

Cost-effective HVAC Improvements in New Manufactured Homes

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ABSTRACT

Manufactured homes represent a sizable part of the single-family housing market with ten million built since federal regulation of the industry under HUD began in 1976 and about 100,000 homes projected to ship nationwide in 2021 (MHI 2021). These highly affordable homes often lack the energy efficiency and performance mandated by local codes for site-built homes. The HUD code (HUD 1994), which regulates the industry nationwide, has not been updated since 1994. This effort, supported by the DOE Advanced Building Construction (ABC) Initiative, focused on improving the energy efficiency of new manufactured homes through innovations related to space heating and cooling.

Current manufactured home HVAC systems can be characterized as low-cost systems delivering expensively conditioned air through ductwork prone to leakage. The challenge is finding pathways to increased manufactured home energy performance that are attractive to manufacturers, dealers, and buyers without substantially raising the purchase price.

This paper presents detailed building models created in EnergyPlus to represent the variety of new manufactured homes across the country and estimate energy savings¹ for various innovations relative to current industry practice. The most promising innovations fell in two broad categories: duct-system improvements and increased adoption of heat pumps for space conditioning. Ducted heat pumps showed the highest impact with potential energy-cost savings in the range of 12 to 60 percent and are likely cost-effective except when competing against natural gas heating in colder climates. Duct-sealing innovations have less savings potential and more uncertainty but may offer the most cost-effective savings opportunities.

Baseline Energy Model Development

Potential HVAC improvements were modeled against a baseline representing the 1994 HUD code. The baseline was run for eight cities, chosen to represent the shipment-weighted climate midpoint by region and HUD thermal zone for the continental US:

- Zone 1: Houston, TX and Atlanta, GA
- Zone 2: Raleigh, NC and Phoenix, AZ
- Zone 3: Baltimore, MD; Chicago, IL; Denver, CO; and Seattle, WA

Geometries of two typical manufactured home types, one single-wide and one double-wide, were replicated from previous modeling work performed by Lucas et al. (2007) and PNNL

¹ All references to energy use and savings represent site energy rather than source energy throughout the paper.

(2014). Equipment efficiencies were brought up to current federal minimums and thermostat set points of 72°F heating and 75°F cooling were used, consistent with all recent DOE/PNNL building code simulation efforts. Baseline geometries are shown in Table 1 and envelope and equipment parameters in Table 2.

Table 1. Baseline model geometries

Component	Double-wide (DW)	Single-wide (SW)
Floor/ceiling area (ft ²)	1568	924
Exterior dimensions (ft)	56 x 28	66 x 14
Wall area (ft ²)	1344	1280
Window area (ft ²) [12% glass-to-floor ratio]	188 Equal area per facade	111 Equal area per facade
Door area (ft ²)	20-front, 20-back	20-front, 20-back

Table 2. Baseline model envelope and equipment parameters

Envelope Component	HUD Zone 1 (Houston/Atlanta)	HUD Zone 2 (Raleigh/Phoenix)	HUD Zone 3 (Baltimore/Chicago Denver/Seattle)
Wall (framing/batt insul.)	2x4 / R-11		2x6 / R-19
Ceiling (blown insulation)	R-30		
Floor (batt insulation)	R-11		R-22
Window U-val/SHGC	0.52/0.60		
Infiltration (ACH ₅₀)	8.0		
Duct leakage (Qn ²)	0.12		
Duct leak % supply/return	0.67/0.33		
Equipment Component	HUD Zone 1	HUD Zone 2	HUD Zone 3
AC + electric furnace	SEER 14 + elec resistance		SEER 13+elec resistance
AC + gas furnace	Not modeled	SEER 14 + AFUE 80%	SEER 13 + AFUE 80%
AC + heat pump	SEER 14 + HSPF 8.2		
Duct location	Ceiling or belly	Belly only	
Crossover duct area & R-val	63 ft ² / R-8 (Double-wide only)		
Total duct area (ft ²)	DW-423 / SW-249		
Setpoint heat/cool	72°F / 75°F		
Whole-house ventilation (continuous)	DW – 55 CFM / SW – 32 CFM (exhaust)		
Water heater (elec. resist.)	UEF 0.94		
Interior lighting	34% CFL		

² Qn is the ratio of duct leakage to conditioned area where duct leakage is to outdoors at the standard duct-pressurization test level of 25 Pascals. (ie 188 CFM25 for DW and 111 CFM25 for SW)

Appl./misc. equip. (kWh/yr)	Misc./Refrig./Range/Dishwash. 2085/718/500/111
Occupancy	3BR + 1 = 4

Further description of the baseline model includes a dark shingle, gabled roof with roof ridge along the long axis of the house. Windows and doors are distributed equally on all four facades in the four cardinal directions without overhangs. The homes are assumed to have an unconditioned and ventilated crawlspace and a vented attic.

Mechanical systems are primarily modeled as split systems with an interior mounted air handler and outdoor unit. The primary air distribution system has ducts located in the belly above the floor insulation such that they are insulated from below and considered inside conditioned space. Return ducting is minimal and also considered inside conditioned space. All double-wide models include a small length of R-8 flex duct (64 ft²) located in the crawlspace for the crossover connection between the two halves.

HUD code requires the provision of a mechanical ventilation system (HUD 1994). This is typically done in one of two ways: (1) a positive pressure system (POS), which introduces fresh air on the return side of the HVAC system whenever the air-handler operates; or (2) a continuous exhaust fan, typically in the bathroom. POS systems are common but require the main air handler to operate in order to properly ventilate the home. Because of this, if operated as intended, a POS requires considerably more fan energy than does the exhaust-fan approach. It is widely believed, however, that for comfort and cost reasons, many households do not operate their POS system year-round.

For this effort, we modeled an exhaust-fan based system providing the HUD-code required 0.035 cfm per square foot of floor area. This effectively models the additional space-conditioning load imposed by code-compliant ventilation but does not include the air-handler fan energy penalty imposed by a POS system.

A significant number of homes built for southern climates are designed with overhead ducts located in the attic. An additional variation found in the South includes packaged units instead of split systems. Prototype models to represent these scenarios include 1) a split system with overhead ducts and 2) an exterior mounted package unit with associated supply and return ducts located in the crawlspace as well as overhead supply ducts in the attic.

Representative Cities

Weather characteristics from eight cities were chosen to represent a combination of HUD thermal zones and Building America climate zones, as shown in Table 3 and Figure 1. Cities were chosen based on the mid-point of the shipment-weighted annual temperature for each region. The eight regions represented by these cities constitute 94 percent of annual new manufactured home shipments.

Table 3. Selected cities to represent HUD thermal zones and Building America climate zones

Weather region	City	HUD thermal zone	BA climate zone	Estimated % of annual new manufactured-home shipments (floors)
1	Houston TX	I	Hot-humid	34%

2	Atlanta GA	I	Mixed-humid	11%
3	Raleigh NC	II	Mixed-humid	16%
4	Phoenix AZ	II	Hot-Dry	6%
5	Baltimore MD	III	Mixed-humid	5%
6	Chicago IL	III	Cold (humid summers)	15%
7	Denver CO	III	Cold (dry summers)	4%
8	Seattle WA	III	Marine	3%
			Total	94%

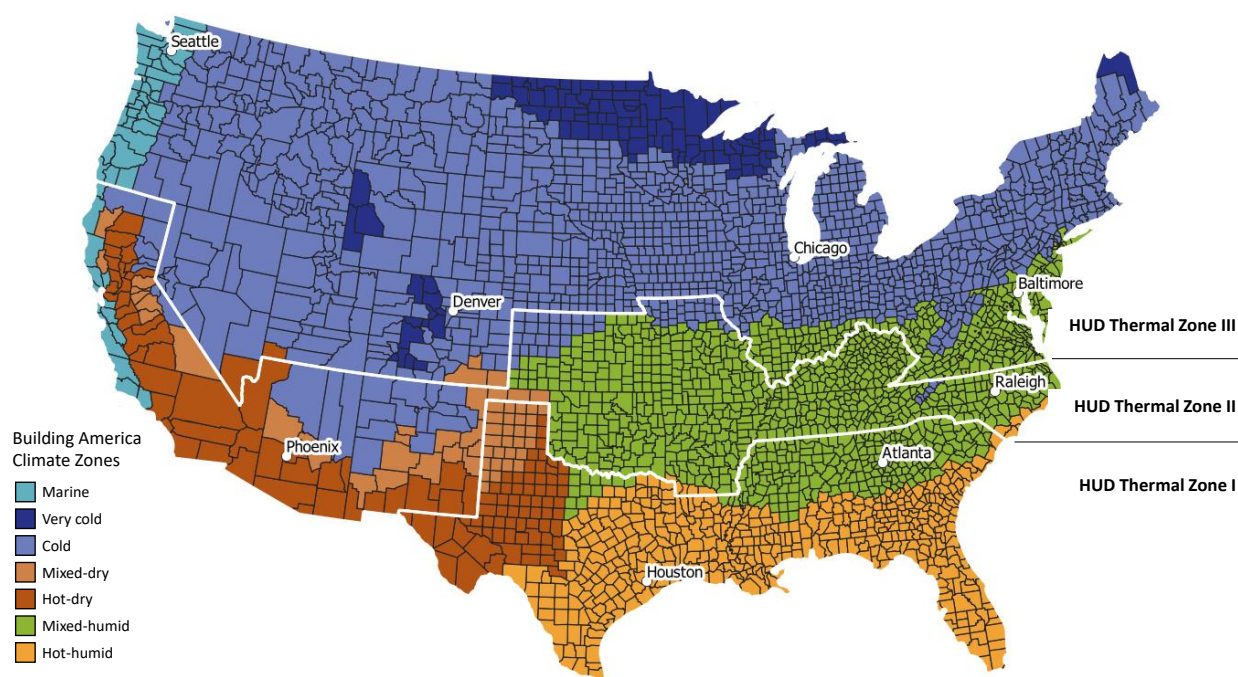


Figure 1. HUD thermal zones and Building America climate zones. Source: [Pigg et al. 2021](#)

Model Assumptions and Limitations

There are noteworthy assumptions and limitations associated with some aspects of the modeling, particularly the modeling of the belly area of manufactured homes and the nature of air leakage from ducts. The “belly” area of a manufactured home is the area below the floor but above the ground. This is the typical location of the ductwork for HVAC system, with the ducts located above a road barrier and layer of insulation (Figure 2). In theory, the space containing the main duct system is close to the temperature of the conditioned space and is isolated thermally from the outside in the same manner as the rest of the home.

However, in practice, the thermal dynamics of the belly area are far more complex and often change over time. The road barrier and belly insulation can be compromised as early as during initial installation of the home and are commonly seriously degraded over time by vermin

and access for plumbing repairs. Structural members and the duct system itself compress the belly insulation in areas and reduces its insulating value. Plumbing and other penetrations through the flooring create infiltration pathways between the living space and the belly area that affect both the temperature of the space where the duct system resides, and dynamics related to leaks of heated or cooled supply air from the duct system.

Duct leakage itself is also complex and time-varying. Leakage of conditioned HVAC air to the outside can have a significant effect on energy consumption, but modeling duct leakage for manufactured homes is especially challenging. For a given home, the degree of leakage to the outside can be measured in a repeatable way (by sealing the registers and pressurizing the ducts and the home to a standard level), but this may not represent leakage under actual operating conditions, and, as noted above, vermin and general degradation of the duct system over time—particularly the field-installed cross-over duct for multi-section homes—can readily change the level of leakage within a few years of siting.

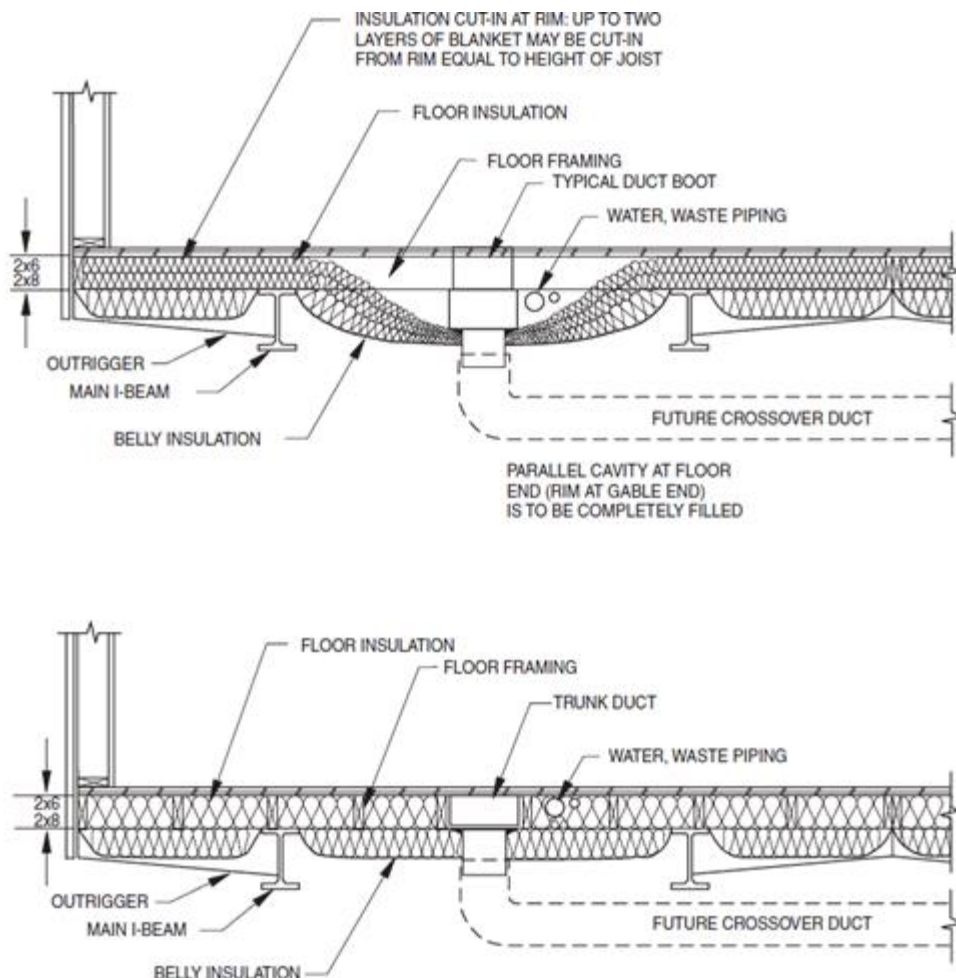


Figure 2. Belly sections showing insulation and routing of HVAC ducts, water and waste pipes. Longitudinal section at top shows main duct trunk running the length of floor causing insulation compression. Transverse section at bottom shows floor framing where short trunk or branch ducts run with full insulation thickness. Source: [Greer et al. 2004](#)

None of these important factors are well addressed with current modeling tools, though some work in the direction has been done in the past (Francisco and Palmiter 2007), and the authors are aware of an effort currently being undertaken by LBNL to model indoor air quality in manufactured housing that takes a more sophisticated approach to airflow dynamics using a software tool specifically designed for that purpose.

Developing better models of the belly area and duct-leakage dynamics is needed for the manufactured-housing industry but was beyond the scope of the project. The following modeling assumptions were used:

- The main duct system is assumed to be “inside” and not subject to conductive losses.
- Belly insulation is modeled at nominal R-values without adjustment for compression or compromise.
- Duct leakage under actual operating conditions is assumed to be the same as that measured under a standard duct-pressurization test level of 25 Pascals.
- Due to issues related to the highly unbalanced nature of duct leaks in manufactured homes, the modeling for duct leakage uses a less-refined, mass-conservation approach for duct leakage instead of EnergyPlus’s more-refined airflow-network model.
- For assessing innovations that rely on the average level of duct leakage to the outside for new homes, a relatively high baseline level of 12 cfm per 100 ft² of floor area was used, matching that from the Lucas study (2007).

Baseline and Improvement Model Results

Baseline model simulations were conducted for both single-wide and double-wide manufactured home types using weather profiles from eight cities to account for a range of climates and regional construction practices. Three mechanical equipment types were modeled for most cities based on their prevalence by region. The small percentage of homes produced with fuel-fired furnaces in Study Region 1 led to this simulation model being dropped in Atlanta and Houston.

All equipment consisted of a centrally ducted air conditioner with one of three heating types: 1) electric resistance, 2) gas furnace, 3) electric heat pump. The vast majority of manufactured homes utilize split-refrigeration systems with separate indoor and outdoor components, but a significant number of packaged systems (evaporator and condenser co-located in a single outdoor unit) are prevalent in hot-humid climates along the gulf coast. Packaged systems thus require a portion of both supply and return ductwork located in the crawlspace to route air from the outdoor air handler to attic ductwork. Table 4 shows which mechanical systems were modeled by HUD Climate Zone and which were excluded from analysis due to low incidence of use in those regions. A total of 28 simulations were required for each home type (single/double-wide) resulting in 56 total baseline runs.

Table 4. Mechanical equipment modeled for each city based on HUD Zone

Mechanical Equipment	HUD Zone 1 (ATL, HOU)	HUD Zone 2 (RAL, PHX)	HUD Zone 3 (BAL, CHI, DEN, SEA)	Unique Energy Models
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Split-system AC + elec.resist.heat	All cities	All cities	All cities	8
Split-system AC + gas furnace	Not modeled	All cities	All cities	6
Split-system heat pump	All cities	All cities	All cities	8
Packaged AC + resist. heat or heat pump (ducts in crawl and attic)	Houston only	Not modeled	Not modeled	2
Floor supply air (ducts in belly)	All cities	All cities	All cities	n/a
Ceiling supply air (ducts in attic)	All cities	Not modeled	Not modeled	4
Total unique energy model simulations				28

All split-system equipment modeled with ducts in belly. Split-system with attic ducts also modeled but only in Atlanta and Houston. Packaged AC systems (both resistance heat and heat pump) modeled in Houston only.

Improvement analysis focused on high-efficiency heat pumps and duct system enhancements including reduced leakage, improved crossover insulation and elimination of crossovers outside conditioned space. These upgrades were chosen based on the findings of an accompanying feasibility assessment report (Stendel et al, 2021) where 13 innovations were assessed for market applicability, energy savings, cost effectiveness, and likelihood of adoption by the manufactured housing industry. Energy savings for the most promising improvements over the baseline are shown in Table 5. The most significant energy savings are attributed to heat pumps relative to electric furnaces with central air conditioning systems that currently dominate the national market. Reductions in duct leakage show lower—but noticeable—savings potential.

Table 5. Modeled energy savings of the most promising three improvements over a baseline double-wide home with electric furnace and SEER 14 central air conditioner

City	Conventional heat pump savings (HSPF 8.2)		Variable-speed heat pump ³ savings (HSPF 11.6)		75% reduction in duct leakage savings	
	kBtu/yr	%	kBtu/yr	%	kBtu/yr	%
Houston	5,800	25%	12,300	53%	1,760	8%
Atlanta	12,200	41%	18,200	61%	2,030	7%
Raleigh	15,500	45%	21,500	62%	3,120	9%
Phoenix	3,000	12%	10,600	41%	1,490	6%
Baltimore	19,100	48%	24,900	63%	4,230	11%
Chicago	27,700	49%	34,200	60%	6,440	11%
Denver	21,200	49%	26,700	62%	5,300	12%
Seattle	19,600	60%	23,100	71%	4,920	15%

Cost Savings and Cost Effectiveness

Estimates of annual energy costs and cost savings were developed from energy-modeling results using regional fuel prices and estimates of heating-fuel and equipment-type proportions for new manufactured-home shipments. Life-cycle cost calculations were applied to examine the

³ Variable-speed heat pump modeled here also qualifies as a cold-climate heat pump to temperature of -22°F (NEEP, 2021)

present value of lifetime energy-cost savings and assess the potential cost-effectiveness of proposed HVAC innovations. In addition, results from the eight modeled locations were rolled up into regional and national estimates of baseline energy costs as well as savings and cost-effectiveness from improvements.

The eight cities were chosen to represent both the three HUD thermal zones as well as a variety of Building America climate zones. In addition, six regions were designated for the purpose of developing regional fuel prices and weighting factors. The regions were selected so that each falls within a single HUD thermal zone and with the intent of minimizing the number of within-region climate zones and range of state-level fuel prices. Figure 3 illustrates these study regions, climate zones and modeling cities and Table 6 provides weighting factors by region and home-type. The weights are scaled to total 100,000 annual shipments of new manufactured homes, which is close to current industry production levels (MHI 2021). Note that the cities of Baltimore and Chicago are listed twice to allow for representation of both mixed-humid and cold climates respectively for Study Regions 4 and 5. Also, notice only Phoenix was chosen for region 3 which includes a diverse range of climate zones. This tends to exaggerate the hot-dry portion of the region, though on a national basis, the entire region represents only 7.5 percent of shipments.

In addition to regional weights, weighting factors were also developed for HVAC system type and fuel, as well as duct location (for Region 1 only). Heating fuel allocations were derived from Census data; the others are our own estimates based on conversations with industry stakeholders. A complete listing of weighting factors used in the analysis can be found in the full report of this effort (Pigg et al. 2021).

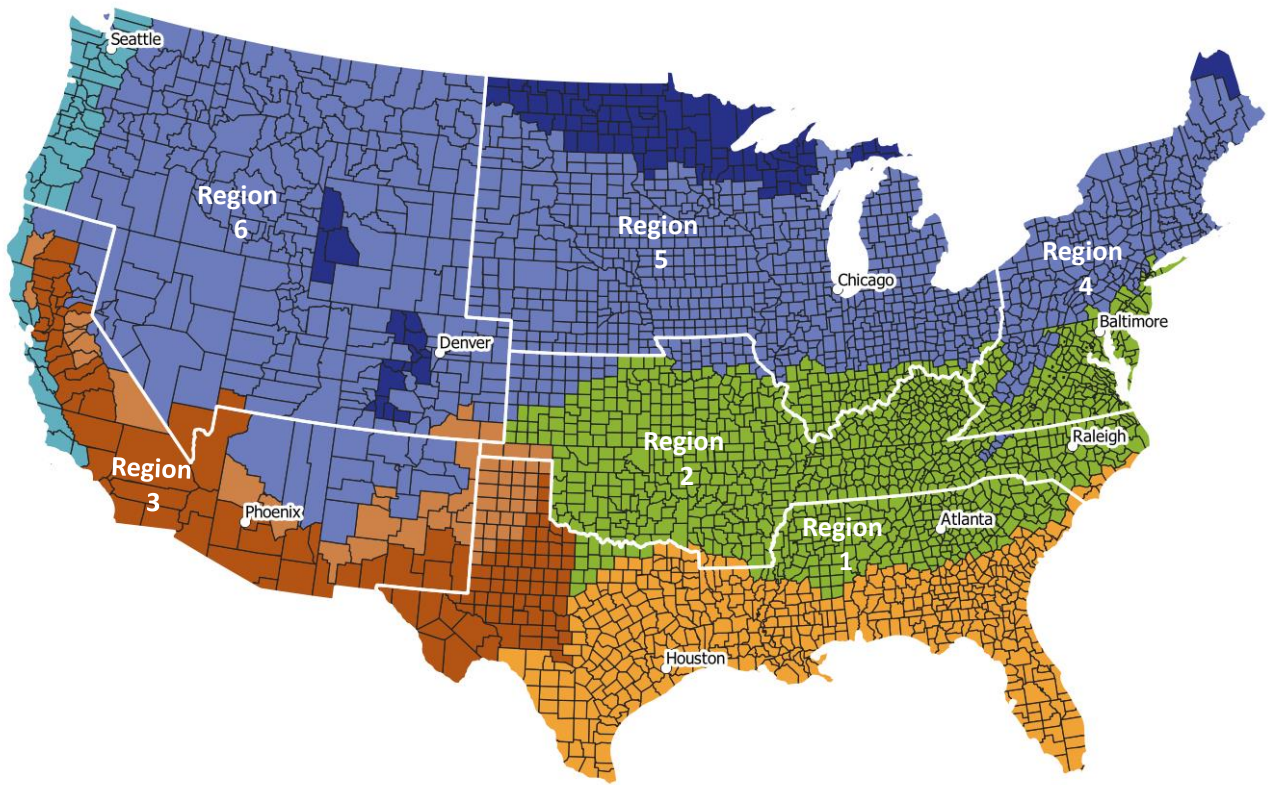


Figure 3. Study regions, Building America climate zones, and selected energy-modeling locations used in the study.
Source: [Pigg et al. 2021](#)

Table 6. Analysis weighting factors by region, Building America climate zone and home type.

Study region	City	HUD Zone	Building America Climate Zones	Weight		
				Single-wide	Double-wide	Total
1	Houston	I	All except Mixed-Humid	17,927	18,264	36,191
1	Atlanta	I	Mixed-Humid	5,606	6,141	11,747
2	Raleigh	II	Mixed-Humid	8,002	8,914	16,916
3	Phoenix	II	All	1,807	5,734	7,541
4	Baltimore	III	Mixed-Humid	1,678	1,840	3,518
4	Chicago	III	Cold and Very Cold	2,381	2,905	5,286
5	Baltimore	III	Mixed-Humid	1,103	489	1,592
5	Chicago	III	Cold and Very Cold	6,821	4,491	11,312
6	Denver	III	Cold and Very Cold	1,384	2,406	3,790
6	Seattle	III	Marine	291	1,816	2,107
			Total	47,000	53,000	100,000

Fuel Prices

Regional fuel prices were developed for electricity, natural gas, propane and (for study region 4) fuel oil. These were based on state-level EIA fuel prices, weighted up to the regional level based on state shipments of manufactured homes.

Electricity and natural gas costs were estimated with two price components: the variable (per-kWh or per-therm) portion and the fixed (per-month) portion of utility charges. This was done by using published state (for electricity) or regional (for natural gas) estimates of monthly residential fixed charges, then calculating the state-level average variable fuel price by subtracting estimated aggregate annual fixed charges from EIA total residential revenues and dividing the result by EIA total annual kWh or therm sales.⁴ Separating the two price components is less common for this type of analysis, but is important, since efficiency improvements only actually affect the variable portion of energy costs and there are fixed-cost implications related to full electrification of homes that would otherwise utilize natural gas.

On average, the price analysis resulted in state per-kWh electricity prices that were about 10 percent less than EIA's published electricity prices, which combine fixed and variable charges into a single per-kWh price. For natural gas, state per-therm prices averaged about 20 percent less than the EIA values. Table 7 shows the regional fuel prices used in the analysis.

Table 7. Regional fuel prices

		Electricity	Natural Gas	Propane	Fuel Oil
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⁴ Estimates of state-level fixed charges for electricity came from a public database of electric utility rates, which was combined with EIA data on utility sales to estimate state-average fixed charges (NREL 2021). Natural gas regional values were developed from the American Gas Association study of customer charges (AGA 2015).

Study region	Modeling City	\$/mo. (fixed)	¢/kWh	\$/mo. (fixed)	¢/therm	\$/gal.	\$/gal.
1	Houston	\$11.22	10.5	\$12.28	95.6	\$2.81	
	Atlanta	\$13.13	11.1	\$12.04	96.6	\$2.51	
2	Raleigh	\$12.84	9.7	\$12.70	81.3	\$2.28	
3	Phoenix	\$14.67	14.2	\$7.32	100.7	\$2.10	
4	Baltimore	\$8.68	11.9	\$10.98	91.9	\$2.90	\$2.91
	Chicago	\$11.14	14.7	\$13.82	104.2	\$2.79	
5	Baltimore	\$11.97	11.2	\$11.38	67.0	\$1.89	
	Chicago	\$9.59	12.7	\$11.66	63.5	\$1.82	
6	Denver	\$12.70	9.4	\$8.98	65.1	\$2.02	
	Seattle	\$10.95	9.3	\$4.95	84.6	\$2.10	

Application of these prices to the modeling results and weighting factors suggests that the average new single-wide manufactured home in the continental U.S. has energy costs of about \$1,410 per year, and the average double-wide home uses about \$1,760 worth of energy annually, with space heating and cooling accounting for about half of those total costs. These costs do vary significantly by region and climate, however.

Life-Cycle Cost Inputs

Key life-cycle cost assumptions were adopted from the current DOE rulemaking related to manufactured-home efficiency standards (DOE 2021), which splits home buyers into three categories depending on their financing option (Table 8). Fuel prices were escalated using the latest supplement to NIST Handbook 135 (Lavappa and Kneifel 2021), using listed regional fuel-price indices that include an assumed 2 percent inflation. All results presented here are based on a 25-year lifetime.

Table 8. Life-cycle cost factors used in current DOE rulemaking (2021) and adopted here.

	Chattel loan	Real-estate mortgage	Cash purchase
Percent of home purchases	54.6%	15.4%	30%
Loan interest rate	9%	5%	
Down payment	20%	20%	
Loan fees	1%	1%	
Term (years)	15	30	
Discount rate	9%	5%	5%
Property-tax rate	0.9%		
Sales-tax rate	3%		

Break-Even Incremental Cost

From a life-cycle energy-savings perspective, a particular innovation can be deemed cost-effective if the discounted present value of its costs—mainly the up-front incremental cost but

also any associated ongoing costs—is less than the discounted present value of lifetime energy savings. However without solid estimates of the incremental cost for some innovations (primarily those related to duct-system improvements), this analysis was turned around to rely on the calculated break-even incremental cost. As the name implies, this is the up-front incremental cost that yields a net present value of zero when combined with the discounted life-cycle value of energy savings and additional on-going costs, such as increased property taxes. At the break-even incremental cost, a buyer should be financially indifferent about whether to choose an innovation over the baseline option. If the actual incremental cost is less than the break-even value, it is financially advantageous to choose the innovation over conventional practice. On the other hand, if the actual incremental cost is greater than the break-even value, it is better to stick with standard practice.

Cost Savings and Cost-effectiveness Results

Table 9 presents energy savings and incremental costs for a blend of both single and double-wide homes. It shows heat pumps are estimated to provide substantial energy-cost savings capable of supporting at least several thousand dollars in up-front incremental cost over the conventional forced-air furnace and split-system central air conditioner that currently dominates the market. At current fuel prices, heat pumps are not cost-effective against natural gas in most areas, and in fact produce negative energy-cost savings. This excludes 10 to 15 percent of the national market for new manufactured homes, but more than 50 percent of homes destined for the Midwest. The economics of heat pumps versus natural-gas heat is sensitive to the price of natural gas, however, and depend on whether the home can be fully electrified and thus entirely avoid natural gas service and its associated fixed monthly charges, as Figure 4 shows for single- and double-wide homes in Chicago under various scenarios for domestic hot water service.

Reductions in duct leakage have the potential for non-trivial savings in new manufactured homes, but there is considerable uncertainty associated with the level of leakage in currently produced homes as well as the degree to which proposed innovations would mitigate leakage.

Table 9. Weighted-average regional energy-cost savings and break-even incremental cost for heat pumps and duct-leakage reduction.. Heat pump results excludes gas-heat shipments where energy-cost savings would be negative.

Region	Conventional Heat Pump ⁵		Variable-Speed Heat Pump ⁵		75% Reduction in Duct Leakage	
	Annual energy-cost savings ⁶	Break-even incremental cost ⁷	Annual energy-cost savings ⁶	Break-even incremental cost ⁷	Annual energy-cost savings ⁶	Break-even incremental cost ⁷
1	\$185	\$2,850	\$355	\$4,450	\$40	\$500

⁵ Excludes ~20% of new homes that are currently shipped with a heat pump, as well as gas-heat homes where a heat pump would result in negative energy-cost savings. The latter excludes ~20% of Region 4 shipments, 55% of Region 5, 30% of Region 6 and 13% of national shipments.

⁶ rounded to the nearest \$5

⁷ rounded to the nearest \$50

2	\$345	\$5,550	\$495	\$7,250	\$60	\$750
3	\$100	\$1,750	\$355	\$3,100	\$50	\$600
4	\$675	\$13,850	\$885	\$16,900	\$130	\$2,050
5	\$575	\$10,200	\$730	\$12,100	\$85	\$1,200
6	\$520	\$8,650	\$625	\$10,050	\$90	\$1,300
National	\$310	\$5,350	\$475	\$6,900	\$65	\$900

Heat pump results exclude gas-heat shipments where energy-cost savings would be negative.

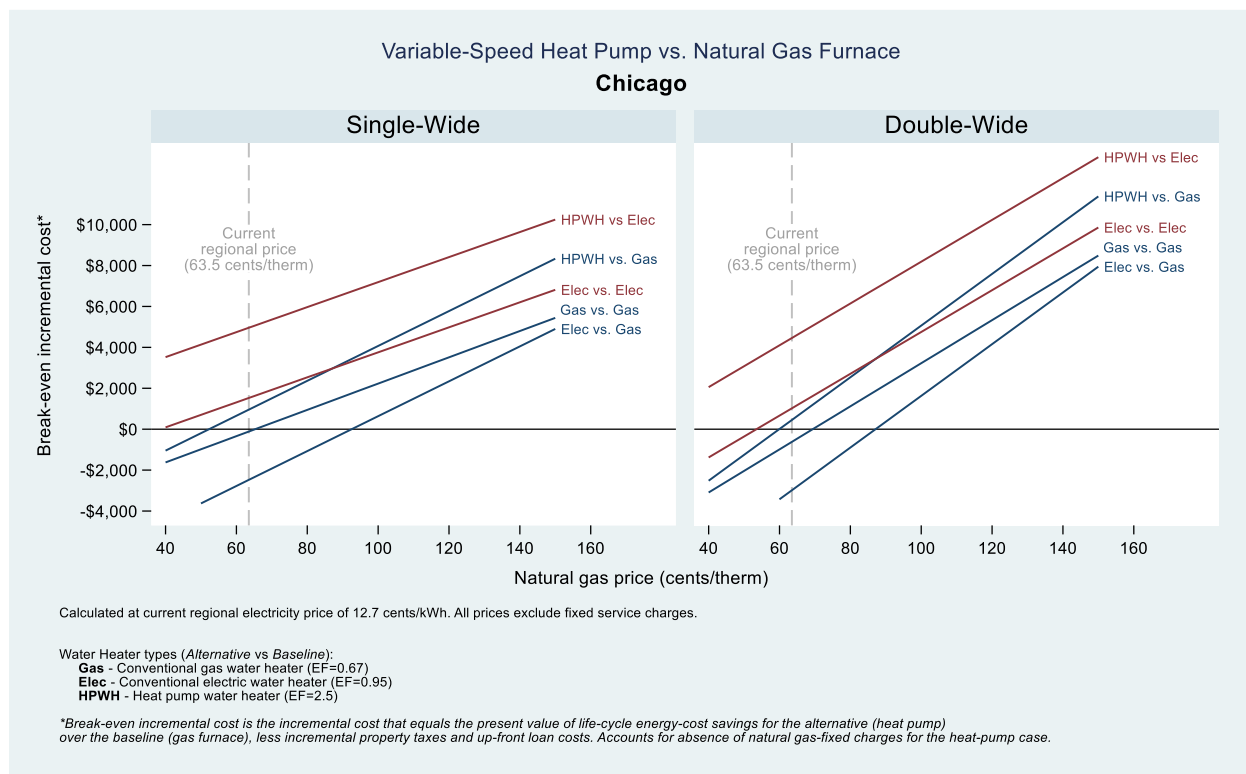


Figure 4. Break-even incremental cost for a variable-speed heat pump compared to a natural gas furnace in Chicago, for five different water heating scenarios.

Conclusions

A range of HVAC-related innovations were assessed for market applicability, energy savings, cost effectiveness, and likelihood of adoption. Results show the greatest impact from ducted heat pumps with energy-cost savings estimated at 12 to 60 percent for conventional heat pumps and 41 to 71 percent for variable-speed heat pumps. Break-even incremental cost calculations show heat pumps are also likely cost-effective except when competing against natural gas heating in colder climates.

Duct-sealing innovations have less savings potential and more uncertainty but may offer the most cost-effective savings opportunities. Modeling results and fuel-price estimates suggest

that each cfm of duct-leakage⁸ reduction per 100 ft² of floor area (that is, each 0.01 reduction in Qn) is worth between about \$3.50 and \$19 in annual energy cost savings and has a break-even incremental cost of between \$35 and \$350, depending on the region of the country. A 75 percent reduction in baseline duct leakage would produce a national-average of about \$50 per year for single-wide homes and \$85 per year for double-wides.

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References

- AGA. 2015. Natural Gas Utility Rate Structure: The Customer Charge Component – 2015 Update. American Gas Association Energy Analysis, EA 2015-03.
- DOE. 2021. Technical Support Document: Supplemental Notice of Proposed Rulemaking Proposing Energy Conservation Standards for Manufactured Housing, U.S. Department of Energy, August 2021.
- Francisco, P., and L. Palmiter. 2007. "Thermal Characterization and Duct Losses of Belly Spaces in Manufactured Homes." *ASHRAE Transactions* 113(2).
- Greer R., B. Peeks, and T. Hewes. 2004. "Northwest Energy Efficient Manufactured Home Program In-Plant Inspection Manual." Oregon Department of Energy. www.neemhomes.com/s/3157.pdf
- HUD. 1994. Manufactured Home Construction and Safety Standards, 24 CFR Part 3280. Washington, DC: U.S. Department of Housing and Urban Development
- Lavappa, P. and J. Kneifel. 2021. "Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis — 2021: Annual Supplement to NIST Handbook 135," National Institute of Standards, NISTIR 85-3273-36, April, 2021.

⁸ Duct leakage at standard duct-pressurization test level of 25 Pascals

- Lucas, R., P. Fairey, R. Garcia, and M. Lubliner. 2007. “National Energy Savings Potential in HUD-Code Housing from Thermal Envelope and HVAC Equipment Improvements.” *ASHRAE Transactions, Volume 113, Part 2*.
- MHI (Manufactured Housing Institute). 2021. Monthly Economic Reports Shipments from 1977-present from IBTS. www.manufacturedhousing.org/annual-production/
- NEEP (Northeast Energy Efficiency Partnership). 2021. Cold Climate Air-Source Heat Pump Specification (Version 3.1). https://neep.org/sites/default/files/media-files/cold_climate_air-source_heat_pump_specification-version_3.1_update_.pdf
- NREL Electric Utility Rate Database. Retrieved November 4, 2021. openei.org/wiki/Utility_Rate_Database.
- Pigg, S., D. Chasar, L. Gu, and R. Vieira. 2021. “Energy Modeling and Cost Effectiveness Report: Reimagining HVAC for New Manufactured Housing” (Draft). Prepared by Slipstream for the U.S. Department of Energy, Control Number 2099-1580, December 10, 2021. slipstreaminc.org/sites/default/files/documents/research/reimagining-hvac-new-manufactured-housing_0.pdf
- PNNL. 2014. Energy Analysis Assumptions and Characteristics for Manufactured Housing. Pacific Northwest National Laboratory, August 24, 2014.
- Stendel, S., S. Pigg, D. Chasar, J. McIlvaine, B. Peeks, and M. Lubliner. 2021. “Feasibility Assessment Report: Reimagining HVAC for New Manufactured Housing” (Draft). Prepared by Slipstream for the U.S. Department of Energy, Control Number 2099-1580, November 1, 2021. https://slipstreaminc.org/sites/default/files/2022-05/reimagining-hvac-new-manufactured-housing_1.pdf