demand, reaching approximately 5 kWh (average power) in Denver and Atlanta, and over 4 kWh (average power) in Medford. Although the retrofit eliminates natural gas consumption, the tradeoff causes increased electrical demand resulting in higher peak demand than the existing Pre-HUD manufactured home. As overall housing performance improves, peak electricity demands progressively decrease through the ENERGY STAR and DOE Net Zero Ready scenarios, reflecting the benefits of enhancing the building envelope and mechanical system efficiencies. In addition to reduced peak demands, the higher-performance homes exhibit smaller fluctuations throughout the day, indicating a reduced sensitivity to outdoor temperature changes and occupant-driven loads.



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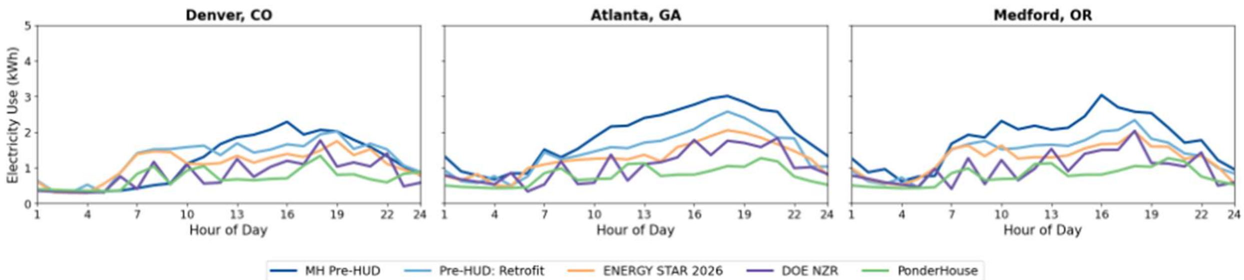


b)

Figure 3. a) Summer and b) winter average daily electricity load profiles for all analyzed homes, Pre-HUD (dark blue), Pre-HUD Retrofit (light blue), ENERGY STAR 2026 (orange), DOE NZR (purple), and PonderHouse (green).

Among modern manufactured homes, the PonderHouse has the lowest peak demand and the smoothest load profile across all three climates. This trend is most evident in Denver and Medford, where heating loads are more significant and the benefits of improved thermal resistance and air tightness are most impactful. Although Atlanta experiences lower heating demand, a similar reduction in peak electricity use is observed as home performance improves, following the energy consumption trend previously mentioned. The flatter load profile indicates a reduced need for large, short duration heating inputs. This demonstrates how the high-performance CLT envelope lowers peak demand while maintaining indoor comfort. The reductions in peak loads complement the annual energy savings presented in Figure 2 and provide additional benefits for affordability, grid resilience, and mechanical system sizing.

Figure 3b shows the average hourly electricity load profiles for a typical summer day in Denver, Atlanta, and Medford. In all three climates, electricity demand is dominated by cooling loads and shows broad afternoon and early evening peaks as outdoor temperatures increase throughout the day. These peaks are largest in Atlanta, where warmer temperatures and greater cooling requirements result in the highest overall electricity demand. The Pre-HUD manufactured home exhibits the largest peak loads, reaching approximately 3 kWh (average power) in Atlanta and Medford. The retrofitted, ENERGY STAR, and DOE Net Zero Ready homes follow the same trend as the winter profiles. They show a steady reduction in peak demand which is attributed to the improved building envelope and more efficient space cooling systems.

Across all three climates, the PonderHouse exhibits the most stable daily load profile and the smallest increase in electricity demand during peak cooling hours. The reduced afternoon load growth indicates that highly insulated, airtight CLT envelope is more effective at limiting heat gain throughout the day and maintaining comfortable indoor temperatures while outdoor temperatures increase. As a result, the PonderHouse requires less mechanical cooling throughout the day and avoids large demand spikes in the afternoon when occupancy activity is typically increased, as opposed to the other housing scenarios. These results show that high-performance homes not only reduce annual cooling-related energy consumption but also improve load stability, help lower utility costs, reduce stress on the electric grid, and enhance the homes' resilience during extreme heat events.

Overall, the results demonstrate a clear progression in performance across the housing options analyzed. While electrification eliminates on-site natural gas consumption, the largest reductions in both annual energy use and peak electricity demand occur when electrification is combined with substantial improvements in envelope performance. The PonderHouse consistently demonstrates the lowest energy consumption, the lowest peak loads, and the steadiest load profile across all three climates, indicating that high-performance envelopes effectively reduces both heat loss during the winter and heat gain during the summer. By lowering heating and cooling requirements, the enhanced envelope decreases overall energy demand while reducing strain on mechanical systems and the electric grid. The benefits translate into lower operating costs, improved resilience during extreme weather events and power outages, and enhanced long-term affordability for homeowners.

Utility Costs and 10-year ownership cost. Figure 4 shows the annual electricity (dark blue) and natural gas (light blue) costs for each home type across Denver, Atlanta, and Medford. The Pre-HUD manufactured home exhibits the highest annual utility costs in all three climates due to its high energy consumption and inefficient mechanical systems and appliances. Although the retrofit, ENERGY STAR, DOE Net Zero Ready, and PonderHouse scenarios are fully electrified, annual utility costs consistently decrease as housing performance and system efficiencies improve. This trend reflects the reductions in energy consumption achieved through improved insulation levels, enhanced air tightness, higher-performance windows, and more efficient mechanical systems.

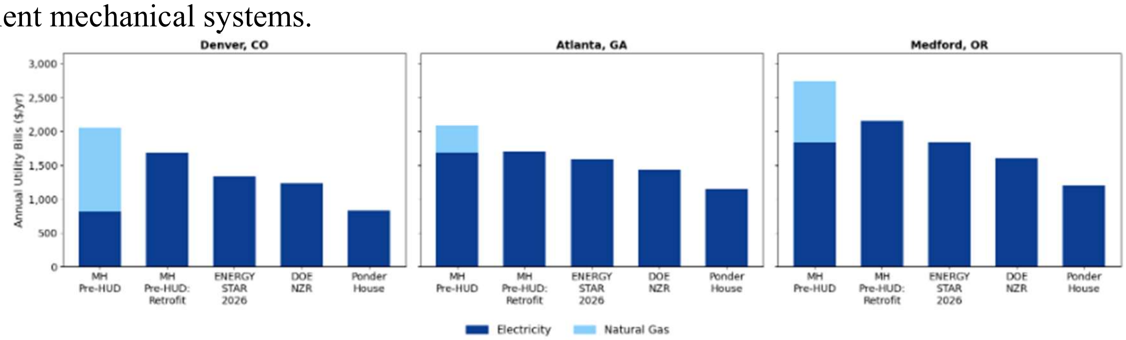


Figure 4. Annualized utility bills by climate zone.

The cost trends closely mirror the energy consumption results, with the PonderHouse achieving the lowest annual utility costs in each climate zone. Annual utility costs are reduced from approximately $2,050 to $850 in Denver, $2,100 to $1,150 in Atlanta, and $2,750 to $1,200 in Medford when comparing the Pre-HUD home to the PonderHouse. The largest savings occur in Medford, where mixed climate conditions create substantial heating and cooling demands throughout the year, allowing the high-performance CLT envelope and high-efficiency systems to deliver savings across both seasons. Relative to the retrofit scenario, the PonderHouse reduces annual utility costs by about 50%, 33%, and 44% in Denver, Atlanta, and Medford, respectively.

For homeowners, these reductions translate directly into lower annual operating expenses. While all replacement scenarios reduce utility costs relative to the existing Pre-HUD manufactured home, the greatest savings are achieved by PonderHouse. Over a ten-year period, the estimated utility cost of operating a Pre-HUD manufactured home is approximately $27,400, compared to about $11,950 for the PonderHouse, resulting in savings of nearly $15,500. The results indicate that investments in higher-performance housing can provide meaningful long-term economic benefits in addition to improvements in energy efficiency and occupant comfort.

HVAC Capacity and Peak Load. Figure 5 shows the heating (dark blue) and cooling (light blue) sizes for each housing scenario across all locations. The retrofit scenario has the largest total HVAC capacity requirements in all three climates, indicating that electrification alone does not inherently reduce peak heating and cooling loads. As housing performance improves through the ENERGY STAR and DOE Net Zero Ready scenarios, both heating and cooling capacities progressively decrease due to improvements in insulation levels, air tightness, and equipment efficiency. The heating and cooling loads are identical in all modern manufactured home scenarios because heat pumps are used as the space conditioning system. The PonderHouse requires the smallest HVAC system in every climate zone. The reduction is most pronounced in Denver, where heating loads dominate, but substantial reductions are also seen in Atlanta and Medford. The reduction in HVAC system sizes also reduces the upfront cost of the systems, an 80 kBtu system is approximately $20,000 while a 20 kBtu system is about $9,000 (Wilson 2024). This also reduces the electrical load and rated amperage on the electrical panel, potentially avoiding an electrical service line upgrade.

Overall, the results show that high-performance envelopes can significantly reduce peak heating and cooling loads, allowing smaller mechanical systems to maintain occupant comfort. The reduction in peak load has three important implications.

1. Smaller mechanical systems reduce first costs, which boosts affordability.
2. Smaller mechanical systems reduce peak electrical demand and required circuit breaker size, which improves grid compatibility and boosts affordability, and reduces strain to the electric grid during extreme weather events.
3. The reduced heat loss extends the duration of the habitable indoor conditions during the winter power outages, directly supporting passive survivability goals.

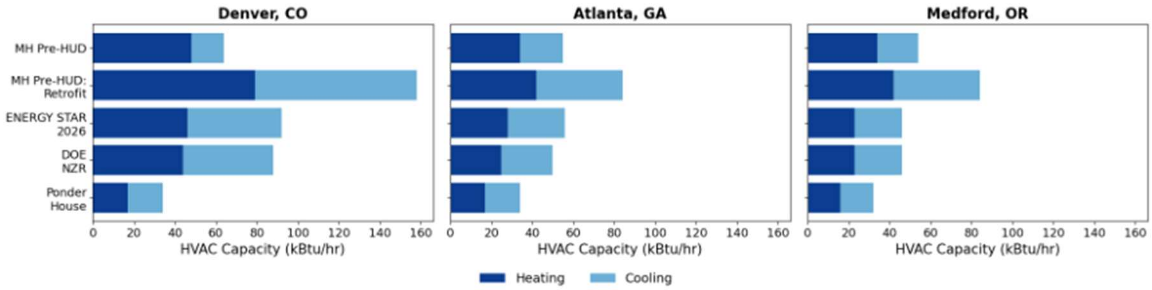


Figure 5. HVAC capacities for each analyzed home by climate zone.

Operational CO_2 Emissions. Figure 6 illustrates the percent reduction in operational CO_2 emissions with respect to the Pre-HUD manufactured home for Denver (dark blue), Atlanta (light blue), and Medford (purple). All housing options achieve measurable reductions in operational emissions despite the newer homes having larger conditioned floor areas than the Pre-HUD home. The retrofit scenario reduces emissions by approximately 18% - 40%, while the ENERGY STAR and DOE Net Zero Ready homes provide reductions of 20% - 50%, with the largest reductions occurring in Denver.

The PonderHouse achieves the largest reduction emissions reductions in all three climates, with operational CO_2 reductions of about 72%, 56%, and 68% in Denver, Atlanta, and Medford, respectively. The consistent progression in emissions reductions across the housing scenarios indicates that improvement in the buildings performance directly translate into lower operational carbon emissions. The larger reductions observed in Denver and Medford reflect the decreases in heating energy demands achieved through the high-performance envelope.

Because the emissions reflect the current grid makeup in each region, these reductions are achievable immediately without requiring onsite PV or a fully renewable grid. As electricity supply becomes less carbon intensive, the operational carbon benefits of the PonderHouse will continue to increase, reinforcing the long-term impact of utilizing Ponderosa pine as a building material in affordable housing.

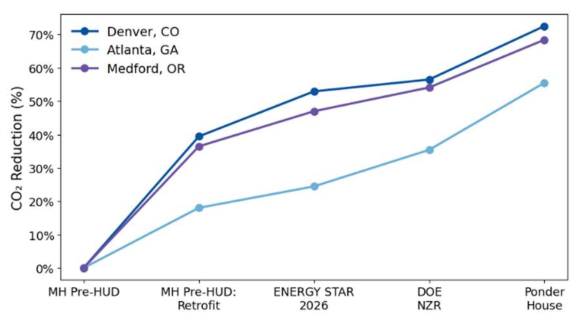
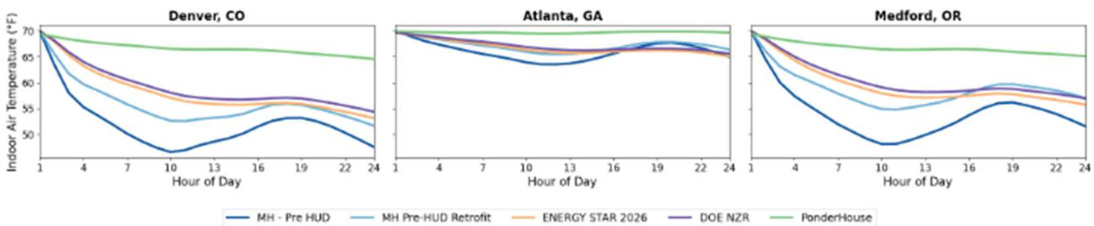


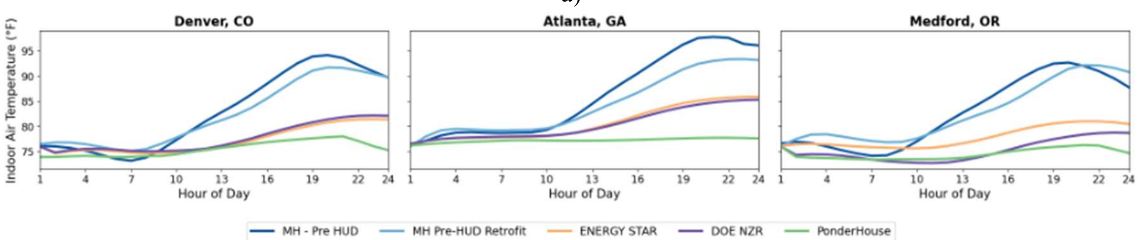
Figure 6. CO2 emissions reduction relative to MH Pre-HUD.

Resilience Performance. Figure 7a presents the indoor air temperature during a simulated winter power outage for each housing scenario across Denver, Atlanta, and Medford during the first 24 hours of the outage. All houses start at the heating setpoint (70°F) after which indoor temperature decreases as heat is lost through the building envelope. The Pre-HUD manufactured home shows the most rapid temperature decay in all three climates, indicating poor thermal retention due to limited insulation, significant air leakage, and inefficient windows. Although the retrofit scenario improves performance relative to the existing Pre-HUD home, indoor air temperatures still decline below the 60°F comfortable temperature threshold. The ENERGY STAR and DOE Net Zero Ready homes provide greater thermal stability, reflecting improvements in building performance.

The PonderHouse maintains the highest indoor temperatures throughout the outage period and demonstrates the slowest rate of temperature decay in all three climates. Assuming a 60° F safety threshold, the PonderHouse is the only scenario that remains above this threshold for the full 24-hour period. The improved resilience is due to the highly insulated R-68 envelope, 0.6 ACH50 airtightness, and high efficiency of the mechanical systems.



a)



b)

Figure 7. a) Winter and b) Summer indoor air temperature during a power outage.

Figure 7b presents the indoor air temperature response during a simulated summer power outage across Denver, Atlanta, and Medford. All homes begin at the cooling setpoint of 76° F and gradually warm as heat accumulates within the building and mechanical cooling becomes unavailable. The Pre-HUD manufactured home experiences the quickest temperature change, similar to the trend of the winter outage. It reaches a peak indoor temperature of 90°F in Denver and Medford and approaches 100°F in Atlanta. The retrofit scenario provides some improvement, but the indoor temperature still rises well above the 80°F comfort threshold during the afternoon and evening hours. Following the same pattern as the winter outage, the ENERGY STAR and DOE Net Zero Ready homes show progressively improved performance, with lower peak temperatures and slower rates of heat gain throughout the day.

The PonderHouse provides the greatest level of summer resilience across the three climates. The high-performance envelope substantially limits the heat gain, resulting in the lowest indoor temperatures and the smallest temperature fluctuations throughout the outage period. In all locations, the PonderHouse remains below the 80°F safety threshold while the other scenarios exceed this limit for extended periods of time. These results demonstrate that improvements in insulation, airtightness, and thermal mass can reduce overheating risk and enhance survivability during summer power outages.

Table 3: Resiliency Results

Location	Model	Hours Above 80°F	Hours Below 60°F
Denver, CO	Pre-HUD	13	22
	Pre-HUD Retrofit	13	21
	ENERGY STAR	6	18
	DOE Net Zero Ready	7	17
	PonderHouse	0	0
Atlanta, GA	Pre-HUD	14	0
	Pre-HUD Retrofit	14	0
	ENERGY STAR	11	0
	DOE Net Zero Ready	11	0
	PonderHouse	0	0
Medford, OR	Pre-HUD	13	21
	Pre-HUD Retrofit	12	19
	ENERGY STAR	7	17
	DOE Net Zero Ready	0	16
	PonderHouse	0	0

Conclusion

This study evaluated five housing options available to manufactured home residents and new homebuyers: an existing Pre-HUD manufactured home, a retrofitted manufactured home, an ENERGY STAR manufactured home, a DOE Net Zero Ready manufactured home, and the proposed PonderHouse CLT home. To address existing gaps in the application of mass timber for affordable housing, this study presented a detailed residential design utilizing Ponderosa pine CLT panels, optimized for efficient manufacturing, high thermal performance, and residential construction. This analysis included energy modeling, operational carbon assessment, and resilience evaluation across Denver, Colorado; Atlanta, Georgia; and Medford, Oregon.

Across all climates, the PonderHouse consistently achieved the lowest energy consumption, utility costs, operational carbon emissions, and HVAC capacity requirements and the highest resiliency to extreme heat and cold. These improvements were driven by the highly insulated and airtight envelope and efficient all-electric systems and appliances. Replacing a Pre-HUD house with a passive CLT house reduces the 10-year ownership cost to $11,950, increases resilience by 92%, and reduces CO_2 by 72%. Overall, the results indicate that high-performance mass timber housing can provide a viable pathway for reducing operating costs, lowering emissions, and improving resilience in affordable housing communities.

Future research should examine construction costs, construction timelines, supply chain considerations associated with CLT housing developments and analysis of policy and funding mechanisms could help enable deployment of similar designs in affordable housing communities. Further research will also explore the integration of renewable energy systems, community-scale energy strategies, and additional resilience measures to enhance long-term sustainability of CLT housing developments.

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AI-assisted tools used: [Grammarly].
Used for: [formatting and grammar edits].
Extent: [light editing].