Reimagining HVAC for New Manufactured Housing
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Feasibility Assessment Report

slipstream

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EXECUTIVE SUMMARY

The feasibility assessment focused on identifying, assessing, and recommending HVAC innovations for new manufactured homes for field testing. HVAC systems included in manufactured homes can be characterized as low-cost systems that deliver expensively conditioned air through ductwork prone to leakage. The challenge is increasing manufactured home energy performance with innovations that are attractive to manufacturers, dealers, and buyers without substantially raising the purchase price.

Market stakeholders and actors provided input on processes, costs, HVAC considerations, and feedback on the proposed HVAC innovations. We developed a detailed characterization of—and weighting factors for—the new manufactured homes market (regional sales, home type, HVAC system type and fuel, and duct system characteristics). We ran energy models to represent the variety of new manufactured homes across the country and estimated the energy savings for various innovations relative to current industry practice.

The HVAC-related innovations fell into two broad categories: duct-system improvements and increased adoption of heat pumps for space conditioning. We assessed 13 innovations for market applicability, potential energy savings, cost effectiveness, and likelihood of adoption (**Error! Reference source not found.**). Ducted heat pumps showed the highest impact with potential energy-cost savings in the range of 35 to almost 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.

Pandemic, labor, and materials supply chain issues combined with the HFC refrigerant phase out impacted our ability to work with industry partners to consider some innovations for new manufactured homes. They are focused on working through challenges to their day-to-day operations and have limited time to focus on research and development, which influenced our selection of innovations to move into the second phase of this project (innovation testing).

We recommend four innovations for further testing: (1) Partial Factory-Install of Ducted Heat Pumps; (2) Improved HVAC QA Protocols; (3) Improved Cross-Over Duct Designs; and (4) Comparative Testing of Different Cross-Over Approaches.

Table ES-1. Overview of feasibility assessment results

Innovation			Market applicability (% of new home sales)	National avg HVAC energy savings (%)	National avg break-even incremental cost[a]	Cost-effective at scale?	Key Drivers	Key Barriers
D1	Improved HVAC quality assurance protocols	a) In-plant testing	100	5-10[b]	$500-$950[b]	Likely	Better plant Q/C. Potential future regulatory requirements.	Duct leakage not seen as an issue by some mfrs. Cost.
		b) Field diagnostics	100	4-8[b,j]	$50-$100[b]	Likely	Better up-front resolution of leakage issues.	Lines of responsibility for resolving issues.
D2	Improved Cross-Over Duct Designs		43[g]	2-5[b]	$200-$550[b]	Possible	Energy waste; comfort issues.	Cross-over installation cost and complexity.
D2a	Comparative testing of different cross-over approaches						Reduced siting costs.	Retooling duct layouts and floor structure.
D3	AeroSeal in a Factory Setting		100	5-10[b]	$500-$950[b]	Unlikely	Better sealing and consistency.	Duct leakage not seen as an issue by some mfrs. Cost.
D4	Interior duct designs to eliminate leakage		100	7-13[b]	$650-$1,150[b]	Unlikely	Better comfort and durability	Re-engineering and retooling costs.
H1	Factory enabled high efficiency ducted heat pumps		65 - 69[c,d]	35-54[c,d]	$5,300-$6,900[c,d]	Likely	Better comfort. Energy savings. Control over HVAC sizing.	Cost. Roadworthiness. HVAC market-structure barriers.
H1a	Partial factory-install of ducted heat pumps						(same as above)	Cost.
H1b	Revive the "Insider" ASHP						Equipment protected. Additional energy savings.	Cost. Noise. Regulatory issues with refrigerants.
H1c	Air Source Integrated Heat Pump (ASIHP)		73[h]	58[h,i]	$9,100[h]	Possible	Smaller mechanical footprint. Energy savings.	New technology. Footprint and plumbing retooling.
H2	Advanced controls and distribution for ductless heat pumps		71	8-15[d,e]	$950-$1,800[d,e]	Possible	Increased comfort and reduced noise	Duplicate HVAC systems.
H3	Quick connect fittings for ductless heat pumps						Reduced installation cost.	Market readiness and regulatory barriers.
H4	Heat-pump ready furnace		68-69[d,f]	44-54[d,f]	$5,900-$6,900[d,f]	Likely	HVAC choice flexibility.	Small market for HVAC mfrs
V1	Smart ventilation control with heat pump water heater		94[h]	17[i]	$2,900	Likely	Energy savings and better ventilation	Cost. Noise.

Notes:
a) break-even incremental cost is the incremental cost that equals the present value of life-cycle energy savings, less up-front loan costs and the present value of incremental property taxes.
b) range reflects uncertainty in average baseline duct leakage and magnitude of innovation impact
c) range reflects different types of heat pump with different efficiency levels
d) excludes homes already sold with a heat pump and those heated with natural gas where savings would be negative at current fuel prices
e) for a ductless displacing 25 to 50% of space conditioning load for the main ducted system. Range also reflects uncertainty in average baseline duct leakage.
f) for multi-stage or variable-speed heat pumps that would be more readily enabled with a heat-pump-ready furnace
g) only applies to multi-section homes
h) excludes homes where savings would be negative at current fuel prices
i) percent of HVAC and water-heating operating costs
j) among homes with identified leaks that are remediated

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INTRODUCTION

Manufactured housing represents one of the most affordable paths to home ownership for American households. Ten million such homes have been built since 1976 when federal regulation of the industry began under the Department of Housing and Urban Development (HUD).[1] HUD-code manufactured homes, which may be single- or multi-section, are built on a permanent metal chassis in one of 136 dedicated facilities around the country, sold through a network of dealers, then transported and set up at their final location. In 2021, the industry shipped about 100,000 homes nationwide (Manufactured Housing Institute 2021).

The manufactured-housing industry operates in a market where buyers tend to be highly price sensitive, and one of the key attractions of a manufactured home is that a person can own a home for less than half the cost per square foot as a site-built home (ibid). However, the HUD code that regulates the industry nationwide has not been updated since 1994 and has not kept pace with progressive tightening of local energy codes that govern site-built housing. As noted in DOE's FOA, residents of these homes spend almost twice as much on energy per square foot to heat and cool their homes. Although many manufacturers offer energy-efficient upgrades to their models, these have had limited uptake in most parts of the country: the national market share for ENERGY STAR® certified manufactured homes is less than 20 percent (ENERGY STAR 2020).

Heating, ventilation, and air conditioning (HVAC) systems currently included in manufactured homes can be characterized as low-cost systems that deliver 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 project identified 13 innovations for the HVAC systems installed in new manufactured homes and recommends four innovations for innovation testing. Innovations in HVAC systems could improve energy efficiency, durability, and indoor air quality to the benefit of manufactured home residents and the industry.

PURPOSE

This report shares the cumulative results of the project's feasibility assessment activities focused on identifying, assessing, and recommending HVAC innovations for new manufactured homes for field testing. Information about the innovations and market actor feedback could be valuable to industry stakeholders and regulators as they consider ways to improve manufactured homes in the future. Innovations not recommended for field testing could be considered in future research efforts as market conditions and industry motivations change over time.

[1] 1994 HUD Manufactured Home Construction and Safety Standards, 24 CFR Part 3280

METHODS

We analyzed data from public sources on the manufactured home market, talked with market stakeholders, and conducted market actor interviews to understand the regional characteristics of new manufactured homes and their occupants.

We identified manufactured home stakeholders from a variety of sources, including industry directories, trade journals, and personal contacts. The team engaged with 72 industry stakeholders from across the country and interviewed 41 of them. We used the manufactured home industry outreach and interviews to collect industry input on processes, costs, HVAC considerations, and for feedback on the proposed HVAC innovations. Efforts were made to incorporate key segments of the industry, for example, both factory-owned and independent dealers/retailers were included. We also made a point to contact stakeholders in a wide variety of locations to avoid bias based on regional practices.

On a parallel track, we developed a detailed characterization of—and weighting factors for—the new manufactured homes market in terms of regional sales, home type, HVAC system type and fuel and duct system characteristics. We ran energy models to represent the variety of new manufactured homes across the country and estimated the energy savings for various innovations relative to current industry practice. Current modeling tools, however, have limitations for modeling manufactured home belly sections. We translated the modeling results into energy-cost savings using regional average fuel prices, and then assessed cost-effectiveness with a discounted life-cycle cost analysis. The details of the energy-savings and life-cycle cost analysis are contained in the companion report "Energy Modeling and Cost Effectiveness Report" (Pigg, et. al 2021), with key results summarized in this report.

STRUCTURE OF REPORT

The report is divided into three major sections:

- U.S. market for new manufactured homes
- Innovation feasibility assessment
- Conclusions

The section on the U.S. market for new manufactured homes shares information about the number of new manufactured homes shipped, where they are shipped, characteristics of the homes, demographics of home residents, and feedback from various market actors. The innovation feasibility assessment describes the innovations in detail and the assessment of each innovation for potential energy savings, cost effectiveness, and—perhaps most crucially—likelihood of adoption by the industry. The conclusions describe the innovations recommended to move into the innovation testing phase of the project.

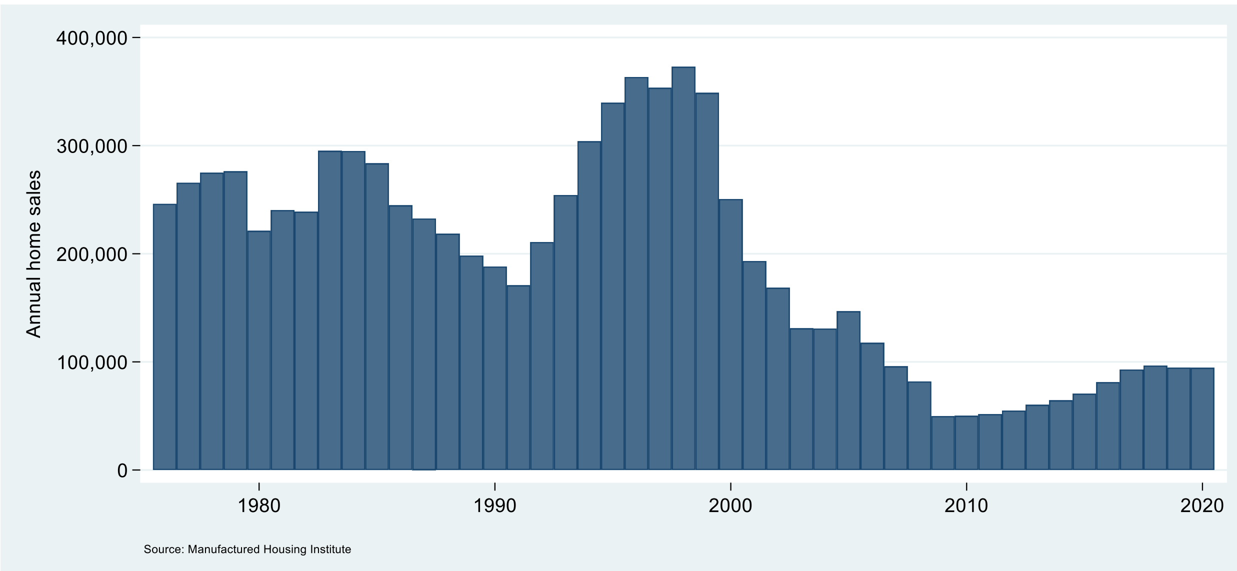
U.S. MARKET FOR NEW MANUFACTURED HOMES

This section of the report shares information on how many and where new manufactured homes are shipped, home HVAC systems and fuels, new homeowner demographics, and perspectives from various manufactured home market actors.

SALES

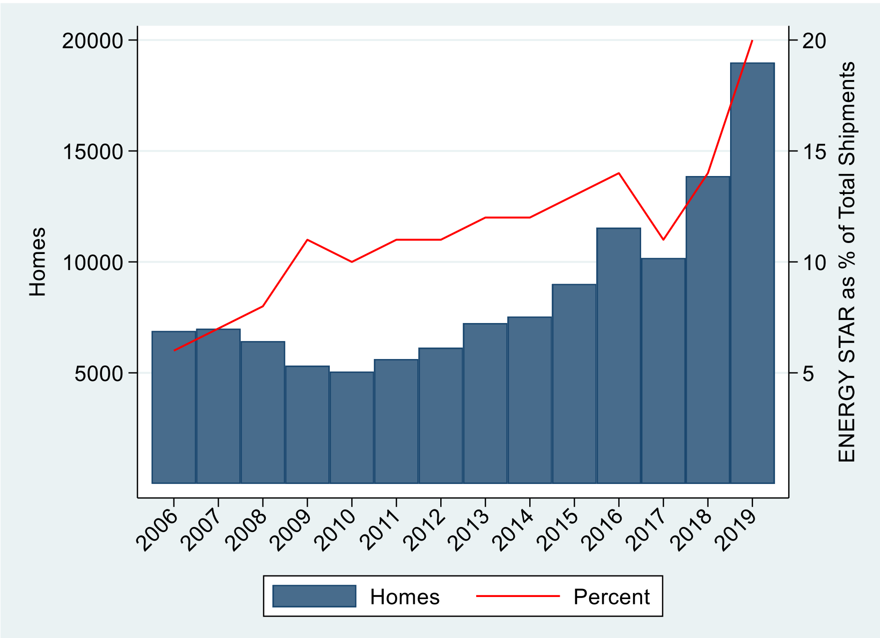
The heyday for manufactured homes was in the latter part of the 1990s when more than 350,000 homes were sold annually (Figure 1). Sales subsequently declined to an all-time low of about 50,000 homes per year immediately following the Great Recession. In recent years, sales have slowly risen to about 100,000 homes per year.

Figure 1. Annual manufactured home sales, 1976-2020.



The federal ENERGY STAR program has a certification track for new manufactured homes intended to spur the market for efficient homes. To gain ENERGY STAR certification, homes must meet a prescribed set of qualification criteria. The national market share for ENERGY STAR homes was at or below 10 percent until about 2018 but has been rising since then (Figure 2). A new version of these criteria (Version 2) went into effect in July 2019. The new qualification criteria reportedly make it easier for manufacturers to attain ENERGY STAR certification, which also qualifies the manufacturer for federal tax credits.

Figure 2. ENERGY STAR Manufactured Home Production by Year



Source: 2020 ENERGY STAR Manufactured Homes Market Share Report (ENERGY STAR 2020)

GEOGRAPHIC DISTRIBUTION

Nationally, slightly more than 40 percent of all homes shipped are multi-section; these are typically two-section, “double-wide” homes. In the industry parlance, each section of a multi-section home or each single-wide home is known as a “floor.” For analysis and reporting we divided the contiguous U.S. into six regions along state lines (Figure 3). About half of all floors shipped nationally are destined for one of seven southern states in Region 1 (Figure 3), with Texas alone accounting for 17 percent of all floors shipped nationwide. The West coast and Florida have the highest proportion of multi-section homes (Figure 4). Multi-section homes are less prevalent in the Midwest (Figure 4).

Figure 3. Percent of new manufactured home shipments (floors) by state and study region.

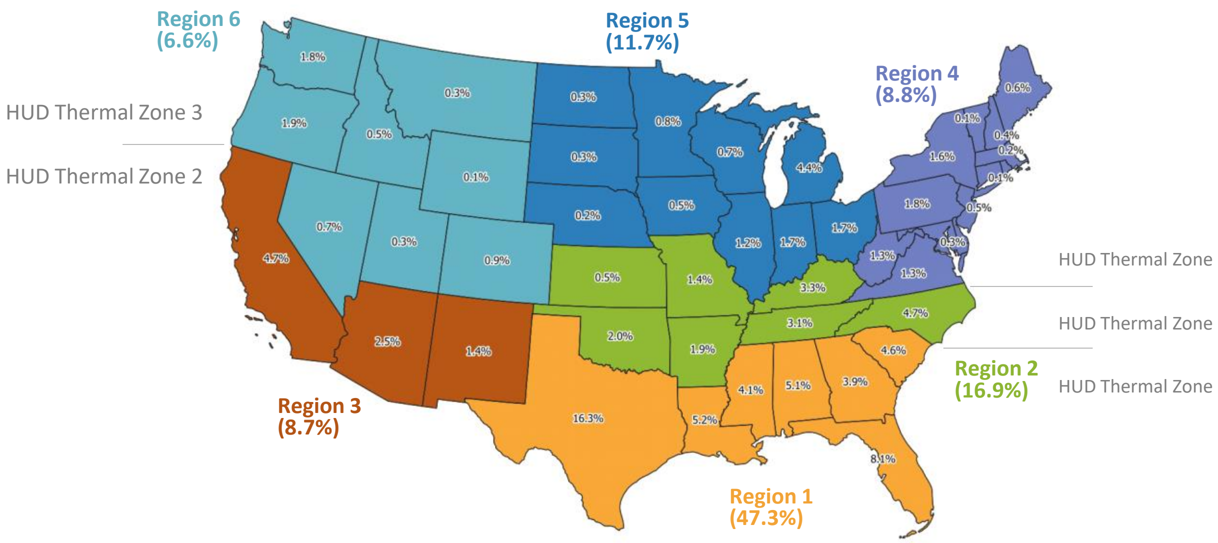
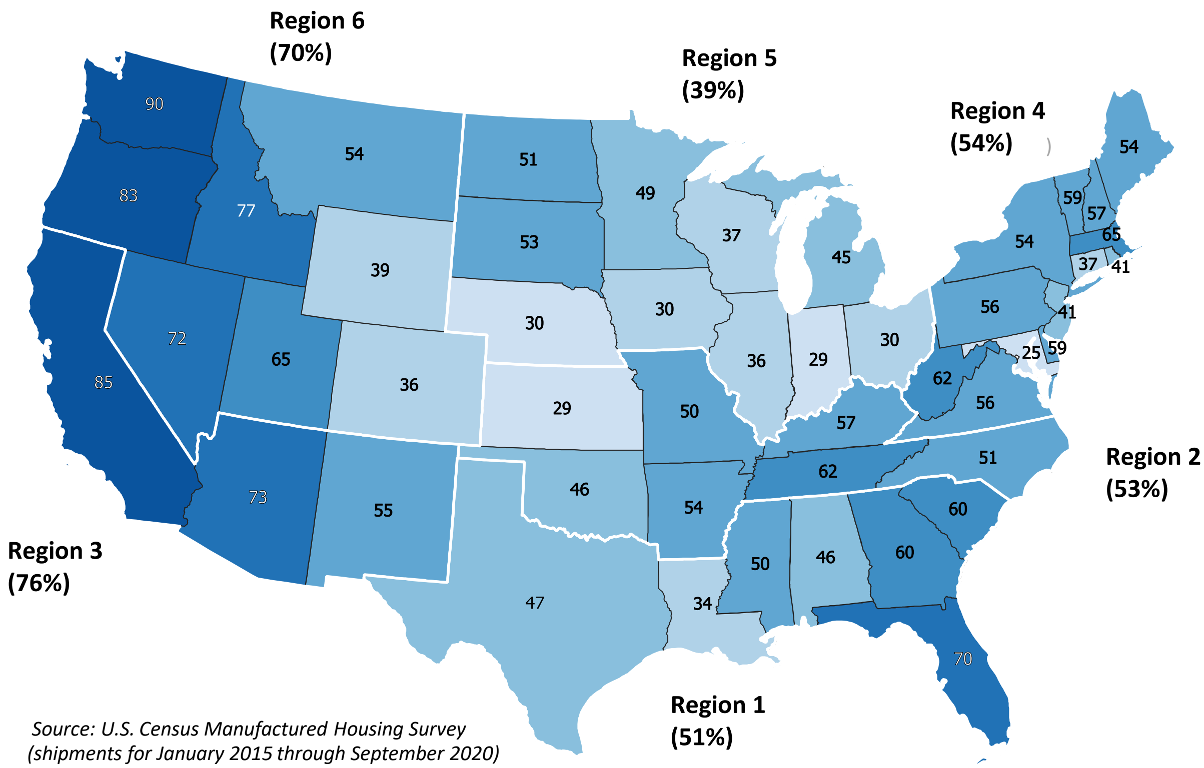


Figure 4. State and regional percent of new manufactured home shipments that are multi-section.



We also estimated how new manufactured home shipments are distributed among Building America climate zones by allocating state-level shipments to counties according to Census data on the number of manufactured homes in each county. The results (Figure 5 and Table 1) indicate that about two-thirds of annual floor shipments are in the Hot-Humid and Mixed-Humid zones, and about 20 percent of shipments are in the Cold climate zone.

Figure 5. Study regions, Building America climate zones, and HUD thermal zones.

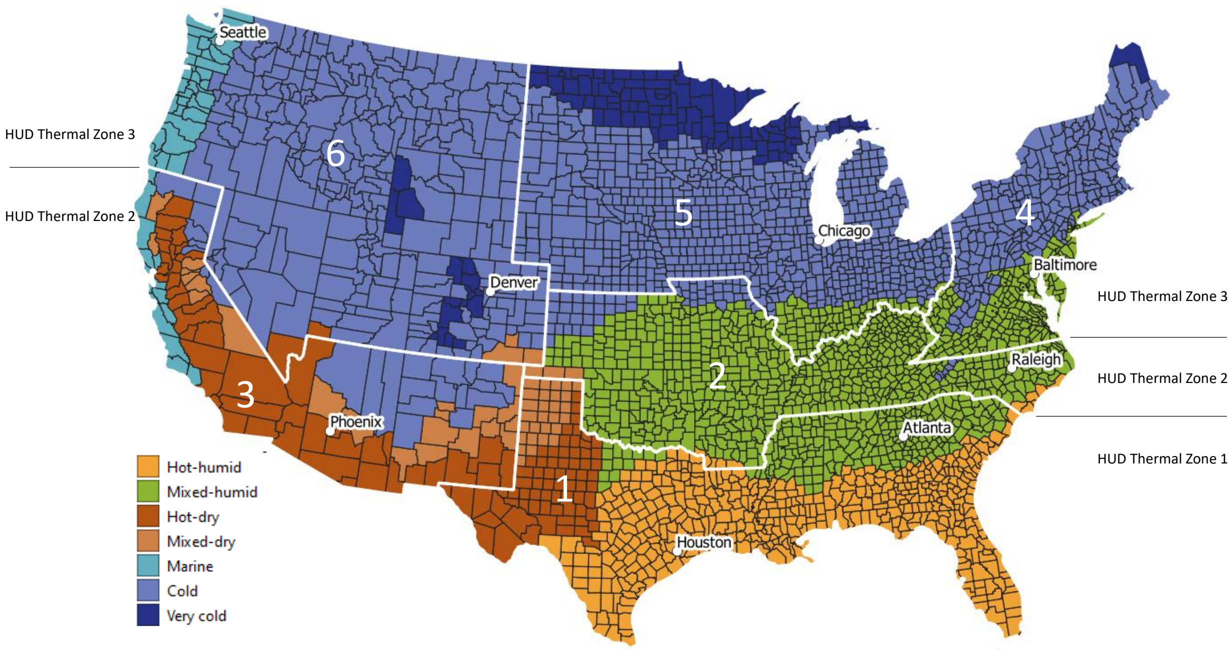


Table 1. Estimated distribution of new manufactured home shipments (floors) by study region and Building America climate zone.

Study Region	Building America Climate Zone							Total
	Hot-humid	Mixed-humid	Hot-dry	Mixed-dry	Marine	Cold	Very cold	
1	33.4%	11.7%	1.7%	0.5%	0.0%	0.0%	0.0%	47.3%
2	0.6%	16.0%	0.0%	0.0%	0.0%	0.3%	0.0%	16.9%
3	0.0%	0.0%	6.0%	0.9%	0.9%	0.9%	0.0%	8.7%
4	0.0%	3.5%	0.0%	0.0%	0.0%	5.3%	0.0%	8.9%
5	0.0%	1.4%	0.0%	0.0%	0.0%	9.6%	0.8%	11.7%
6	0.0%	0.0%	0.3%	0.0%	2.6%	3.7%	0.1%	6.6%
Total	34.0%	32.5%	8.0%	1.4%	3.5%	19.7%	0.9%	100.0%

CHARACTERISTICS OF MANUFACTURED HOME HVAC SYSTEMS

This section describes the heating and cooling systems and ductwork used in manufactured homes across the country.

Heating and Cooling Systems

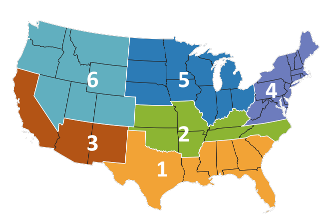
HUD code requires that a manufactured home have a heating system installed at the time of shipping, unless the home is "manufactured for field application of an external heating or combination heating/cooling appliance..."[2] In practice, this means that most homes are shipped with a central electric or gas furnace, except in warmer climates where packaged ducted heat pumps or central air conditioners with electric resistance heating may be shipped loose in homes and connected to the home's duct system by the setup contractor on site. Homes built outside of HUD's standards require an "alternative construction letter" (AC letter) where the home manufacturer submits construction information to HUD for approval and additional inspection requirements, which adds additional costs. For example, HUD determined a home with a package heat pump does not require an AC letter, but a home destined to receive a split-system air source heat pump (ASHP) on site and shipped with a central air handler with no strip would need an AC letter.

Nationally, electricity dominates as the main heating fuel for newer manufactured homes, especially in the South and the Pacific Northwest (Table 2, Figure 6). Natural gas heat is dominant in the Midwest, some western states, and California. Propane heat is common in New England and plays a role in some Midwestern states. Fuel oil is rare outside of New England.

Table 2. Heating fuel proportions for occupied manufactured homes built in 2010 or later, by study region.

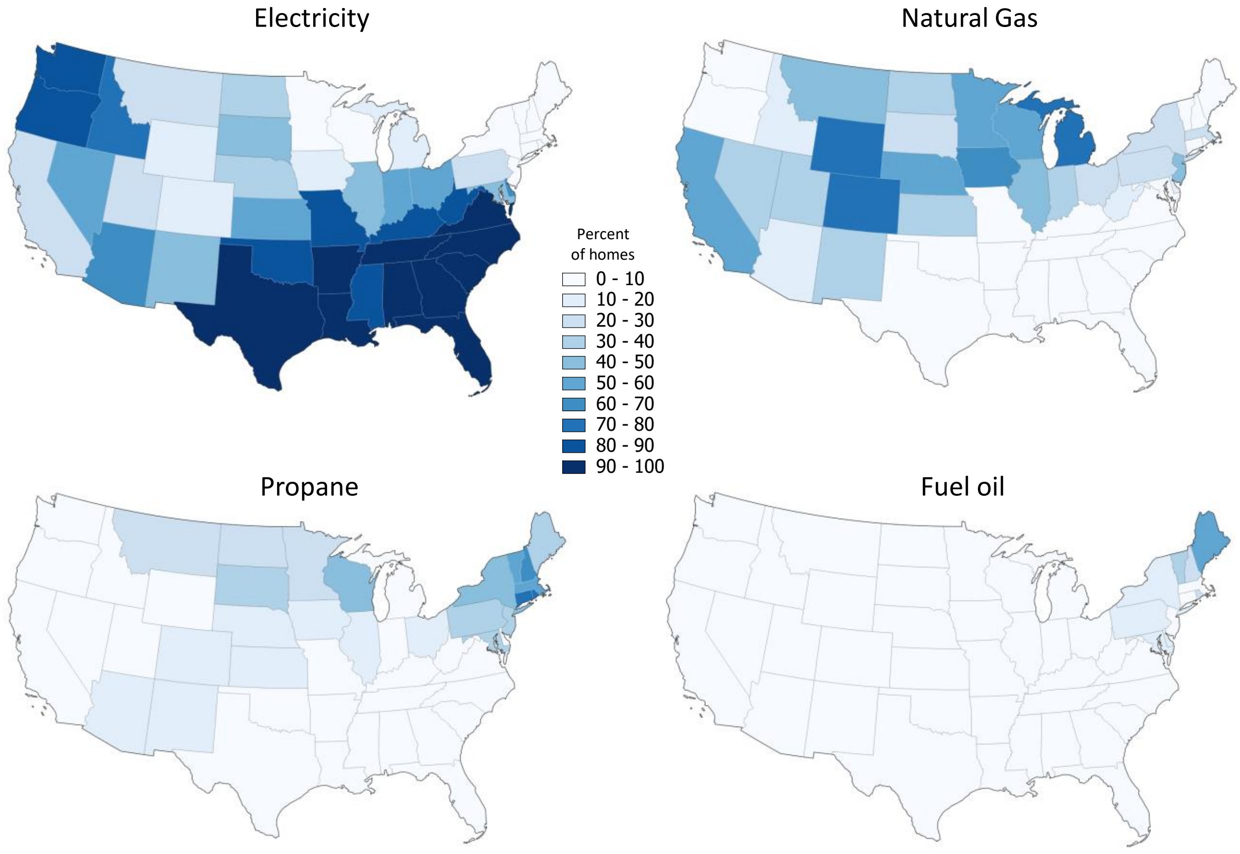
	Study Region						Overall
	1	2	3	4	5	6	
Electricity	94%	89%	38%	41%	33%	46%	73%
Natural gas	2%	5%	43%	15%	50%	39%	15%
Propane	3%	4%	11%	29%	14%	10%	8%
Fuel oil	<1%	<1%	<1%	12%	<1%	<1%	1%
Other	<1%	1%	5%	3%	2%	5%	2%
None	1%	1%	3%	<1%	1%	<1%	1%

Source: Census ACS PUMS 2014-2018.



[2] Manufactured Home Construction and Safety Standards – 24 CFR §3280.707

Figure 6. Primary heating fuel for occupied manufactured homes built in 2010 or later.



Source: U.S. Census ACS PUMS 2014-2018

The most common HVAC system is a central forced air furnace connected to ducts in either the floor or the attic. In Florida, about half of homes make use of package units for space conditioning, but such systems are rare in most heating-dominated regions of the country. Unlike split A/C or heat pump systems, package units sit entirely outside the home, and have supply and return air ducted to the unit. This frees up a small amount of interior space that would otherwise be occupied by an air handler, but the required exterior ductwork is prone to being compromised by the elements and animals.

In general, heat pumps are relatively rare in manufactured homes, occurring in only about 1 in 10 homes nationally.[3] In contrast, about 40 percent of all manufactured homes in the U.S. have central air conditioners, and the 2015 RECS data suggest that more than 80 percent of newer manufactured homes have central air. Feedback from retailers in the Southeast report that 100%

[3] Based on a sample of 286 manufactured homes (of any vintage) in the 2015 Residential Energy Consumption Survey (RECS 2015).

of their homes are sold with A/C. Most of those retailers offer a heat pump with highly varied uptake from all houses to an occasional house being sold with a heat pump.

Ducts

Ductwork in manufactured homes is typically located underneath the home's floor. In-floor ductwork is located above the floor insulation and road barrier, in a "basement" zone that has high thermal regain into the home. This is very different than under-floor duct systems in site-built construction, where the ducts are typically located in unconditioned space below the floor insulation. Manufactured homes are typically built with a trunk duct in each floor, made of either continuously formed sheet metal or of fiberglass duct board. The ductwork in each floor is connected by what is called a crossover duct, which is either a flexible duct run below the home to connect each home section's trunk duct together or ductwork that runs from the trunk duct and extends through the marriage line rim joist (Figure 10 and

Figure 11). Flexible crossover ducts under the home can be vulnerable to damage by animals, service technicians, and general deterioration.

However, in some cooling-dominated areas, the duct system is built into the attic of each home section. Ducts in the attic are likely to have a lower HVAC distribution efficiency because—unlike floor ducts—they run outside the thermal envelope of the home. In manufactured homes with "overhead ducts," the crossover connection between supply plenums in adjacent sections is made "through-the-ridge" (**Error! Reference source not found.**). In this context, "ridge" refers to the attic framing at the marriage line which is akin to a ridge beam in its location under the peak of the roof. This approach is something of a hybrid between a traditional flex-duct cross-over and the through-the-rim approach used for under-floor duct systems.

Ducts located in the attic is the norm in Florida, extending as far as parts of Texas and Arizona and is offered as a standard or optional practice by some manufacturers in South Carolina, Alabama, Kentucky, and Louisiana. In the Southeast, there is a degree of flexibility at the point of sale, depending on the model, that allows buyers to choose floor or overhead ducts. Buyer selection of overhead ducts may be driven by a desire to avoid blocking supply registers and customer perceptions that having ducts in the attic make the homes appear more like site-built homes in cooling-dominated climates where ceiling ducts are the norm. This practice echoes duct placement in the general housing stock where slab on grade foundations is the norm. Housing developers are interested in building homes as similar to site-built as possible, which includes building ductwork in the attic in some locations (Arizona and Louisiana).

Homes that have an external package unit will have flexible ducts running through the crawl space, similar to cross-over ducts, from the package unit to each home section's ductwork. In addition, the home will have a return grill in the floor that is connected by flexible duct to the package unit. Connections to flexible duct in the attic are not readily accessible for repair or inspection.

DEMOGRAPHICS

This section shares demographics of new home buyers and residents living in new manufactured homes.

Income

Households residing in newer manufactured homes have incomes greater than the general population of households living in manufactured homes, though less than that of the overall U.S. population (Table 3). There are no strong geographic differences in income among households living in newer manufactured homes.

Table 3. Annual income for selected housing categories.

	Household residing in...

		...any manufactured home	...a newer manufactured home[a]	...any home
Median annual income		$33,960	$45,580	$58,470
Income distribution (% of federal poverty guideline (FPG)[b])	<100% of FPG	22%	16%	13%
	100-199% of FPG	30%	25%	17%
	200-299% of FPG	20%	21%	16%
	300-399% of FPG	12%	15%	13%
	400+% of FPG	16%	23%	41%
	Total	100%	100%	100%

Source: Census ACS PUMS 2014-2018 data for Lower 48 states. Household income adjusted to 2018 dollars.
[a]Built in 2010 or later.
[b]2018 FPG is $12,140 for the first household member and $4,320 for each additional member.

Household Size and Composition

Households residing in newer manufactured homes are somewhat larger than the overall manufactured homes' population and the general U.S. population (Table 4). They are also less likely to have elderly household members and more likely to have children. On average, households in newer manufactured homes in the South are the largest and those in the Northeast are the smallest (Table 5).

Table 4. Household size and age characteristics for selected housing categories.

		Household residing in...		
		...any manufactured home	...a newer manufactured home[a]	...any home
Median number of household members		2.46	2.76	2.49
Number of household members	1	30%	22%	28%
	2	33%	30%	34%
	3	15%	18%	15%
	4	11%	16%	13%
	5+	11%	14%	10%
	Total	100%	100%	100%
Households with at least one person age 65+		31%	23%	29%
Households with at least one child		31%	43%	31%

Source: Census ACS PUMS 2014-2018 data for Lower 48 states.

Table 5. Household size and age characteristics for households in newer manufactured home, by study region.

		Study Region					
		1	2	3	4	5	6
Median number of household members		2.90	2.77	2.59	2.39	2.69	2.71
Number of household members	1	20%	21%	28%	30%	23%	23%
	2	29%	29%	32%	34%	33%	31%
	3	19%	21%	15%	16%	18%	19%
	4	17%	16%	13%	12%	12%	14%
	5+	15%	13%	12%	8%	14%	13%
	Total	100%	100%	100%	100%	100%	100%
Households with at least one person age 65+		20%	20%	35%	29%	20%	27%
Households with at least one child		46%	46%	33%	32%	38%	40%

Tenure

Households residing in newer manufactured homes have about the same home ownership rate (75%) as those in the overall manufactured home population (71%) but not surprisingly are more likely to have a mortgage or other loan on the home (Table 6). The incidence of renters is noticeably higher in the upper Midwest, however (Table 7).

Table 6. Tenure for selected housing categories.

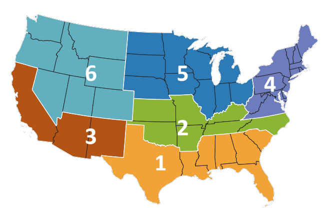
	Household residing in...		
	...any manufactured home	...a newer manufactured home[a]	...any home
Owned with a mortgage or loan	23%	46%	40%
Owned free and clear	48%	29%	23%
Rented	25%	22%	35%
Occupied without payment of rent	4%	3%	2%

Source: Census ACS PUMS 2014-2018 data for Lower 48 states.

Table 7. Tenure for households in manufactured home built in 2010 or later, by region.

	Study Region					
	1	2	3	4	5	6
Owned with a mortgage or loan	50%	51%	35%	40%	32%	42%
Owned free and clear	29%	28%	35%	35%	24%	30%
Rented	18%	18%	26%	22%	42%	23%
Occupied without payment of rent	3%	3%	4%	3%	2%	5%

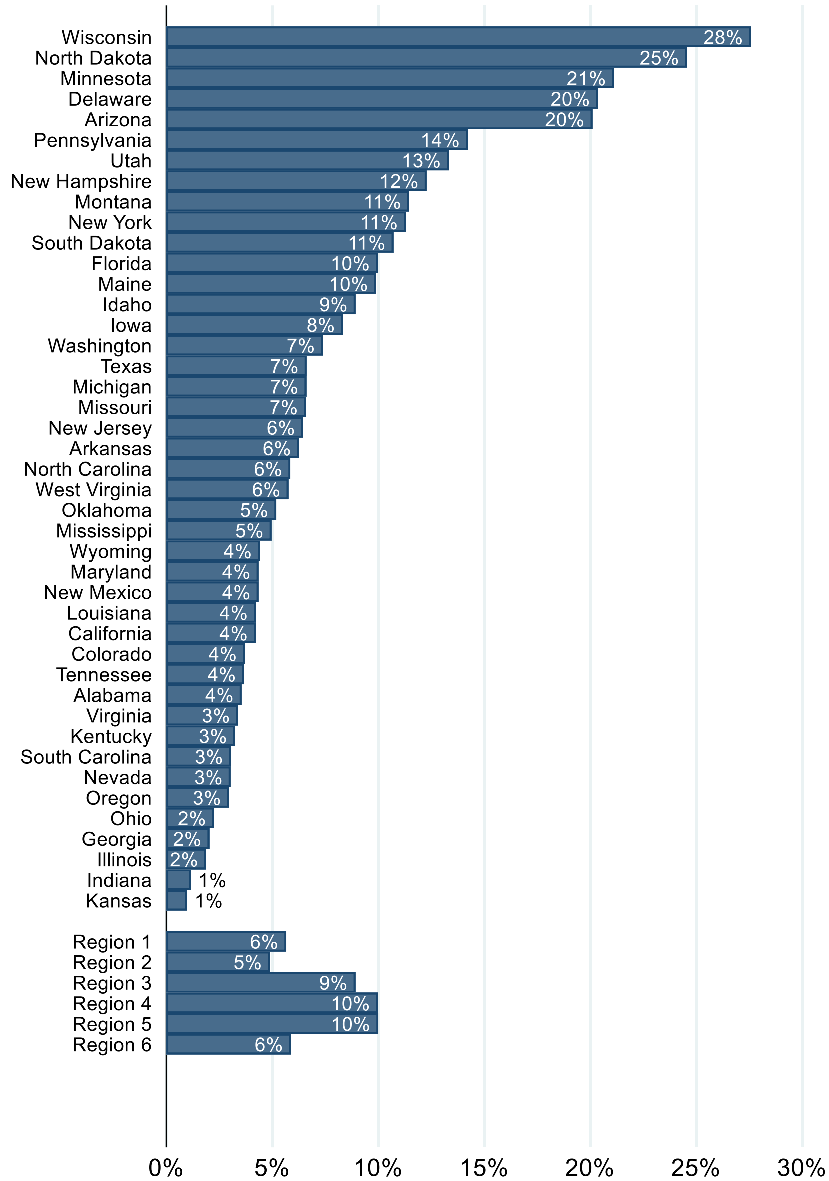
Source: Census ACS PUMS 2014-2018 data for Lower 48 states.



Vacancy and Seasonal Use

About one in five newer manufactured homes was vacant at the time of the ACS survey, a vacancy rate that is on par with the overall population of manufactured homes but higher than that of all U.S. homes (12%). Of interest here is the fraction of newer manufactured homes that are for seasonal or other occasional use. Nationally, this stands at about 7 percent, but some states have much higher proportions of such seasonal use (Figure 7).

Figure 7. Percent of manufactured homes built in 2010 or later used for seasonal, recreational, or other occasional use, by state and region.



(Five states (CT, MA, NE, RI and VT) omitted due to insufficient sample (n<30).

Site Rent, Personal Property Taxes, and Other Costs

The ACS questionnaire asks the following of respondents who own manufactured homes:

"What are the total annual costs for personal property taxes, site rent, registration fees, and license fees on this mobile home and its site?"

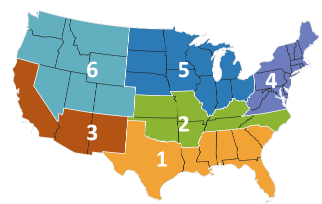
Households in a newer manufactured home are slightly less likely to report incurring such costs (62%) than the overall manufactured home population (67%), and also report slightly lower annual costs on average when these costs are incurred ($2,170 vs. $2,250). There are some substantial regional differences in these costs (Table 8).

Table 8. Manufactured home-related costs for households in manufactured homes built in 2010 or later, by region.

	Study Region					
	1	2	3	4	5	6
% of households reporting such costs	56%	59%	74%	71%	77%	73%
Mean annual cost when >0	$1,560	$1,110	$4,480	$3,050	$2,600	$3,860
Aggregate average annual cost[a]	$870	$660	$3,330	$2,170	$2,000	$2,830

Source: Census ACS PUMS 2014-2018 data for Lower 48 states. Costs are for personal property taxes, site rent, registration fees and license fees related to owning a manufactured home.

[a]Includes households reporting zero costs.



MARKET ACTORS

The team focused its interviews and stakeholder engagement on industry stakeholders who are directly involved with building, selling, and setting up the HVAC system or new home. The manufactured home and general HVAC industries are currently experiencing supply chain disruptions impacting the ability to get the materials needed to build homes and provide HVAC equipment. For example, several manufactured home plants are having ongoing difficulty getting flexible ducting and insulation products from their regular distributors. They report having purchased insulation from retail home improvement box stores and online resellers to prevent home production slowdowns. These supply chain issues and increased material costs are increasing the price of new manufactured homes.

At the same time the manufactured home industry is seeing a high volume of home orders causing long customer wait times for home deliveries. Plants that previously fulfilled orders for new HUD-code homes in weeks now have wait times well more than 12 months. Manufactured home industry partners are focused on working through these challenges to their day-to-day operations and have limited time to focus on RD&D or implementing new systems. This has made it challenging to engage with some industry stakeholders to get feedback on the HVAC innovations identified in this project. Some stakeholders, HVAC contractors, home inspectors, and home installers, are currently difficult to reach because they are busy supporting the high volume of new homes. This section of the report shares what we learned as we engaged with various manufactured home industry market actors. Table 9. Number of interviews by market actor typeshows the number of interviews conducted for each of type of market actor.

Table 9. Number of interviews by market actor type

Market Actor Type	Interview Count
Corporate home manufacturers	4
Home manufacturing plants	6 (3 NW, 1 MW, 1 SE, 1 NE)
Home retailers	14 (4 SE, 3 E, 3 MW, 4 SW)
HVAC contractors	3
Home installers	8 (5 NE, 1 E, 3 MW)
Home inspectors	2
Affordable housing developers	3
Manufactured home financial institution	1

Home Manufacturers

According to the Manufactured Housing Institute, there are 33 manufactured home manufacturers with 136 manufacturing plants in the United States. Manufactured homes are produced in a factory and manufacturers are driven to keep the homes affordable and to keep the production line moving. Manufacturers focus on managing the ease of home production, production cost, quality control, safety, and profit margin while trying to maximize the number of homes produced and minimize the number of warranty claims. Changes that could slow down the production line are challenging for manufacturers to adopt. In some cases, manufacturers build both modular and manufactured homes in the same factory and in the same factory line. As noted earlier in this report, recently there has been a shift in the industry with more plant operators building more homes to ENERGY STAR specifications. This shift is believed to be driven by revisions to the program requirements that simplified the certification process in much of the country, as well as to federal tax credits available to manufacturers for each ENERGY STAR certified home.[4]

The largest home manufacturers have both corporate and individual plant operators. The corporate level makes various decisions affecting all their plants, including reducing materials costs for all plant operators by having corporate-wide contracts with large materials suppliers. Corporate level decisions are focused on major home components or systems including the brand(s) and types of HVAC equipment, windows, etc. Plant level decisions include whether they build homes to ENERGY STAR specifications, build overhead or floor ducts, build through-the-rim or flex duct for marriage ductwork, and choice of ductwork materials. HVAC sizing calculations are run at either the corporate or plant level, depending on if plant staff have

[4] Energy Policy Act of 2005: H.R. 6 – 431 Sec. 45L. New Energy Efficiency Home Credit

experience running the calculations. Manufacturers have recommendations for plants, but do not make it a requirement for all plants to follow. For example, one of the largest home manufacturers recommends multi-section homes use the through-the-rim marriage ductwork approach but does not require it.

Home manufacturers do not provide any warranty on any of the equipment in the home, including the HVAC system. If there is an issue with the HVAC equipment during the home's warranty period, the home manufacturer passes it along to the HVAC equipment manufacturer or the HVAC contractor. One corporate manufacturer shared that oversizing air conditioners is their biggest warranty issue. The factory encounters situations where the local HVAC contractor refuses to accept the factory-specified equipment matches, preferring to up-size the equipment to meet perceived larger loads. Past research shows that air conditioners installed in manufactured homes in cooling dominated climates were often oversized by one ton, which was causing performance issues and the home manufacturer was motivated to improve. Oversizing cooling equipment is more expensive for consumers when buying the equipment and the equipment cycles on and off frequently lowering efficiency and increasing power bills. (ENERGY STAR 2005). Another more common warranty issue is customer comfort issues due to uneven air flow and home manufacturers expressed interest in exploring better duct designs.

Home Retailers

Manufactured home buyers purchase homes from retailers, who may be independent or affiliated with a home manufacturing company. Retailers show buyers display homes from one or various home manufacturers and work with the buyer to order the home, often with customizations. Buyers purchase homes from the retailers and then the retailer purchases the home from the manufacturer (Levy and Dentz 2018). Retailers typically arrange for home installation, transportation and delivery, set-up and either complete the HVAC installation themselves or hire a HVAC contractor. Retailers are driven by home setup costs, product quality, product marketability, and the ease of home and HVAC installation all while trying to reduce the number of warranty claims. If a buyer has an issue with the home, the first person they call is the retailer who sold them the home and provided a warranty on the home for an initial time period. Retailers may handle repairs with in-house staff or subcontract repair to a local HVAC contractor.

Retailer sales staff play a critical role in guiding buyers in their decision-making. Sales staff understand the floor plans and upgrades available for all the homes they sell and support buyers in making tradeoff decisions within the buyers' budget. The home manufacturers provide information to the sales staff about HVAC equipment specs and model numbers for each home, which is referenced in the sales process. Buyers choose the fuel type for their HVAC system, which may depend on where the home is being sited and electricity prices. They can also choose to upgrade from an electric furnace to a heat pump or from a standard efficiency fuel-burning furnace to a high efficiency model, which is highly recommended by some retailers. In some southern states, customers get to choose floor or attic ducts as well.

Sales staff have varying levels of knowledge and experience with HVAC systems, which influences the types of conversations they can have with buyers regarding HVAC related decisions or upgrades. Another major influence in this sales process is that sales staff are more incentivized to sell certain upgrades like kitchen cabinets where the retailer makes a higher profit margin, rather than recommending upgrades to the HVAC system. Additionally, they report rarely getting questions about HVAC or energy efficiency, with the bulk of the buyers' concerns focused on finance and design decisions related to floor plans, finishes, and fixtures. On the surface, this appears to indicate a lack of concern about efficiency. However, many manufacturers include information about whole house energy efficiency on their websites and promotional materials. The level of detail provided by manufacturers varies widely with some making energy efficiency a central theme and others providing only general specifications with no attempt to exceed minimum requirements. Buyers can study and compare efficiency treatment as part of their initial decision making about which manufacturers to pursue.

Retailers have mixed reviews on the value of the ENERGY STAR certification. Some retailers don't participate in ENERGY STAR because buyers don't ask for it and they don't think it helps them sell homes. Another retailer noted they sell homes that are high efficiency but aren't ENERGY STAR certified.

Home Installers

Manufactured home installers are hired by the retailer to move and install manufactured homes. Installers can also prepare the site by excavating and leveling the site. Installers may be affiliated with specific retailers or be independent. Home installation includes: blocking and leveling the house, sealing and painting the exterior of a multi-section home, finishing interior trim on a multi-section home, connecting the marriage ductwork, connecting to water, sewer and electricity, and testing appliances (Grissim 2008). Split system heat pump and air conditioning installation, when ordered by the home buyer, is completed by a licensed HVAC contractor, not the home installer. Proper home setup is important for maintaining the quality and durability of the home.

Most states require home installers to obtain a home installer license. State license requirements vary greatly. Installers operating in states where HUD administers the Manufactured Home Installation Program are required to obtain a HUD license, which is valid for three years and requires meeting certain experience or education requirements and completing a HUD-approved training program. (HUD FAQ)

Installers want the home to be road worthy and for the home installation to be as easy as possible. The most commonly reported energy and durability related problems when installing manufactured homes were homes not lining up well (in multi-sections); the low pitch of the roof (causing issues with facia and/or ice damming); and issues with the duct work causing air flow and condensation issues.

Home Inspectors

Retailers and installers are responsible for arranging for a third-party to complete a home inspection 10 days before the home's completion, per HUD code.[5] According to the Manufactured Home Installation program, a home inspector could be a manufactured home or residential building inspector with local authority, professional engineer, registered architect, HUD-accepted Production Inspection Primary Inspection Agency (IPIA) or Design Approval Primary Inspection Agency (DAPIA), or International Code Council (ICC) certified inspector. Inspectors complete the HUD Manufactured Home Installation Certification and Verification Report (HUD 309) when homes are installed.

Minimum inspection elements include: siting location according to home design and construction specifications; site preparation and grading for drainage; foundation construction, anchorage; completion of ductwork, plumbing, and fuel supply systems; electrical systems; exterior and interior close-up; skirting; and operational checks (HUD Memo 2015). One of the home inspectors we interviewed said they "certify the systems are working correctly, not that they are efficient" and that manufactured home industry standards are behind site-built homes.

HVAC Manufacturers

HVAC manufacturer R&D efforts are focused on transitioning away from common HFC refrigerants like R-410A that are scheduled for phase-out in 2024. This limited HVAC manufacturer's willingness to explore major HVAC system product innovations. In addition, there are a limited number of HVAC manufacturers who make heating equipment that fits within the small footprint of the cabinet where the heating equipment is installed in manufactured homes. One HVAC manufacturer stated the biggest challenge is getting the manufactured home industry to make changes, such as increasing the size of the cabinet to be able to fit more efficient HVAC equipment.

Home manufacturers have contracts with HVAC manufacturers for the HVAC equipment they install in the homes. Home manufacturers run the HVAC sizing calculations and determine the size of equipment to be in the home based on the load calculations and fuel choice made by the homebuyer, which is sent with the home for the home buyer and HVAC contractor to reference when adding a split system heat pump or air conditioner to the system. HVAC manufacturers are driven to produce a quality HVAC product that is easy to install and with limited warranty claims. If there is an issue with the HVAC equipment during the home warranty period, either the home manufacturer sends the issue to the HVAC equipment manufacturer to resolve, or the home buyer is left to file a warranty claim with the HVAC manufacturer directly. HVAC manufacturers expressed concerns about heat pump and air conditioning innovations that remove the HVAC contractor from the installation process, because then there is no clear party involved with the capability or inclination to make repairs in the field.

Currently, HVAC manufacturers and distributors may provide low-end furnaces at little or no markup on the premise that this makes it more likely that an after-market central air

[5] 24 CFR 3286.409

conditioner or heat pump will more likely be the same brand. This keeps the initial price of the home low and provides after-market installation, service and maintenance business for distributors and local contractors.

One HVAC manufacturer expressed concerns about humidity control issues in the South with non-ducted systems in manufactured homes. At least two smart thermostat manufacturers are working with the manufactured home industry to include smart thermostats in homes. One home installer shared that they currently remove smart thermostats from new manufactured homes as a service to customers, because some home buyers report that they do not like technology. Experience in the Northwest has found that smart thermostats can pose a setup challenge, because internet service rarely is active on site during the home setup process. If the home buyer did not express an active desire to obtain a smart thermostat, they may be unlikely to go through the process of setting up an account and connecting the thermostat to the internet. Some smart thermostats rely upon access to local weather data to control resistance heat lockout and weather-dependent recovery functions, so the thermostat may not deliver the expected energy savings and comfort benefits if not set up with an internet connection.

HVAC Contractors

The process of HVAC system installation in manufactured homes differs from that for site-built homes, in that a single HVAC contractor typically installs the entire HVAC system in a site-built home, and a manufactured home ships with a factory supplied furnace and thermostat. A local HVAC contractor then installs an air conditioner or heat pump equipment, if ordered by the home buyer. The brand of equipment installed at the factory is largely determined by the contracts the home manufacturer has with the HVAC manufacturers.

HVAC contractors care about the quality of the HVAC product, ease of installation, and reducing homeowner callbacks. Local HVAC contractors are responsible for any split system heat pump or air conditioning equipment installation when the home is installed. If the home will receive a central air conditioner, the home manufacturer ships the home with information about the appropriate size, which the HVAC contractor is supposed to reference when installing the equipment. Some HVAC contractors choose to ignore those recommendations and oversize the A/C, which leads to poor air flow and customer complaints.

Once the HVAC system is installed the customer is likely to call that HVAC contractor in the future if they have any issues with the HVAC system equipment. That contractor's familiarity with the factory-supplied thermostat can have a significant influence on how well the controls get configured, or if they get changed out in favor of the contractor’s preferred equipment.

Home Buyers

Manufactured homes cost significantly less to build per square foot than site-built homes: $57 per square foot for manufactured home and $119 per square foot for site-built (MHI 2021). Manufactured home buyers are often looking for an affordable new home with 71% citing affordability as a key driver for choosing a manufactured home (MHI 2021). Buyers are hoping to purchase a high quality, comfortable home for a lower cost than a site-built home.

Buyers, often influenced by the retailer, make HVAC system decisions in the homebuying process. In some areas of the South, buyers can choose attic or floor ductwork. Buyers can also choose to upgrade to a more efficient HVAC system and whether to have a central A/C or heat pump. The HVAC system's fuel type is often influenced by the fuel available where the home will be set up and current electricity prices. For example, if the home is being shipped to a park with natural gas service, it will likely have a natural gas furnace. In the interest of affordability and comfort, manufacturers often describe the energy efficiency characteristics of their homes on their websites which may influence which manufacturer a buyer pursues.

A retailer based in the Southwest mentioned the most common furnace complaint they receive is due to the pilot light blowing out from the winds of the Sierra Nevada mountains. One benefit to the retailers of encouraging an upgrade from an 80% efficient to a 90% efficient natural gas furnace is the electronic ignition. Customers would see additional benefits upgrading from an 80% efficient natural gas furnace to an electric heat pump.

We originally planned to call home buyers but shifted our focus to try to engage more HVAC contractors instead. We were, however, able to interview two housing developers and one non-profit supporting housing developers who are buying HUD-code manufactured homes to support urban housing developments.

Housing developers present a new market opportunity for HUD-code home manufacturers. A housing developer in New Orleans has a proof-of-concept project working through city zoning issues to provide HUD-code homes for urban in-fill housing. They are working with a home manufacturer to bring HUD-code homes up to local stick-built standards.

Next Step is a nonprofit that supports housing developers in employing factory-built homes in their projects. These homes are always ENERGY STAR certified, set low to the ground on a permanent foundation, have dry wall throughout, and have a front porch, garage, or car port to ensure the homes look as similar to local site-built homes as possible.

Another housing developer in Arizona is building a 38-unit development of all HUD-code homes. They are working with Clayton to build these homes, which are designed to have multiple HVAC systems – a package heat pump with ductwork in the attic designed to distribute air to the bedrooms and a 2-head ductless mini-split to condition the kitchen and living room space. Their idea behind the multiple HVAC systems is that the central air conditioner could be downsized.

INNOVATION FEASIBILITY ASSESSMENT

OVERVIEW

The team assessed 13 innovations for potential energy savings, cost effectiveness, and—perhaps most crucially—likelihood of adoption by the industry. This section of the report provides the innovation assessment framework and detailed information about each innovation. The savings potential and cost effectiveness for each innovation is derived from detailed energy modeling and energy-cost estimation described in more detail in our separate Energy Modeling and Cost Effectiveness Report (Pigg, et al, 2021). Each innovation's market motivators and barriers and readiness to adopt is based on feedback from talking with various market actors.

INNOVATIONS CONSIDERED

We initially considered HVAC-related innovations for new manufactured homes in two broad categories: duct-system improvements and increased adoption of heat pumps for space conditioning. Table 10 shows the full list of 13 potential innovations that we ultimately vetted. Items in bold were part of our starting list of potential innovations; the others came up in discussions with industry stakeholders. In two cases (improved cross-over duct designs and factory enabled heat pumps), we expanded an original innovation into one or more variants worthy of separate consideration: these are denoted with a letter in the third position of the ID.

Table 10. List of potential innovations.

ID	Name	Description
D1	**Improved HVAC quality assurance protocols**	Protocols and toolkit for more efficiently measuring duct (and envelope) leakage in the factory (in-plant testing) and HVAC system airflow, in the yard or after siting (field diagnostics)
D2	**Improved Cross-Over Duct Designs**	Better duct cross-over connections for multi-section homes: more energy efficient, less prone to degradation
D2a	Comparative testing of different cross-over approaches	Various opinions in the industry on performance of through-the-rim versus traditional cross-overs.
D3	**Demonstrate AeroSeal® in a Factory Setting**	Seal ductwork in the factory using Aeroseal technology
D4	**Interior duct designs to eliminate leakage**	Use a small diameter duct system routed through interior wall cavities
H1	**Factory enabled high efficiency ducted heat pumps**	Fully factory install an air-source heat pump on a home before shipping with no onsite HVAC labor needed
H1a	Partial factory-install of ducted heat pumps	Factory installs indoor unit and pre-charged line sets, and ships outdoor unit with home. No on-site HVAC labor required.
H1b	Revive the "Insider" ASHP	Revamp the prior "Insider" ASHP product to meet or exceed current efficiency standards

H1c	Air Source Integrated Heat Pump (ASIHP)	Integrated package combining ASHP to serve space heating and cooling and domestic hot water and also providing energy-recovery ventilation.
H2	**Advanced controls and distribution for ductless heat pumps**	Better integration of ductless and central ducted HVAC systems within the new manufactured home market
H3	**Quick connect fittings for ductless heat pumps**	NREL quick-connect concept applied to ductless mini-splits for manufactured homes
H4	Heat-pump ready furnace	Develop electric and gas forced-air furnaces that are factory ready for multi-stage and variable-speed heat pumps by exposing the full capabilities of existing ECM blower motors to external control, as well as providing a ready means to transition a factory-shipped furnace from a primary heating role to being secondary to a heat pump.
V1	Smart ventilation control with heat pump water heater	Integrate a heat pump water heater with home ventilation using ASHRAE standard 62.2 equivalent ventilation requirements

ASSESSMENT FRAMEWORK

Our assessment of the 13 potential innovations followed a structured approach that considered four key attributes:

- Energy savings potential
- Cost effectiveness
- Market motivators and barriers
- Market readiness

Energy savings potential

Innovations that offer significant national or regional energy savings potential are higher priority than those with less technical potential for savings. We modeled energy and energy-cost savings potential accounting for regional differences in construction practices and fuel prices: a more detailed accounting of that effort is contained in a separate report (Pigg, et al, 2021) with results summarized here.

Energy cost effectiveness

Innovations that are cost effective in energy terms are more likely to be adopted than those where incremental costs exceed expected energy-cost savings, though—as noted below—our assessments also recognized that other motivators, such as improved comfort or durability can sometimes be more important than energy cost effectiveness alone. Incremental costs proved difficult to gauge for several innovations. However, by calculating the break-even incremental cost—that is, the incremental cost that would yield a net present value of zero in relation to lifetime energy savings—for each innovation, we classified innovations as *likely*, *possible,* or *unlikely* to be cost-effective from an energy-savings standpoint based on the limited information available on costs.

Market motivators and barriers
Innovations with notable non-energy market drivers and few market barriers are more feasible than those that lack additional drivers or face other challenges to bring to market. At the outset of the project, we established a matrix of market actors and product attributes that we used for the assessment (Table 11), which we used for flagging key market drivers and barriers for each innovation.

Market readiness
Innovations that can be readily deployed at scale are more immediately feasible than those that require additional development. We judged the market readiness of each innovation according to the degree to which it involves existing products, services, and market infrastructure versus needing additional development in any of these areas.

Table 11. Matrix of market actors and product attributes.

Manufactured Home Market Actor	**Attribute**							
	Primary			*Secondary*			*Tertiary*	
	Cost	***Quality***	***Comfort***	***Convenience***	***Durability***	***Energy***	***Safety***	***Waste***
Manufacturer	Production cost / profit margin	Production quality control	Marketability of comfort	Ease of production	Warranty claims	Marketability of energy efficiency	Production and transport safety	Production waste
Home retailer	Siting cost / profit margin	Overall product quality / Road worthiness	Marketability of comfort	Ease of home and HVAC installation	Warranty claims / siting callbacks	Marketability of energy efficiency	Transport and siting safety	
Home installer	Siting cost / profit margin	Road worthiness		Ease of home installation	Siting callbacks		Siting safety	Siting waste
Home buyer	Purchase cost	Overall product quality	Comfort / IAQ	HVAC ease of operation and maintenance	Maintenance costs / overall longevity	Operating cost		
HVAC manufacturer	HVAC profit margin	HVAC product quality	Marketability of comfort	Ease of HVAC installation	HVAC warranty claims and callbacks	Marketability of energy efficiency		
HVAC contractor	HVAC installation profit margin	HVAC product quality	Marketability of comfort	Ease of HVAC installation	HVAC callbacks	Marketability of energy efficiency		
Regulatory (HUD, DOE, EPA)	Energy cost effectiveness		Impact on IAQ			Energy savings potential	Life/Safety code compliance	

ASSESSMENT SUMMARY

We assessed innovations for market applicability, potential energy savings, cost effectiveness, and likelihood of adoption by the industry based on information collected from industry stakeholders. **Error! Reference source not found.** summarizes the assessment results for each innovation, including cost effective likeliness and key market drivers and barriers for adoption. These findings are addressed in more detail for each innovation in the sections that follow.

With potential energy-cost savings in the range of 35 to almost 60 percent, ducted heat pumps (H1, H1a, H1b, H1c and H4) are the highest-impact innovations. We judge ducted heat pump innovations as likely to be cost-effective, though this varies on a regional basis, and our analysis finds that the operating cost for even an advanced heat pump is higher than that of a natural gas furnace in many parts of the country at current fuel prices. While homes with natural-gas heat constitute only about 10 percent of the national market, they make up more than half of new-home sales in the Midwest. Energy savings, comfort—particularly humidity control in hot-humid climates—and controlling HVAC sizing are industry drivers for these innovations, while upfront cost is a barrier.

For ductless heat pumps, we consider the most likely path to market acceptance to be partially offsetting the space-conditioning load of a central, ducted system with a single-head ductless system in a central portion of the home. This reduces the energy-savings potential, but if properly integrated with controls to maximize the benefit of the heat pump (H2), these could still be a cost-effective upgrade for new manufactured homes. Advanced quick-connect refrigerant fittings for these units (H3) could further reduce field-installation costs.

Duct-sealing innovations (D1, D2, D2a, D3 and D4) have estimated energy savings that are generally less than 10 percent of space-conditioning costs. However, the innovations themselves are likely to be less expensive than, say, upgrading to a heat pump, so can still be cost effective. Cross-overs used to connect duct systems for multi-section homes are a particular point of vulnerability, though the potential market for cross-over innovation (D2 and D2a) is limited to the 43 percent of the market that is multi-section homes. In general, there is more uncertainty in savings potential and cost-effectiveness associated with duct-related innovations due to a lack of data from modern manufactured homes about typical existing leakage levels, the incidence and magnitude of leakage issues, and in some cases the efficacy of particular innovations in mitigating these. Reducing energy waste call-backs is a driver for these innovations, while home manufacturer motivation to address duct leakage and costs are barriers.

Two innovations (H1c and V1) go beyond the boundaries of space-conditioning and involve heat pump water heaters in ways that help reduce combined space-conditioning and water heating costs. These involve higher up-front costs but also offer enhanced savings potential.

Table 12. Overview of assessment results.

	Innovation		Market applicability (% of new home sales)	National average HVAC energy savings (%)	National average break-even incremental cost[a]	Cost-effective at scale?	Key Drivers	Key Barriers
D1	Improved HVAC quality assurance protocols	a) In-plant testing	100	5-10[b]	$500-$950[b]	Likely	Better plant Q/C. Potential future regulatory requirements.	Duct leakage not seen as an issue by some mfrs. Cost.
		b) Field diagnostics	100	4-8[b,j]	$50-$100[b]	Likely	Better up-front resolution of leakage issues.	Lines of responsibility for resolving issues.
D2	Improved Cross-Over Duct Designs		43[g]	2-5[b]	$200-$550[b]	Possible	Energy waste and comfort issues.	Cross-over installation cost and complexity.
D2a	Comparative testing of different cross-over approaches						Reduced siting costs.	Retooling duct layouts and floor structure.
D3	AeroSeal in a Factory Setting		100	5-10[b]	$500-$950[b]	Unlikely	Better sealing and consistency.	Duct leakage not seen as an issue by some mfrs. Cost.
D4	Interior duct designs to eliminate leakage		100	7-13[b]	$650-$1,150[b]	Unlikely	Better comfort and durability	Re-engineering and retooling costs.
H1	Factory enabled high efficiency ducted heat pumps		65 - 69[c,d]	35-54[c,d]	$5,300-$6,900[c,d]	Likely	Better comfort. Energy savings. Control over HVAC sizing.	Cost. Roadworthiness. HVAC market-structure barriers.
H1a	Partial factory-install of ducted heat pumps						(same as above)	Cost.
H1b	Revive the "Insider" ASHP						Equipment protected. Additional energy savings.	Cost. Noise. Regulatory issues with refrigerants.
H1c	Air Source Integrated Heat Pump (ASIHP)		73[h]	58[h,i]	$9,100[h]	Possible	Smaller mechanical footprint. Energy savings.	New technology. Footprint and plumbing retooling.
H2	Advanced controls and distribution for ductless heat pumps		71	8-15[d,e]	$950-$1,800[d,e]	Possible	Increased comfort and reduced noise	Duplicate HVAC systems.
H3	Quick connect fittings for ductless heat pumps						Reduced installation cost.	Market readiness and regulatory barriers.
H4	Heat-pump ready furnace		68-69[d,f]	44-54[d,f]	$5,900-$6,900[d,f]	Likely	HVAC choice flexibility.	Small market for HVAC mfrs
V1	Smart ventilation control with heat pump water heater		94[h]	17[i]	$2,900	Likely	Energy savings and better ventilation	Cost. Noise.

Notes:
a) break-even incremental cost is the incremental cost that equals the present value of life-cycle energy savings, less up-front loan costs and the present value of incremental property taxes.
b) range reflects uncertainty in average baseline duct leakage and magnitude of innovation impact
c) range reflects different types of heat pump with different efficiency levels
d) excludes homes already sold with a heat pump and those heated with natural gas where savings would be negative at current fuel prices
e) for a ductless displacing 25 to 50% of space conditioning load for the main ducted system. Range also reflects uncertainty in average baseline duct leakage.
f) for multi-stage or variable-speed heat pumps that would be more readily enabled with a heat-pump-ready furnace
g) only applies to multi-section homes
h) excludes homes where savings would be negative at current fuel prices
i) percent of HVAC and water-heating operating costs
j) among homes with identified leaks that are remediated

INNOVATION DETAILS

The following sections provide a more detailed accounting of each potential innovation and our assessment of its market potential.

(D1) Improved HVAC quality assurance protocols

Description

This innovation seeks to streamline measurements and protocols to provide quality assurance for four HVAC-related parameters:

- Duct leakage
- Supply register airflow, including HVAC-system airflow
- Ventilation system airflow
- Building envelope tightness

With regard to duct leakage, current HUD code requires only that the duct system be made, "substantially air-tight," and states that it can be demonstrated by finding that "the static pressure in the duct system, with all registers sealed and with the furnace air circulator at high speed, is at least 80 percent of the static pressure measured in the furnace casing, with its outlets sealed and the furnace air circulator operating at high speed."[6] This test would find only very significant duct leakage, and multi-section homes could only be tested after cross-over ducts are installed. This test is sufficiently cumbersome, so it is performed at most on an occasional basis.

ENERGY STAR program requirements for manufactured housing recently changed, making duct testing no longer required for new homes to be ENERGY STAR certified. Some home manufacturers already factory-test all homes for duct leakage, but others have a corporate policy that requires only occasional testing. It is likely that many plants do not test for duct leakage at all. This could change in the future: recent proposals to HUD's Manufactured Housing Consensus Committee recommend requiring duct leakage testing to a maximum of 0.08 CFM per square foot at 25 PA test pressure using a duct blaster (HUD 2020, HUD 2021).

In addition to duct tightness, HVAC system airflow and building envelope tightness can impact indoor moisture levels, occupant comfort, and energy use. Similarly, bath and kitchen exhaust fan measurement of ventilation airflow typically occurs only after complaints of poor indoor air quality or excessive humidity. While not necessarily tied to overall HVAC energy use, room to room airflow balancing is a known issue for manufactured homes, especially multi-section homes. Chronically hot or cold rooms can lead homeowners to adjust thermostat settings or close supply register openings to improve room-to-room comfort—both things can increase energy use, while providing only modest improvements in comfort.

[6] 24 CFR Part 3280.715 (4)

While a factory can readily accommodate fairly bulky equipment for testing duct and envelope leakage, much happens to a manufactured home between the time it rolls off the production line and when it gets set up on site. Service technicians called out to a home to solve comfort complaints or moisture issues typically do not have the means to perform pressure diagnostics and air leakage testing—and it generally does not make sense to always equip and train them with such equipment, given that these issues are not common among things that they are asked to address. However, service technicians, installers, and inspectors could benefit from quick and easy quality-assurance checks of key HVAC-system parameters.

This innovation explores ways to streamline testing both on the factory floor (duct leakage) and post-siting (duct leakage, ventilation airflow, supply register airflow, and building envelope tightness).

Factory-Floor Duct Leakage Testing

Factory-floor testing using a duct-leakage tester (e.g., Duct Blaster®) can be used on the production line to test every home section as it gets built. For homes that are built with ducts in the floor, it is often possible to test the duct system for leakage before any walls are installed. Register openings and cross-over takeoffs can be blocked with foam or taped over and the duct testing fan set over a furnace or register opening. This test would provide a clear indication of duct leakage, and it can be quick and easy enough to perform so that plants could adopt it for every home section, making it a basic early function check of the duct system's air tightness.

A duct test can often be performed by one to two people in two to four minutes per home section when the home section on the factory production line is simply a floor with duct registers in it. There are no walls to navigate around or toe kick registers to access under cabinets. Nine factories in the Northwest perform such tests on all ENERGY STAR homes certified by the region's Northwest Energy Efficient Manufactured Housing Program (NEEM). The crew tests the ducts to a maximum total leakage threshold of 0.06 CFM per square foot at 50 PA test pressure. Some factories have set a simpler threshold—if the fan pressure (with the most restrictive ring in place on the tester) rises above 25 PA, which corresponds to duct leakage of about 28 CFM50 PA, then the home section is considered to have a leak. The crew corrects the leak and does not allow the home to advance down the production line until the ducts test tight. The NEEM program finds that the in-plant testing reliably delivers sited homes with duct systems that have duct leakage to outside testing at or below 0.06 CFM per square foot at 50 PA. (Baylon et al 2009; Davis et al 2000; Davis 2004)

Post-Siting Diagnostics

After a home is sited, simplified pressure diagnostics testing protocols can be employed by a technician with just a manometer. Adding an exhaust-fan flow measuring device would make the test more precise, but it is not necessary. In short, the technician turns off all exhaust fans and closes all windows and doors in the home and takes a baseline pressure differential reading between inside and outdoors. Then, the technician turns on one or more exhaust fans in the home and records the new pressure differential. Finally, they run just the furnace blower and read the new pressure differential. The change in pressure differential from fan-induced depressurization gives a sense of the home's overall airtightness. The furnace-induced change in pressure differential gives a sense of the magnitude of duct leakage, as compared to the assumed (or measured) flow of the exhaust fan(s). It may also be possible to create a "flapper" that is placed into a window opening and its action (degree of opening into the home) compared between baseline, fan operation, and furnace operation. These protocols are simple enough that they could readily be employed by installers or inspectors on every home as a basic quality-assurance check for large issues with duct leakage and ventilation performance. The test is expected to take less than 15 minutes under mild wind conditions. Innovation testing will explore the tests' sensitivity to wind conditions.

The project team is working with The Energy Conservatory (TEC) to develop a manufactured home diagnostic testing toolkit that would provide all the testing equipment, protocol, QA/QC documentation, and training on the use of the tool kit for manufactured home industry stakeholders. This will include lower cost screening tools for field use as well as a complete package of building science tools required for programs such as ENERGY STAR. The toolkit would enable verification of field and/or factory related HVAC and envelope measure installation and commissioning, internal factory or retailer QA/QC, and troubleshoot building science issues to be able to find the root cause. The TEC manufactured home toolkit would include: a DG8 digital manometer, a flow box for measuring exhaust flows, a TrueFlow for measuring air handler flow, a duct blaster for duct leakage measurements, a fog puffer for diagnosing leakage sites, and possibly a new software tool similar to TECLOG and TECTITE. A blower door is not included in the toolkit, because the duct blaster can measure both home air leakage and duct leakage.

As a side note, while focused here on new construction, the protocols developed under this innovation should be readily applicable to weatherization of existing manufactured homes as well. They could potentially be adopted by the federal Weatherization Assistance Program and utility energy efficiency programs around the country.

Savings Potential and Cost Effectiveness

Because they involve different intervention mechanisms, we consider the savings from factory-floor testing separately from in-field diagnostics. Savings estimates for both are rooted in parameterized modeling of energy consumption at different leakage levels, but subject to considerable uncertainty about the degree of achievable leakage reduction. We handled this uncertainty by specifying key inputs as uncertainty ranges, then probabilistically combining these to report savings and break-even incremental cost ranges.

Factory-floor duct leakage testing: We assumed that routine testing and remedial sealing would reduce leakage by 70 to 90 percent relative to average baseline leakage of 6 to 12 cfm per 100 ft^2 of floor area. These ranges yield national-average space-conditioning savings of somewhere between 5 and 9 percent, with a break-even incremental cost of \$500 to \$950 (Table

13). Since testing and remedial sealing can be accomplished in a matter of minutes by an experienced crew, this innovation is likely to be highly cost-effective. In fact, our analysis suggests it would be cost-effective even if the average leakage reduction was as low as 10 percent relative to current practice and the testing and sealing work could be performed for $100 or less.

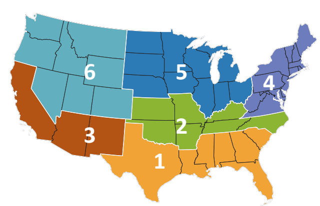
Table 13. Annual energy-cost savings and break-even incremental cost for factory-floor duct leakage testing and remediation for all homes, by region.

Region	HVAC energy savings[b]	Annual energy-cost savings[b]	Break-even incremental cost[a,b]
1	4% - 8%	$25 - $45	$250 - $500
2	5% - 9%	$35 - $65	$400 - $850
3	3% - 7%	$30 - $55	$300 - $650
4	5% - 11%	$70 - $140	$1,100 - $2,200
5	5% - 10%	$45 - $90	$650 - $1,250
6	7% - 13%	$50 - $100	$700 - $1,400
National avg.	5% - 10%	$35 - $70	$500 - $950

Notes:

(a) Break-even incremental cost is the incremental cost that equals the present value of life-cycle energy savings, less up-front loan costs and the present value of incremental property taxes. Based on regional fuel prices and energy modeling. Includes effect on present-value of delayed onset of leakage.

(b) Ranges shown are the 5th and 95th percentiles of probabilistic analysis from assuming 70 to 90% duct leakage reduction relative to baseline average of 6 to 12 cfm per 100 ft^2 of floor area. Duct leakage is to the outdoors at 25 Pa of pressure.



Post-Siting Diagnostics: We assume that the diagnostics will lead to identifying and remedying leakage of 50 to 100 cfm in 5 to 15 percent of tested homes. The results suggest 4 to 7 percent space-conditioning savings nationally among homes where leaks are identified and remediated, with a break-even incremental cost in the range of $30 to $100 per tested home (Table 14. Annual energy-cost savings and break-even incremental cost for simplified field diagnostics for duct leakage, by region. Since the simplified diagnostics are meant to be quick (under 15 minutes) and easy to implement, we consider this innovation to be likely to be cost effective.

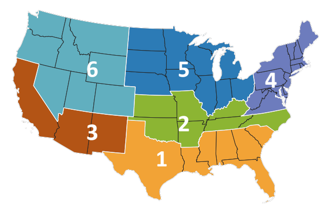
Table 14. Annual energy-cost savings and break-even incremental cost for simplified field diagnostics for duct leakage, by region.

Region	HVAC energy savings (homes with leaks)[b]	Annual energy-cost savings (homes with leaks)[b]	Break-even incremental cost[a,b]
1	4% - 7%	\$20 - \$35	\$15 - \$50
2	4% - 8%	\$30 - \$50	\$25 - \$85
3	3% - 5%	\$20 - \$40	\$20 - \$60
4	5% - 8%	\$60 - \$110	\$65 - \$220
5	5% - 9%	\$40 - \$80	\$40 - \$135
6	5% - 9%	\$40 - \$70	\$40 - \$125
National avg.	4% - 8%	\$30 - \$55	\$30 - \$100

Notes:

(a) Break-even incremental cost is the incremental cost that equals the present value of life-cycle energy savings, less up-front loan costs and the present value of incremental property taxes. Based on regional fuel prices and energy modeling. Includes effect on present-value of delayed onset of leakage.

(b) Ranges shown are the 5th and 95th percentiles of probabilistic analysis from assuming that duct leaks averaging between 50 and 100 cfm (to the outdoors at 25 Pa of pressurization) are identified and remediated in 5 to 15 percent of tested homes. Savings values shown are for tested homes with leakage needing remediation; break-even incremental cost takes into account testing in all homes.



Market Motivators and Barriers

The fact that some plants already test for duct leakage is an indication of manufacturer interest in minimizing this issue. The main barrier to more plants conducting such testing is likely a combination of a perception that duct leakage is not an important issue and concerns about the time and cost implications of testing. The main focus of this innovation is to provide a streamlined approach to factory testing for duct leakage that minimizes these concerns.

Regarding post-siting testing and diagnostics, three factory service managers in the Northwest region have contacted the project team regarding homes in the field experiencing issues with airflow, comfort, and/or moisture build up. After describing the field-testing protocol to them, they each responded with interest in adding such a capability to their service technicians. A field technician in Louisiana uses a similar testing protocol using a kitchen range exhaust hood fan instead of the bath fan to measure and diagnose issues in new homes.

At the same time, home installers we interviewed reported not testing for duct leakage when installing homes. They expressed initial concerns with being able to perform this test because typically there is not power at the site and expectations for who would be responsible for resolving any issues found through the testing. Testing the ducts for leakage at the factory and at siting would allow for easier root cause analysis in understanding where the duct leakage issue may have started in the process. These barriers would need to be overcome to make post-siting diagnostic testing widespread in the industry.

Market Readiness

For the most part, the tools and techniques needed for this innovation are readily available, and the innovation is mainly centered on validating and documenting streamlined approaches. Some proprietary software development related to streamlining field diagnostics with manufacturer-specific test equipment may be desirable.

(D2) Improved cross-over duct designs

Description

National sales data show that 43 percent of all manufactured homes shipped each year are multi-section homes that must be joined during siting**.** Because these homes are outfitted with a single forced-air furnace for heating, a means of connecting the duct system between sections during siting is needed. This is typically done by installing a length of 10- or 12-inch diameter flexible duct between the two halves of the duct system. (Note that some homes are instead constructed to join the duct system with a through-the-rim approach, as discussed in more detail under Innovation D2a, starting on Page 37.) For most of the country, this cross-over section of ductwork is below the belly of the home and connects trunk ducts in each section. However, in the Southeast, where ceiling ducts are more common the cross-over is made in the attic (as we describe in more detail in the next innovation section).

The cross-over is typically installed by the home installer when the sections are joined during siting. However, one HVAC installer interviewed in the Southeast prefers to install the cross-over ductwork themselves due to past cross-over installation issues done by home installers.

Flexible cross-over ducts that run below the home can be vulnerable to damage by animals, service technicians, and general deterioration—especially if poorly installed to begin with (Figure 8).

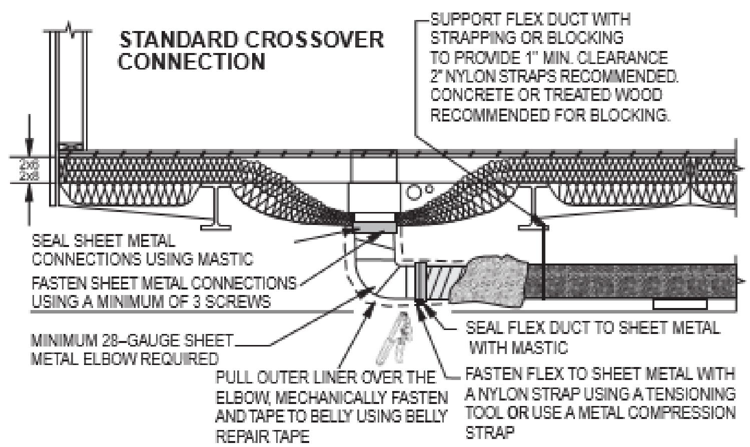
Figure 8. Example of a failed cross-over duct connection under a multi-section manufactured home.

The improved cross-over duct design innovation is focused on low-cost means of improving the efficiency and durability of traditional under-floor cross-overs, which are currently R-8.

One approach to improving the efficiency and durability of the cross-over is to replace at least part of the flexible duct with field-installed rigid duct. Levy and Dentz (2018) explored a hybrid cross-over approach that was mostly rigid with a minimal flex duct connection. They found it to be effective and likely more durable, but also more complicated and somewhat more costly to install.

A more limited innovation along these lines that is in wide use in the Northwest is to add a metal elbow at each trunk connection and join the flex duct horizontally to the elbows instead of vertically directly to the trunk openings (Figure 9). This helps relieve stress on flexible duct connections, improve airflow, and reduce flex duct exposure to high heat from close proximity to the furnace discharge.

Figure 9. Cross-over connection specifications for the Northwest Energy-Efficient Manufactured Housing Program.



Retailers expressed interest in improved cross-over detailing despite reporting that disconnected cross-over ducts are uncommon (during the retailer's involvement with the house) and typically repaired by retailer staff with relatively little burden. Home installers would like to see improved materials and methods for cross-over connections. The team engaged with an insulation manufacturer in its outreach efforts and considered trying to prototype a rigid duct board crossover. Our contact retired and we stopped pursuing this approach because the combined metal-elbow and improved flex duct cross-over concept is more market ready.

The innovation explored here is to combine the metal-elbow concept used in the Northwest with an improved flex duct cross-over consisting of a smaller diameter flex duct nested inside a larger diameter flex duct. This double-flex duct approach would improve the durability of the cross-over and increase the R-value of the cross-over to R-16.

Savings Potential and Cost Effectiveness

We modeled the savings from an improved cross-over design as a combination of reduced thermal conduction losses from increased R-value of the cross-over itself, plus reduced potential for leakage as the house ages due to less degradation of duct connections. The improved R-value component is the smaller of the two, contributing an average of $8 per year worth of energy-cost savings. Savings from reduced leakage are potentially larger, but also subject to considerable uncertainty, because those savings depend on assumptions about the incidence of leaks, their magnitude and when they occur.

For estimation purposes, we assumed that an improved cross-over design might prevent leaks averaging between 50 and 200 cfm in 10 to 40 percent of homes from occurring 1 to 5 years after siting. We then probabilistically calculated the expected range of energy-cost and break-even incremental cost (Table 15). The results suggest 2 to 5 percent space-conditioning savings (after leaks would otherwise have developed), with a break-even incremental cost of $200 to $550, which we considered to be within the possibility of being cost-effective, depending on details of the improvement that are yet to be worked out.

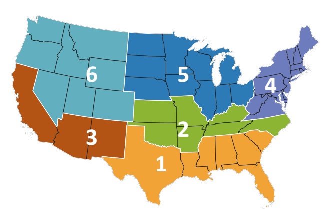
Table 15. Annual energy-cost savings and break-even incremental cost for improved cross-over design, by region.

Region	HVAC energy savings[b]	Annual energy-cost savings[b]	Break-even incremental cost[a,b]
1	2% - 4%	$15 - $30	$200 - $350
2	1% - 4%	$10 - $30	$100 - $400
3	1% - 3%	$5 - $25	$100 - $300
4	1% - 5%	$20 - $75	$350 - $1150
5	1% - 5%	$15 - $50	$200 - $750
6	2% - 6%	$15 - $50	$200 - $700
National avg.	2% - 5%	$15 - $40	$200 - $550

Notes:

(a) Break-even incremental cost is the incremental cost that equals the present value of life-cycle energy savings, less up-front loan costs and the present value of incremental property taxes. Based on regional fuel prices and energy modeling. Includes effect on present-value of delayed onset of leakage.

(b) Ranges shown are the 5th and 95th percentiles of probabilistic analysis from assuming 10 to 40% of homes develop leaks that average 50 to 200 cfm (to the outdoors at 25 Pa of pressurization) after 1 to 5 years. Savings values are for the period after leaks develop.



Market Motivators and Barriers

Cross-over failures are a significant source of comfort complaints and energy waste. Home manufacturers, retailers, installers, and buyers all have incentives to avoid failure of this critical component of the HVAC system in multi-section homes. However, the cost and complexity of cross-over installation is also a significant concern and can be expected to be a barrier to adoption of improved cross-over designs that are considerably more expensive or complicated to implement in the field. There is significant variability in crossover duct routing under the home, depending upon the home's floorplan. Differing locations for the furnace in the house and differing locations for support piers under the home, combine with the chassis axles and varying amounts of clearance in the crawlspace to make crossover duct routing more challenging than is suggested by many illustrations. Any changes to crossover ducting that reduce one's ability to route it around obstacles and through constrained spaces can lead to installation difficulties.

Market Readiness

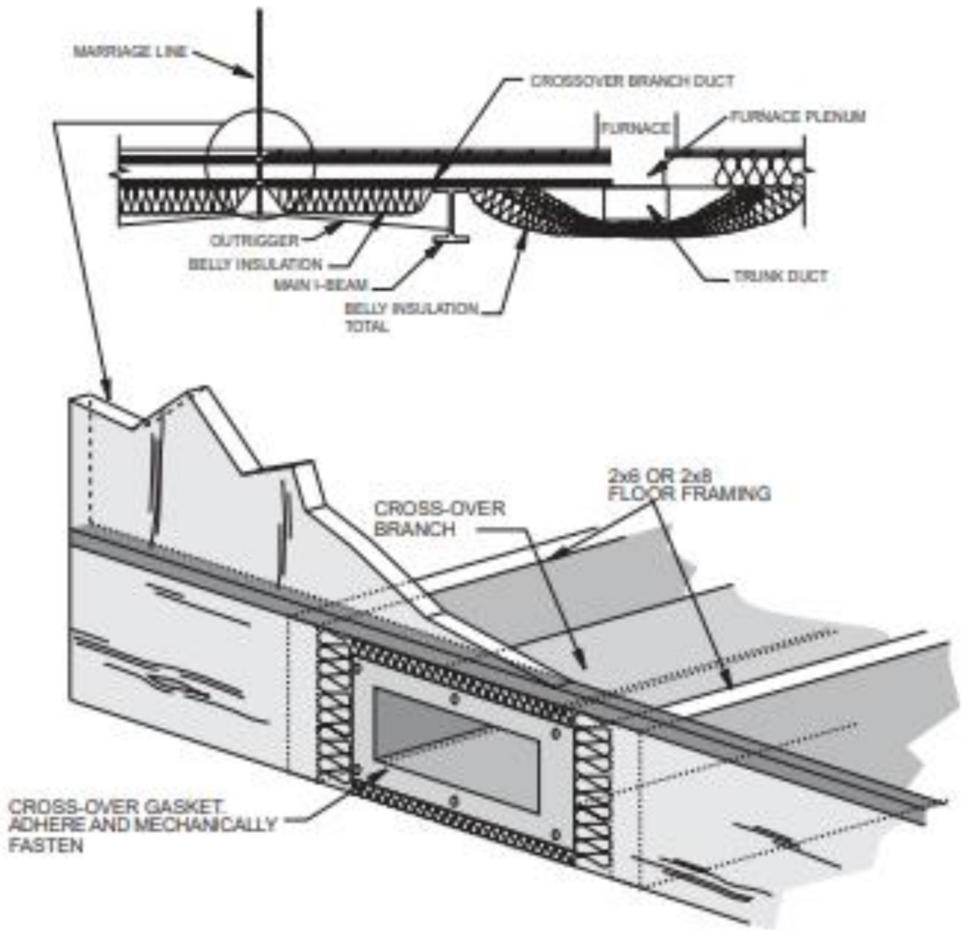
This innovation relies on the novel application of readily available materials, allowing it to be immediately deployed and scaled with appropriate education and training of manufactured-home installers. Training for factory drafting and engineering staff may also be necessary to help them ensure that significant under-floor obstacles like support piers, chassis axles and plumbing drain lines are not competing with space for the crossover duct.

(D2a) Comparative testing of different cross-over approaches

Description

An alternative to a conventional underfloor cross-over is a “through-the-rim” approach, which eliminates the need for running flexible duct under the home. Factory-installed gaskets at each cross-over connection increase the chances that an airtight seal is achieved (Figure 10).

Figure 10. In-Floor "through the rim" cross-over (Greer et. al 2004)



The through-the-rim cross-over approach is already in use in some factories throughout the U.S. However, market actor interviews revealed disagreement about the efficacy of this approach and differences in the details of how it is implemented. The reliability of the gasket materials commonly in use at the marriage line seals may present some issues, as we have anecdotal evidence of gasket failure during the process of mating together home sections. Home installers believe there is a challenge with the way the gasket is installed at the factory.

Figure 11. “Through-the-rim” mock-up produced by Cavalier Homes (Moyer et. al. 2008)

Some factories do a combination of conventional cross-over ducts and in-floor cross-overs in their product lines. The system used to connect cross-over ductwork may depend on the factory where the home is built or customer preference. One industry stakeholder sees the flex-duct and through-the-rim cross-over duct designs as being equivalent in long-term performance. The homes they work with pass blower door tests and exceed ENERGY STAR HERS ratings. Most retailers preferred the through-the-rim approach.

One study (Levy and Dentz, 2018) of duct leakage for 64 ENERGY STAR homes built in 2006 and 2007 and tested within a year of siting showed somewhat higher average leakage levels for through-the-rim homes (4.1%) compared to homes with conventional under-floor flex-duct cross-overs (3.1%).[7] Neither of these leakage levels are particularly high, however—and none of the individual homes tested (of either cross-over type) showed more than about 6% leakage. These results may owe much to higher quality-control standards for ENERGY STAR homes as well as the limited elapsed time after siting when the testing occurred.

In the Southeast where ceiling ducts predominate, a “through the ridge” approach is typically used (Figure 12). In this context, “ridge” refers to the attic framing at the marriage line which is akin to a ridge beam in its location under the peak of the roof. This approach is something of a hybrid between a traditional flex-duct cross-over and the through-the-rim approach used for under-floor duct systems. The through-the-ridge approach may benefit from improved detailing such as creating framed rough openings, adding gaskets, or using off-the-shelf duct components (Moyer et. al. 2008. Moyer and Stroer, 2008). Manufacturers in the Southeast expressed interest in a simple and effective method for set crews to execute a leak free

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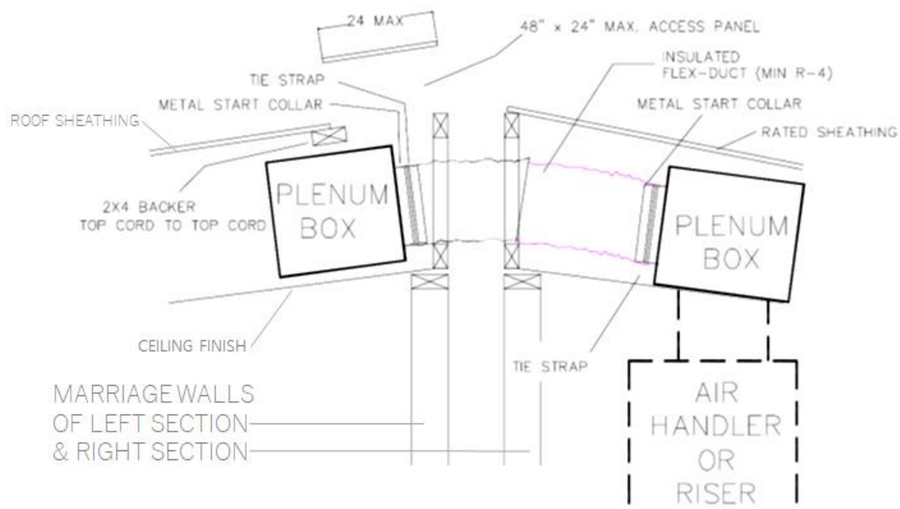
[7] Duct leakage is commonly reported in terms of cubic feet per minute of leakage to outside (at a duct pressurization level of 25 Pascals), expressed as a percent of the conditioned floor area of the home.

connection with reduced pressure drop such as a through-the-ridge hard connection design similar to through-the-rim crossovers used for floor systems.

Figure 12. Detail for current "through the ridge" cross-over duct connection. Courtesy of Palm Harbor Homes



All of this suggests a need for comparative field evaluation of through-the-rim versus traditional cross-overs for multi-section homes. By keeping the cross-over within the thermal envelope of the home, the through-the-rim approach suggests the potential for greater efficiency and longevity. But the need to align multiple duct sections without gasket damage during the difficult process of marrying sections raises the potential for duct leakage at the cross-over points, and industry stakeholders disagree about the ability of through-the-rim cross-overs to effectively deliver conditioned air between home sections. The innovation may also consider having home installers spray foam around the duct connection. Field evaluation can compare the crossover approaches, materials used (metal vs. graduated ductboard), and branch vs. in-line supply register flows. The measured flows from supply registers with various configurations and placements could be valuable data home manufacturers could use in their duct design software to get a better representation of air flow and static pressure in the system.

The manufactured home duct system is a highly value-engineered system that will be difficult to convince plants to replace. We are looking to improve its function without increasing construction costs or complexity. If the through-the-rim approach can be shown to be less leak-prone over time, more thermally efficient, and provide good air distribution throughout the home, it could spur wider adoption in the industry.

Savings Potential and Cost Effectiveness

Although a through-the-rim cross-over differs structurally from a below-the-belly cross-over, both should substantially reduce—or in the case of through-the-rim, eliminate—long-term leakage from cross-over failure. We thus applied the same leakage-reduction scenario ranges to this innovation as for the (D2) Improved Cross-Over innovation.

We also used the results from the D2 innovation regarding improved duct insulation. A through-the-rim system typically involves only about R-11 insulation under the bottom of the cross-over (compared to R-16 around the circumference of the improved traditional cross-over), but a through-the rim system only requires about six feet of additional cross-over ducting compared to 20 feet or more for a traditional cross-over.

Given the fundamental limitations of current tools to model manufactured-home belly sections in general—as well as the large uncertainty associated with estimating the extent of post-siting leakage—we did not attempt a more refined model of through-the-rim for the current effort. Instead, we assigned the same savings potential as for the D2 innovation. Per Table 15 above, we thus estimate 2 to 5 percent HVAC energy savings for this innovation, with a break-even incremental cost of $200 to $550.

As to actual incremental costs for a through-the-rim approach, some would argue that this approach is actually *less* expensive, because it involves only a small amount of additional ductwork at the plant, plus cutting and reinforcing the cross-over points in the rim itself—while entirely avoiding the need for cross-over installation in the field. Levy and Dentz (2018) estimated the costs of two types of through-the-rim systems and found one type to be about $90 more expensive and the other type to be $16 less expensive than a traditional under-floor flex-duct cross-over. Both of these are well within the break-even incremental cost range above. Future work could better establish these costs. For the current effort, we conservatively judge this cross-over approach as *possibly* cost effective.

Market Motivators and Barriers

Some home manufacturers are already employing the through-the-rim cross-over approach, so there are clear motivators in favor of adoption in some cases. The approach promises simpler setup on site, primarily by reducing the amount of work that must be done in the crawlspace of the home and leaving the crawlspace free from cross-over ducting. The through-the-rim cross-over also has the benefit of omitting flexible ducting as a material that must be purchased by the factory and shipped with the home—a cost savings.

Switching over a home design from a traditional under-floor cross-over involves work for the home manufacturer. The rim joist is almost entirely eliminated where the cross-over duct passes through it. This necessitates re-engineering of the home's load bearing paths and requires wood and/or steel reinforcement across the area of compromised rim joist. The reinforcement material sits below the level of the floor framing, so it is important that it not interfere with chassis members. Because the cross-over duct(s) are located between floor joists, extra care must be taken when building the duct system to ensure it fits into the floor framing properly. Other utilities located in the floor assembly also must be located out of the way.

Perceptions about through-the-rim versus under-floor cross-over ducts are highly varied. Home manufacturers, retailers, and HVAC contractors often share strong opinions about the inferiority of one cross-over system compared to the other, and those opinions largely are supported by personal worst-case anecdotes. While some home manufacturers have undertaken some degree of duct airflow testing to ensure minimum acceptable system performance, this research project uncovered no solid data comparing register flow and static pressure between the two cross-over systems. It will likely take clear and compelling information and design suggestions to change opinions among those in the industry.

Market Readiness

Knowledge of how to construct through-the-rim cross-over duct systems exists within the industry. Most, if not all, of the industry engineering and design approval entities have experience with the systems, so it is largely a matter of a home manufacturer making the commitment to have existing home plans modified to change the cross-over duct system. Modest factory modifications might be needed in some cases to facilitate the changes in construction processes, but most facilities should be able to make the change without undue burden. Installation crews will need some additional training to know how to treat through-the-rim cross-overs if they have not worked with them before.

(D3) Demonstrate AeroSeal® in a factory setting

Description

Home manufacturers currently seal ductwork manually in the factory with only some homes receiving duct leakage testing. Factories seal ducts manually, using either mastic or tape, while the duct system is on a bench. The duct is then brought to the floor and installed. In the production environment, the ducts are being handled and installed into the floor before mastic has time to cure. A duct system with adequate mastic applied to it often results in workers inadvertently smearing mastic on themselves as they install ducts, or workers apply less mastic to the ductwork to avoid the mess. Proper use of tape involves pre-cleaning the ductwork to remove oils and dust, which is a step that is often neglected. After the duct system is installed in the floor, it takes another process to plug the openings and test the system for leakage. Most manufactured homes only have supply ductwork and do not have return ductwork.

Aeroseal® duct sealing technology could be applied to a manufactured home's ductwork while it is being built in a factory setting resulting in reduced duct leakage.[8] Reducing duct leakage would provide energy savings and improved comfort. Aeroseal technology could be integrated into a factory setting and would provide duct sealing and duct leakage measurement while the sealant is applied. It is also possible that the flexible sealant used in the Aeroseal process could prove to be more road worthy than traditional mastic sealing, which can crack, resulting in a lower incidence of duct-sealing failures during transportation of the home to its final site.

Compared to site-built homes, most manufactured homes have a smaller footprint and don't have return ductwork, so sealing the ductwork in a manufactured home using Aeroseal is expected to be more efficient than the same process in a site-built home. A manufactured home factory would need to become an Aeroseal dealer to integrate the technology into their processes. The factory would need to make an investment to purchase the equipment and proprietary sealant, keep at least one certified employee on staff, and pay a license fee per job. We also learned that a contractor used Aeroseal® to retrofit manufactured home ductwork in Arizona and Montana on existing homes. Aeroseal is not able to seal large holes or disconnected ductwork.

Only one manufactured home retailer in the Southeast stated that potential buyers are aware of duct leakage and ask about it. That retailer makes a point of promoting energy efficiency and that may result in inquiries from consumers looking for high performance features such as sealed ducts. The other southeastern retailer indicated that duct sealing is decided by the manufacturer and makes little to no impact on sales. Home installers think duct sealing at the factory could be beneficial but expressed concerns for additional costs to the consumer when buying the home.

Savings Potential and Cost Effectiveness

Similar to Innovation D1a (factory-floor duct leakage testing), we estimate the saving from this innovation as a 70 to 90 percent reduction in duct leakage that averages 6 to 12 cfm per 100 ft^2 of floor area. On a national basis, this yields an estimated 5 to 10 percent savings on space heating and cooling costs, with a break-even incremental cost range of $500 to $950 (Table 16). Aeroseal states that the average cost of sealing a 2,000 ft^2 single-family home is between $1.00 to $1.50 per ft^2.[9] At the low end of this range, sealing a typical single-wide home would cost about $900, and sealing a double-wide would run about $1,500. Based on this, we judge this innovation to be unlikely to be cost-effective.

[8] Envelope sealing can be accomplished in the same way, but generally needs to be done before finished surfaces are in place, which could be difficult to accomplish for manufactured housing given the current construction-process flow.

[9] https://aeroseal.com/lp/home-comfort/, accessed October 28, 2021.

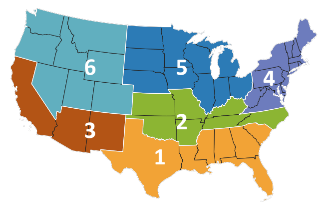
Table 16. Annual energy-cost savings and break-even incremental cost for factory Aeroseal, by region.

Region	HVAC energy savings[b]	Annual energy-cost savings[b]	Break-even incremental cost[a,b]
1	4% - 8%	$25 - $45	$250 - $500
2	5% - 10%	$35 - $65	$400 - $850
3	3% - 7%	$30 - $55	$300 - $650
4	6% - 11%	$70 - $145	$1,150 - $2,250
5	5% - 10%	$45 - $90	$650 - $1,250
6	7% - 13%	$50 - $100	$700 - $1,400
National avg.	5% - 10%	$35 - $70	$500 - $950

Notes:

(a) Break-even incremental cost is the incremental cost that equals the present value of life-cycle energy savings, less up-front loan costs and the present value of incremental property taxes. Based on regional fuel prices and energy modeling. Includes effect on present-value of delayed onset of leakage.

(b) Ranges shown are the 5th and 95th percentiles of probabilistic analysis from assuming 70 to 90% duct leakage reduction relative to baseline average of 6 to 12 cfm per 100 ft^2 of floor area. Duct leakage is to the outdoors at 25 Pa of pressure.



Market Motivators and Barriers

If duct sealing and leakage testing could be automated without increasing cost or production time, home manufacturers would be likely to consider its adoption. As it stands, the Aeroseal system is largely unknown to the industry and is expected to increase costs compared to current duct sealing practices.

Market Readiness

Aeroseal is a commercially available product. The duct systems in manufactured homes are simple and should be a good fit for the application. Significant questions remain around the time required for the Aeroseal machine to seal a duct system, how much maintenance the machine would require between floors and at day's end, and how the cost compares to current sealing practices.

(D4) Interior duct designs to eliminate leakage

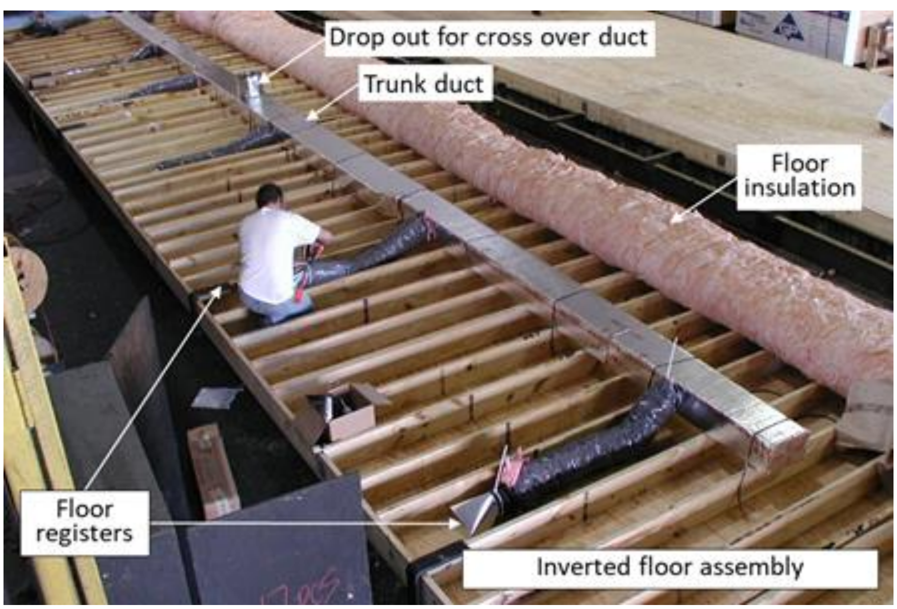
Description

As previously discussed, ducts in manufactured homes are typically located in the floor assembly except for homes in the Southeast, where ducts are installed in the attic ("overhead ducts") as standard practice or as an option.

Figure 13 shows the standard assembly of a floor duct system on an inverted floor assembly of a single manufactured home section. The inverted floor assembly will be flipped over after the duct system and other components are completed. A duct-board trunk duct runs the length of the section with flex duct run-outs to floor registers. The pink floor insulation will be rolled out to cover the duct system and the whole floor assembly. Next a protective layer called "belly board" is attached to cover the whole insulation layer to form a protective barrier to reduce damage during transport. The "drop out" shown will be accessible from the crawl space under the house. A cross over duct, will connect it to a similar drop out on an adjacent house section.

Some would argue that ducts in this configuration (excluding the cross over duct) are already in conditioned space because they are interior to the insulation and air barrier. At best, floor ducts are in a semi-conditioned space. While the belly board may be an air barrier material, installation details are not sufficient to create a continuous whole house air barrier. Specifically, it is not sealed at seams, edges, or penetrations for plumbing or electrical components. Further, it is common for the road barrier to sustain some damage during transport, and the setup process also involves making some holes in the barrier. The quality of field repairs to the road barrier is highly variable, or not done at all.

Figure 13. Duct system being installed on an inverted floor section that will be flipped over once completed



Installing the ducts within the conditioned living space lowers the temperature difference between conditioned air and the air surrounding the duct. This reduces conductive heat gains and losses across the duct wall and reduces temperature changes between the supply plenum and supply registers. Additional benefit accrues from capturing duct leakage in the conditioned space that would normally be lost into the floor assembly and crawlspace or the attic assembly. Air lost as duct leakage can create unbalanced air pressures throughout a house, driving several undesirable air flow effects including increased whole house infiltration, dust accumulation, poor temperature control in individual rooms, moisture risks from warm and cold air streams meeting surfaces at extreme temperature differences, and drafting of unfiltered air into the conditioning equipment, degrading indoor air quality and equipment performance.

Installing ducts inside the conditioned space can guard against these effects. Moving ducts into conditioned space typically requires constructing a duct chase below the ceiling that is completely isolated from the attic above by a continuous air barrier. The necessary size of the chase has an impact on the aesthetics of a home’s interior spaces.

The proposed innovation employs a small diameter duct system made by Rheia, www.rheiacomfort.com, that can be routed through interior wall or other cavities achieving the required isolation from unconditioned space with far less aesthetic impact.

Rheia is currently working with Oakwood Homes in Denver featuring a floor-mounted supply boot that may translate well to many manufacture home designs.

Figure 14 shows the boot installed with 2x4 blocking and 1.5-inch setback from top of floor truss. A riser transition piece is used to connect this to a floor-mounted supply register. Figure 15 shows a rendering of the Rheia floor supply register with two-inch duct attached. It is important to note that the Rheia small diameter ducts are by design, not insulated, which requires the duct zone to maintain non-condensing conditions during cooling applications. This presents a significant design challenge in humid climates.

Figure 14. Floor-mounted supply boot

Figure 15. Rendering of ducted floor register provided by Rheia

Savings Potential and Cost Effectiveness

Energy savings are modeled here as complete elimination of duct leakage, with some uncertainty regarding the average level of baseline leakage. As Table 17 shows, this translates into a national-average 7 to 13 percent space-conditioning savings, with a break-even incremental cost of $650 to $1,150. It is unlikely that this innovation will be cost-effective because the upcharge for this technology is unlikely to be in that range in the near future. As Rheia or others evolve their products for the manufactured home market perhaps integration into the factory process can be achieved more cost effectively.

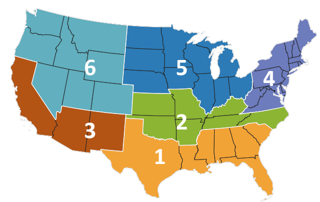
Table 17. Annual energy-cost savings and break-even incremental cost for interior ducts to eliminate duct leakage, by region.

Region	HVAC energy savings[b]	Annual energy-cost savings[b]	Break-even incremental cost[a,b]
1	5% - 10%	$30 - $55	$350 - $650
2	6% - 11%	$40 - $80	$550 - $1,000
3	4% - 8%	$35 - $65	$400 - $750
4	7% - 13%	$90 - $170	$1,450 - $2,700
5	7% - 13%	$60 - $110	$850 - $1,550
6	8% - 16%	$65 - $120	$900 - $1,650
National avg.	7% - 13%	$45 - $85	$650 - $1,150

Notes:

(a) Break-even incremental cost is the incremental cost that equals the present value of life-cycle energy savings, less up-front loan costs and the present value of incremental property taxes. Based on regional fuel prices and energy modeling. Includes effect on present-value of delayed onset of leakage.

(b) Ranges shown are the 5th and 95th percentiles of probabilistic analysis from assuming 100% duct leakage reduction relative to baseline average of 6 to 12 cfm per 100 ft^2 of floor area. Duct leakage is to the outdoors at 25 Pa of pressure.



Market Motivators and Barriers

Manufactured homes can benefit from fully interior duct systems with reduced space conditioning costs, improved long-term durability, and superior air distribution on well-designed systems. Adoption of interior duct design among home builds at larger typically stems from striving for very high whole house performance such as certification under DOE's Zero Energy Ready Home program where the strategy chips away at already-low peak load and annual energy use. Interior ducts provide benefits during both heating and cooling seasons whereas other improvements that reduce cooling costs can sometimes increase heating costs and vice versa.

While homeowners value comfort, durability, and efficiency, most don't associate duct work with those factors. As with many measures that improve air, heat, and moisture control, ducts themselves are largely invisible. Manufactured home retailers in the Southeast indicate that they receive very few complaints about dust accumulation, moisture problems, and other impacts of ducts in unconditioned spaces. When complaints arise, they are typically related to uneven room temperatures which are overcome by supply register adjustments (opening, closing, changing flow direction). Most retailers considered the concept of moving ducts into the conditioned space favorably. However, retailers indicated the lack of buyer awareness of duct work and its role in whole house performance would make promoting the benefits of interior ducts challenging, possibly diverting attention away from key brand messages.

Regardless of point-of-sale dynamics, manufacturers often implement improvements that have nothing to do with curb appeal such as upgraded plumbing or electrical components which are similarly invisible to buyers. The physical dimensions of duct work make this a more difficult shift, one with implications for overall floor plan design, multiple sub-assembly stations, and worker skills. The proposed innovation of installing small diameter ducts in interior walls eliminates the need to find space in every room for a standard size duct which is a major barrier. However, research is needed to determine impact on the overall construction and system performance. An iterative process of large-scale mockup, process analysis, and full-scale pilot implementation will reveal implementation barriers related to, for example, materials, tools, subassembly stations, mainline assembly, personnel training, and quality controls, transport, system integrity at set up, and long-term performance. One essential difference with this approach is that the overall integrity of the system will be determined not by a specialist that deals primarily with the duct system as a whole, but by workers in many different segments of the construction and assembly process. This alone may pose a workforce training barrier.

Market Readiness

The proposed small diameter duct system made by Rheia is currently on the market with application in site-built homes. The company has worked with Oakwood Homes of Denver to conceptualize and prototype components specifically suited to manufactured housing. Rheia leadership is committed to engaging in this process, producing prototypical fittings as needed and remains interested in serving the manufactured home industry. However, our inquiries with home manufacturers about this concept generated little interest.

DOE partners in the Building America program have developed and implemented several other methods of interior duct system design, installation, and quality control as standard construction for typical duct materials. Key strategies are profiled in the Building America solution center including case studies and field guides.[10] These provide fully market ready solutions, several of which could be deployed in manufactured housing. FSEC previously worked with Cavalier and Southern Energy Homes (now Clayton Homes) in Addison, Alabama to explore the production impact of a fur-down (drop ceiling) interior duct chase in ceiling-ducted homes. (Moyer, et. al. 2008). Figure 16 illustrates a full-scale mock-up identifying both construction changes and aesthetic details. This exercise helped the manufacturer visualize the concept and understand the impact it would have on the construction process. It met with approval, but ultimately the manufacturer was not motivated to adopt the practice.

[10] Building America Solution Center: https://basc.pnnl.gov/search?keywords=interior+duct

Figure 16. Interior duct chase mock up by Southern Energy Homes (Moyer, et at. 2008)

(H1) Factory enabled high efficiency ducted heat pumps

Description

Heat pumps offer considerable heating-cost savings over electric furnaces and represent the main pathway to reducing reliance on fossil fuels for space heating to reduce our climate-change impact. Moreover, the latest generation of variable-capacity air-source heat pumps offer unprecedented efficiency and good performance in cold weather. For all these reasons, air-source heat pumps are being promoted by utility efficiency programs and government policymaking in many areas of the country. Heat pumps also support DOE’s electrification goals.

Multi-stage and variable-speed heat pumps offer comfort and energy-efficiency advantages in both northern heating-dominated, and southern cooling-dominated climates. Multi-stage cooling capability—especially if combined with the ability to respond to a humidity-sensing thermostat by further reducing airflow—offers the promise of better dehumidification and some level of protection in the face of equipment oversizing by local installers.

Practices related to the selection and purchase of heat pumps for manufactured homes vary regionally. Retailers in the Southeast universally state that their buyers opt to have an air conditioning coil installed at the time of purchase. They offer the option of a heat pump, which may be less of a mental leap when air conditioning is a given, and report that 25 to 50 percent of buyers make the heat pump selection. One retailer in Kentucky, though, reported installing a heat pump in every house they sell in the interest of helping the buyer with utility bills. As noted previously (page 8), in this part of the country when a customer opts for a heat pump, the retailer typically will order the home without a furnace and will instead field-install an exterior packaged ducted heat pump unit that includes both sets of coils, a fan for the outdoor coil and an exterior air handler, all in a single weatherized enclosure. These may be mounted on the ground or (less commonly) on the roof of the home. In most cases in the Southeast and Southwest, retailers reported that when the buyer opts for a heat pump, the cost is rolled into the overall cost of the house. One retailer reported a $500 labor cost associated with installation of package-unit heat pumps, whereas another in Florida reported $3500 for a four-ton package unit including labor and equipment.

In colder climates, central air conditioners and heat pumps are generally an after-market upgrade for new manufactured homes: the home ships with a simple electric or gas furnace, and then buyers and retailers work with a local HVAC contractor to install the air conditioner or heat pump. A retailer in Oregon reports a $700 retail price to upgrade from a central split-system air conditioner to a heat pump.

Electric and gas furnaces used by the industry typically have a smaller footprint than conventional residential HVAC equipment, and the furnace is often located in an enclosed cabinet with minimal clearance between the walls and the equipment. This serves to limit the selection of split-system ducted heat pumps to coil and compressor matches that will work with the original furnace and air handler, and typically results in base-efficiency ducted heat pumps being installed. The packaged heat pump units used in warmer climates means routing large-diameter ductwork to the exterior of the home to connect it to the heat pump: these exterior ducts are exposed to the elements and vermin, and can easily be compromised over time, potentially leading to significant distribution-system losses.

In addition, after-market selection and installation of heat pumps puts sizing decisions in the hands of local contractors. More than one home manufacturer expressed concerns that a large source of comfort issues that come back to the factory in the form of warranty claims for southern homes arises from pervasive over-sizing of cooling equipment by after-market installers.

Paradoxically, the opposite may be the problem in the North: anecdotal evidence from the general housing market suggests that cold-climate installers are fearful of creating comfort problems in the summer and are reluctant to upsize the capacity of heat pumps to meet the larger heating load of the home. Systems that are sized to meet the home's heating load are then oversized for cooling needs and do a poor job of dehumidification in the summer. This reluctance is evident even in the case of variable-speed equipment that can readily modulate down to meet summer cooling and dehumidification needs.

Factory installation of heat pumps could potentially avoid all these problems by providing homes with properly matched and sized equipment from the outset. Factory installation at scale could also reduce the ultimate cost of heat pumps by making the installation process more labor efficient.

We considered four variants of factory installation of ducted heat pumps: (1) full factory installation of off-the-shelf heat pump equipment (Innovation H1), which we discuss in this section; (2) partial factory-installation of heat pumps (Innovation H1a); (3) revival of an earlier-generation factory-installed heat pump known as the "Insider" (Innovation H1b); and (4) factory installation of a so-called air-source integrated heat pump that combines space conditioning and domestic hot water—and in some cases ventilation.

The general approach for fully factory-installed ducted heat pumps relies on mounting a mini-split-type outdoor unit on the exterior of the home and connecting it in the factory to a matched indoor unit with a coil and air handler so the system is ready to run as soon as electricity is provided to the home. The flattened, horizontal-discharge "suitcase" form factor of the compressor lends itself to mounting on the rear end wall of the home or on a frame rail extension that extends beyond the home's end wall.

Savings Potential and Cost Effectiveness

We considered the energy savings and cost-effectiveness of three types of heat pumps: (1) conventional, single-stage; (2) two-stage; and (3) variable-speed. Two-stage heat pumps are generally more efficient than single-stage (in addition to providing better sizing flexibility for heating climates), and variable-speed heat pumps are more efficient (and flexible). For all three, we evaluated HVAC energy costs against baseline systems of electric, propane, and natural-gas furnaces with a field-installed central air conditioning system.

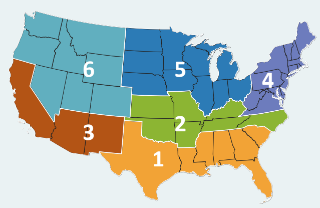
The modeling shows that all three types of heat pumps provide significant energy-cost savings compared to electric and propane furnaces, but that even high-efficiency variable-speed heat pumps cannot compete well against natural gas in some parts of the country at current fuel prices (see Figure 17 for results for variable-speed heat pumps). This is especially true in the Midwest, where more than half of new homes are shipped with a natural-gas furnace, and where natural-gas prices are among the lowest. In this region it is actually *more* expensive to operate even a high-efficiency heat pump than a gas furnace. After eliminating the portion of the market where a heat pump would be a more expensive option from an operating-cost standpoint—as well as the estimated 20 percent of new homes nationally that currently are installed with a heat pump—we estimate that roughly two-thirds of new manufactured homes would see energy-cost savings if installed with a heat pump instead of a furnace and central air conditioning system.

With respect to cost-effectiveness, Table 18 shows our estimated break-even incremental cost for various heat pump options over an electric or propane furnace and central air conditioner. These values appear to be favorable against the plausible range of incremental costs for factory-installed heat pumps. Although we do not have data for actual incremental costs to factory-install heat pumps in manufactured homes, we do have estimates of the incremental cost associated with field-installed heat pumps in site-built housing (Fairey 2015).[11] These suggest about $1,000 to upgrade from a furnace and air-conditioner to a conventional, single-stage heat pump, $2,000 to upgrade to a two-stage heat pump and $3,500 to $4,000 to upgrade to a

[11] See, for example, Appendix B (Fairey 2015).

variable-speed unit—and are generally below the break-even values shown in Table 18. Factory installation would presumably be less expensive than field installation of equipment, so the estimates from site-built housing are likely conservative. On the other hand, home manufacturers would likely put a markup on their costs, which would narrow any gap between field-installed and factory-installed costs. Nonetheless, the math appears to be likely cost-effective for heat pumps as an alternative to the electric and propane furnaces that make up almost two-thirds of the current market.

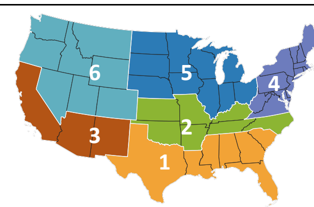
Figure 17. Annual energy-cost savings for a variable-speed heat pump versus a furnace and central air conditioner, by furnace fuel, home type and region.



Notes:
All baseline cases assume presence of a SEER 14 central air conditioner
Propane and natural-gas furnace efficiency (AFUE) assumed to be 80%
Based on regional average fuel prices

Table 18. Estimated break-even incremental cost for a heat pump versus an electric or propane furnace with central A/C, by home type, type of heat pump and region.

Study Region	Single-Wide Home Conventional HP	Single-Wide Home Two-stage HP	Single-Wide Home Variable-speed HP	Double-Wide Home Conventional HP	Double-Wide Home Two-stage HP	Double-Wide Home Variable-speed HP
1	$1,900	$2,400	$3,100	$3,000	$3,700	$4,700
2	$4,100	$4,800	$5,300	$6,400	$7,400	$8,100
3	$1,000	$2,400	$3,100	$1,700	$3,300	$4,300
4	$10,100	$11,000	$12,100	$16,800	$18,100	$20,000
5	$7,300	$8,000	$8,900	$12,000	$13,100	$14,800
6	$5,200	$6,000	$6,300	$8,400	$9,300	$9,900
National Avg.	$3,700	$4,300	$5,100	$5,700	$6,600	$7,600



Market Motivators and Barriers

Potential market motivators for home manufacturers include increased profits from markup on more expensive factory HVAC installations, as well as the ability to better control system selection and sizing, which could lead to fewer manufacturer callbacks related to poor field installation practices. Perhaps because of these potential upsides, interviewees reported some level of current and past activity on the part of home manufacturers to factory install both ducted and ductless systems in homes, and the Project Team has direct knowledge of instances of factory-installed ducted heat pumps in the Pacific Northwest.

However, there are some clear barriers to factory-installed heat pumps. First among these is the increased cost of the home in a market that is dominated by buyers of limited means who are first-cost sensitive. This is especially true for variable-capacity equipment that is generally positioned as a premium HVAC product—with a premium price tag—in the current market. The installed cost for a high-end variable-speed heat pump in the northern part of the country can easily run upwards of $10,000 in site-built housing, though anecdotal evidence suggests that a signification portion of this may be attributable to substantial markups by installation contractors due to their relative unfamiliarity with the technology and perception of a profit opportunity. However, even in a factory-installation setting, the hardware for variable-speed ducted heat pumps may be more expensive than the equipment cost of a basic central air conditioning system or packaged heat pump.

In addition, manufacturers have legitimate concerns about the road-worthiness of factory-installed split-system heat pumps that need to withstand the rigors of transport and siting. One large home manufacturer reported exploring factory-mounting equipment years ago but found that the refrigerant connections were not road-worthy and tended to leak. They mounted a seismometer on one unit being transported and found that it experienced the equivalent of a magnitude 4.1 earthquake for the entire four-hour trip. Similar factory-installation efforts in the Pacific Northwest showed issues with kinked refrigerant lines during installation and damage to exterior compressors when maneuvering in tight quarters during siting when the compressor is mounted on the hitch end of the home.

One major manufactured-home HVAC manufacturer stated that past attempts to fully factory-install HVAC systems foundered on the problem that the factory then takes on responsibility for service issues within the warranty period that would otherwise be the responsibility of a local contractor. This manufacturer stated that a better solution is for the factory to ship the exterior compressor with the home for installation by a local contractor— as we discuss in more detail under Innovation H1a. This also helps ensure that the central air conditioning or heat pump system is appropriately sized for the factory-specified heat loss/gain calculations for the home.

For HVAC contractors, loss of business is obviously a key concern, but interviews also revealed that contractors believe they have a role to play in identifying and managing issues missed in the factory quality-control process. Some contractors believe that removing the HVAC contractor from the initial setup process could adversely impact homeowner comfort.

There are also some complicated cross currents in the relationships among home manufacturers and HVAC equipment manufacturers, distributors, and local contractors. Currently, HVAC manufacturers and distributors may provide low-end manufactured-home furnaces at little or no markup on the premise that an after-market central air conditioner or heat pump will be more likely be of the same brand. This keeps the initial price of the home low and provides after-market installation, service, and maintenance business for distributors and local contractors. Changing this business model is not impossible but will require thoughtful understanding of interests among market actors to ensure that there are as many win-win alignments as possible.

Interviews with home retailers revealed a general lack of understanding of what constitutes a heat pump and how effectively it can heat and cool a home, which would tend to inhibit upselling heat pumps to buyers. In the Southwest, one retailer stated that heat pumps do not work well in that climate, while simultaneously asserting that ductless mini-split systems do an excellent job of heating—apparently not recognizing that ductless mini-splits are in fact heat pumps. Another Southwest retailer commonly installs split-system air conditioners on electric furnaces, unaware that the modest cost to specify even a conventional heat pump would quickly be offset by electric bill savings for space heating. It is possible that many retailers retain misperceptions of poor heat pump performance from decades past.

In the Southeast, retailer reaction to the idea of eliminating the local contractor from the sales and set-up process by factory-installing a heat pump was mostly negative. One retailer explained that the local HVAC contractor plays a critical role in long term customer satisfaction. They rely on the contractor to warranty the on-site installation and handle any problems that arise with the HVAC system after the home is occupied.

On the other hand, a notable positive response about factory-installation of heat pumps was received from a retailer in Florida who provided the unique perspective that factory-installation of heat pumps would eliminate the uncertainty currently associated with field installation costs of outdoor package units, which are common in that part of the country. The exact placement of a package unit is not typically known at the time of sale, so this creates uncertainty regarding the length and complexity of duct connections between the house and the package unit—and any higher-than-anticipated costs come out of the retailer's profit margin. This retailer also indicated that having the outside equipment installed off the ground would be a resiliency benefit in flood-prone areas.

Retailers in the Northwest were similarly mixed in their response to having heat pumps already installed in the factory. The issues of warranty service and long-term customer satisfaction were the primary concerns expressed. Retailers acknowledged the potential benefit of simplifying the home set-up process and potentially eliminating the need for an HVAC inspection.

Retailers and home manufacturers in the Midwest were not very familiar with heat pumps and did not think many people in the Midwest were familiar with the technology. One retailer expressed concern with the idea of having a heat pump mounted on a frame rail extension, because they strive to have homes that look like site-built homes.

Most home installers interviewed thought that installing and servicing heat pumps in their area would be an issue and generally thought heat pumps might be too costly to customers.

Market Readiness

Full factory installation of heat pumps can generally be accomplished with off-the-shelf products, especially those with minimal-footprint air handlers and horizontal-discharge suitcase-style outdoor units. Another research project funded by the U.S. Department of Housing and Urban Development is currently exploring a fully factory installed heat pump with no onsite HVAC contractor involvement. More work needs to be done on approaches for mounting and protecting the outdoor unit during transport.

(H1a) Partial factory-install of ducted heat pumps

Description

This innovation is a variant of factory-installed ducted heat pumps (H1). Instead of fully factory-installing a heat pump, the indoor unit, refrigerant lines, and electrical connections are installed at the factory, and the home is shipped with the outdoor unit loose for final placement and field connection by either an HVAC contractor or home installer during siting.

Utility-sponsored energy efficiency programs in the Pacific Northwest are beginning to see traction with retrofitting mini-split-style ducted heat pump systems in existing manufactured homes, thus demonstrating that current products can be successfully deployed in this housing stock. Contractors report that the equipment fits in the existing cabinet, and anecdotal feedback suggests that the heat pumps are performing well in cold weather and delivering good customer satisfaction.

Equipment performance information supplied by one manufacturer (Carrier) indicates that the 24kBtu/hr compressor mated with their air handler has an HSPF 11.6 rating and delivers full capacity at 17F. Moreover, a Carrier factory representative believes that the retail price to a home buyer for this heat pump system would not be appreciably more expensive than current add-on heat pump systems, provided that the air handler was installed at the factory. The Carrier air handler has provision for electric heat strips, so a factory could install the unit as a stand-alone electric furnace, which is considered a complete heating system, and thereby simplifying the home setup process. [12]

Savings Potential and Cost Effectiveness

The same basic energy savings and cost-effectiveness calculations associated with full factory installation heat pumps holds true for partial factory-installation as well, the key difference being the addition of some field labor required to complete the installation during siting. Since heat pumps appear to be cost effective against electric and propane furnaces based on estimated incremental costs associated with fully field-installed units, they will likely be cost-effective for partial factory installation.

Market Motivators and Barriers

Partial factory installation of heat pumps would provide the same benefits of factory-installed heat pumps, while avoiding some of the key barriers to full factory installation of these systems. First, partial factory installation would largely solve the road-worthiness problem since final refrigerant connections would be made during siting and the outdoor unit would be protected from damage during transport. Second, if HVAC contractors are used to install the outdoor unit and make final refrigerant connections, it would help alleviate manufacturer concern about service and warranty claims down the road. In addition, involving HVAC contractors in the final field installation would alleviate some of the manufacturer and distributor worries about

[12] Carrier Performance™ Series heat pump announcement - https://www.carrier.com/residential/en/us/news/news-article/carrier-introduces-new--fully-communicative---ductless-heating-and-cooling-products.html
Carrier Performance Heat Pump with Basepan Heater - https://www.shareddocs.com/hvac/docs/1010/Public/02/01-DLS-008-01.pdf

alienating local HVAC contractors with full factory installation of HVAC systems. Note that both concerns could return, however, if home installers took up the job of final installation of the system during siting instead of HVAC contractors.

Market Readiness

As noted above, the type of heat pumps needed for this innovation are already being retrofitted into existing manufactured homes, so there are no overarching issues with market readiness in terms of the basic equipment. In addition to the Carrier system the team has examined in the most detail, other HVAC manufacturers, such as Mitsubishi and Fujitsu also produce mini-split-style ducted heat pumps that would likely readily work in the confines of a manufactured home.

To potentially solve issues with kinked refrigerant lines installed by non-HVAC factory personnel, there are now plastic composite refrigerant line set materials available that promise to eliminate the issues with kinking of refrigerant lines and the use of unreliable quick-connect or flare fittings that are factory-installed by workers who are not trained HVAC technicians (Yogapipe ACR and Excel Air Systems are two such systems). However, it may take some time and effort to convince HVAC equipment manufacturers to support these alternatives: Carrier, for example, currently does not recommend plastic line sets for its equipment.

HUD code language related to requiring homes to have a heating system at time of shipment may need revision to make it easier for homes with a partially installed heat pump to be code compliant. Alternatively, a method to provide code-compliant electric-resistance heat that can be readily field-modified to serve as back-up to the heat pump could be developed.

(H1b) Revive the "Insider" ASHP

Description

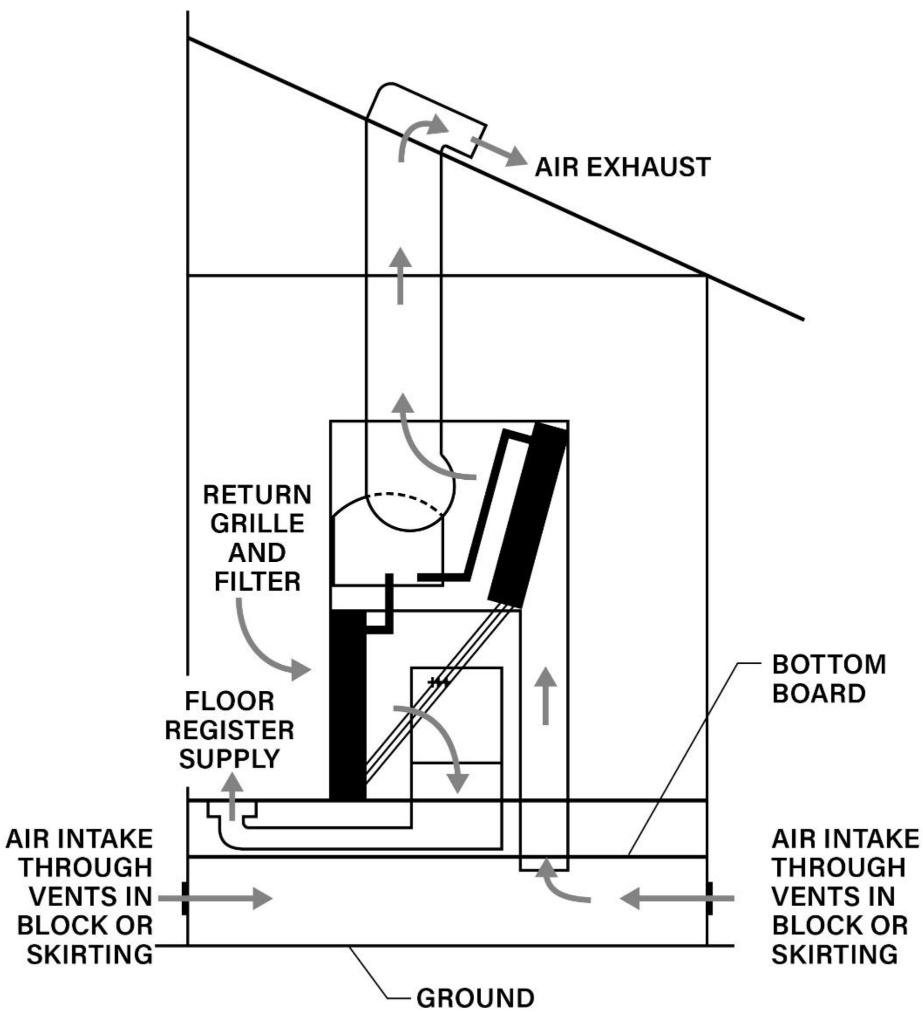
The “Insider” was a factory-installed ducted heat pump developed with DOE funding and produced by several manufacturers until the early 2000s (Lubliner et al. 2007).[13] In contrast to current heat pump configurations, the Insider was a fully self-contained, indoor package unit with both sets of heat pump coils housed in a single cabinet (Figure 18). Notably, the unit draws outdoor air from the home’s crawlspace and exhausts it through a roof vent after passing it over the ‘outdoor’ coil that absorbs heat in the winter and rejects it from the home in the summer. Using air from the buffer zone in the home’s crawlspace helps enhance the performance of the heat pump because crawlspace air is typically somewhat warmer than outdoor ambient conditions in the winter and cooler in the summer. This reduces the indoor-outdoor temperature difference that the heat pump must work against. Monitoring in two research homes suggested a heating COP of about 2 to 4 at outdoor temperatures between 20F and 50F (Lubliner et al. 2007).

[13] “Insider” was the brand name for the system, which was produced by several manufacturers over its life.

Several thousand Insider units were produced and installed in homes in the Pacific Northwest and the Southeast in the 1990s and early 2000s. However, demand for the product was low, and it was unable to meet improved federal cooling and heat pump efficiency standards in 2006, leading to its withdrawal from the market (Lubliner et al. 2007). While still in production in the early 2000s, the cost of the unit to home manufacturers was $1,600 to $1,700. The units required little maintenance and had a long life according to anecdotal evidence from a manufactured home park owner who had the equipment.

Today's variable-capacity mini-split compressor technology should make possible a highly efficient revised version of the Insider heat pump that could meet or exceed current efficiency standards. Such a unit would allow for a drop-in system that can be completed on the production line, without need for refrigeration connections or other special training—and without concerns about road worthiness of outdoor compressors and long refrigerant lines. Because the unit takes advantage of crawlspace buffering, its field performance would likely exceed that of current split-system or outdoor package heat pumps.

Figure 18. Airflow schematic for the "Insider" ASHP



Savings Potential and Cost Effectiveness

Savings and cost-effectiveness for a revived Insider heat pump should generally be similar to the range shown for factory-installed heat pumps in general. As noted above, this innovation should show somewhat better performance than other heat pumps because of the tempering effect of drawing air from under the home, but we did not attempt to account for that here. Thus, our generic heat-pump savings estimates are likely somewhat conservative for this innovation. This innovation is likely cost-effective.

Market Motivators and Barriers

Relative to other heat pumps, the Insider potentially offers better efficiency due to its ability to take advantage of temperature-buffered crawlspace conditions. Buyers and park operators may also see benefit in the elimination of outdoor HVAC equipment because it could have a longer useful life as the equipment is protected within the home. In addition, outdoor equipment can be perceived as unsightly and vulnerable to damage or vandalism. Outdoor HVAC equipment is also prone to adverse weather events, such as, flooding and hurricanes as well, which could damage the unit and release the refrigerant.

However, a revived Insider heat pump would face similar market challenges to those noted above for any factory-installed heat pump:

- Higher first cost for the home itself—though still lower than the full purchase cost of a home plus a field-installed heat pump
- Potential home manufacturer reluctance to take on responsibility for service needs and warranty claims for factory-installed units
- Potential concerns on the part of home retailers and HVAC manufacturers and distributors about alienating local HVAC contractors by eliminating their business for field installation of air conditioners and heat pumps in manufactured homes.

In addition, the Insider faces a few market challenges of its own:

1. **Noise** — The Insider approach puts both sets of coils and their fans inside the house, which—along with noise associated with compressor defrost switchovers—results in more indoor noise than a conventional split system or outdoor package heat pump. The product would need to be designed to minimize noise and would need to be fit in a limited sized footprint located in the home away from bedrooms. Improved defrost controls and VRF could limit defrost runtime.
2. **Refrigerants** — As the industry transitions to refrigerants with lower global warming potential starting in 2023, there is likely to be a shift to refrigerants that are rated as mildly flammable (notably, R-32). Regulatory requirements for such refrigerants could pose a challenge to indoor package systems such as a revived Insider heat pump.
3. **Market size** — A product tailored specifically to manufactured housing limits the market for the product to a fraction of the roughly 100,000 new units sold annually,

though its potential applicability to multi-family housing could promise a larger market. HVAC manufacturers may be reluctant to undertake the R&D and manufacturing retooling needed to bring a new product to market if they perceive limited uptake.

Market Readiness

The Insider would need to be re-engineered to meet current efficiency standards and re-introduced to the market by an HVAC-industry manufacturer. Because there is a considerable track record for the product, the development effort would likely be less than would be the case for a completely new product. Another research project funded by the U.S. Department of Housing and Urban Development is currently exploring this concept.

(H1c) Air Source Integrated Heat Pump (ASIHP)

Description

Another variant on a factory-installed heat pump would go a step further and employ an indoor package system to serve not only the home's space-heating and space-cooling needs but also domestic hot water and/or ventilation requirements. Combi units that meet multiple residential end-use needs have been around for decades, but aside from boiler-based systems for space-heating and domestic hot water, these have never gained much traction in the U.S. market.

What is new and noteworthy for the manufactured housing market is the introduction of small-footprint indoor-package combi systems primarily intended for multifamily new construction and retrofit applications. One current DOE Advanced Building Construction project being implemented by an RMI-led team is looking at adapting a European product for the U.S. market.[14] Another system provides packaged space-heating, space-cooling, and energy-recovery ventilation.[15]

Such systems could in theory be readily adapted for use in manufactured housing, thus providing home manufacturers with a drop-in, self-contained system that could require less valuable floor space than floor plans with separate HVAC and domestic hot water mechanical closets.

Savings Potential and Cost Effectiveness

We explored using a special ORNL energy model being developed for this innovation but were unable to implement it for this report. In lieu of that approach, we estimated the savings impact by combining separately calculated savings for a variable-speed heat pump and for employing a heat pump water heater, assuming no indirect space-conditioning effects from the latter. We

[14] The "Genius" unit by SystemAir.
[15] The "VHP 2.0" by Ephoca.

did not attempt to estimate savings from also integrating heat-recovery ventilation into the system.

This analysis leads to the same space-conditioning impacts as shown above in Figure 17 and Table 18, with the addition of the savings from applying heat pump technology to domestic hot water needs. For the latter, our analysis suggests significant energy-cost savings against a conventional electric or propane water heater, but little to no savings against a natural-gas water heater (Table 19).

Table 19. National average energy-cost savings and break-even incremental cost for a heat pump water heater versus a conventional water heater, by baseline water heater fuel.

Baseline water heater fuel	Estimated share of new-home market	Annual water-heating energy-cost savings for a heat pump water heater	Break-even incremental cost
Electric	87%	$175	$2,700
Propane	3%	$210	$4,400
Natural gas	10%	-$30	-$400

After eliminating the roughly 6 percent of the market with natural gas service where this technology would not provide positive energy savings at current prices—along with the 20 percent of the market that already employs a heat pump for space conditioning—we estimate national average annual energy-cost savings of about $625 from the combination of providing space-conditioning and domestic hot water needs with heat pump technology. These savings carry a break-even incremental cost of more than $9,000, so any actual implementation of this innovation with an incremental cost below this amount will possibly be cost-effective from an energy-savings standpoint.

Market Motivators and Barriers

The reduced mechanical-system footprint for ASIHPs could be a significant motivator for home manufacturers, retailers and buyers in a market where useable living space is at a premium, especially for single-wide models. Energy costs for domestic hot water would be less than half that of a conventional electric water heater and likely comparable to the performance of heat pump water heaters—but without the undesirable wintertime cooling of indoor spaces associated with the latter.

There are a few non-trivial barriers to ready adoption of this technology in the manufactured-housing market. First—and probably most importantly—home manufacturers would need to be convinced to put their faith in HVAC systems and manufacturers that currently have little or no presence in the U.S. market. At the very least, this exacerbates concerns about field servicing of factory-installed units that are subsequently shipped around the country. Second, because they are primarily intended for use in individual multifamily housing units that share walls, floors and ceilings with other units, the capacity of currently available systems may be inadequate for larger multi-section manufactured homes. Finally, integration of HVAC and domestic hot water would likely mean some factory retooling for plumbing runs.

Market Readiness

While ASIHP products exist in Europe and elsewhere, the North American market is nascent at best. Manufacturers of HUD-code homes are unlikely to lead the charge for adoption of this technology given their traditional first-cost sensitivity and the unique nature of the business that ships homes and HVAC systems to disparate parts of the country.

A more realistic medium-term scenario would be for ASIHPs to first gain a foothold in the U.S. in the much larger multifamily new-construction and retrofit markets—and then potentially be picked by the manufactured-home industry once a retailer and service infrastructure is in place, costs have come down, and the technology has demonstrated itself.

Also, as noted above, the capacity of currently available ASIHP products may be inadequate for some homes in certain parts of the country with high heating or cooling loads. Meeting the full market potential for these systems will require a wider array of models.

(H2) Advanced controls and distribution for ductless heat pumps

Description

Ductless heat pump manufacturers and third parties produce controls for integrating ductless heat pumps with other heating and cooling systems. These controls vary in how they work, and how they affect the operation of the ductless system. However, none of these controls are optimized for use in new manufactured homes.

Ductless heat pumps offer the promise of providing efficient heating and cooling with the allure of eliminating the need for ductwork entirely. In practice, however, fully conditioning a manufactured home with a ductless system is an expensive proposition due to the number of indoor “heads” needed. A single-head ductless heat pump in the central portion of the home can offset a significant fraction of what would otherwise be less efficient space conditioning energy consumption, but field studies have shown the full potential is often unrealized due to lack of integration of the ductless and main systems. There are several products on the market that attempt to better integrate ductless and central systems—and field investigations of the efficacy of these continue—but none are tailored specifically for manufactured housing.

This innovation area looks at better integration of ductless and central ducted HVAC systems within the new manufactured-homes market. This could range from an add-on integration control kit to make ductless systems an easy and effective retrofit or upgrade option for a portion of the home to engineered solutions that make a factory-installed ductless system the sole source of space conditioning for a portion of the home, thus reducing the needed capacity and ductwork requirements for the “central” system. Research is informed by previous DOE studies that explored integration and design of controls for retrofit scenarios (Sutherland, et. al. 2016.) and DHP’s as primary HVAC systems (Martin, et. al. 2018).

Other researchers have explored both multi-head ductless systems to entirely condition a manufactured home and using pass-through grills to expand the distribution of single-head systems. Neither of these approaches appear to be promising. The federal furnace-fan efficiency standard that came into effect two years ago has resulted in most manufactured-home furnaces being equipped with ECM blowers that are more efficient and have a wider airflow range than traditional (PSC) blowers. This new general capability for low airflow circulation could potentially be combined with remote thermostats and a central control system to provide a means to distribute conditioned air from a centrally placed ductless system to other parts of the home when the home’s overall heating/cooling load is less than the capacity of the ductless heat pump.

Savings Potential and Cost Effectiveness

The performance of a ductless heat pump should be similar to the ducted variable-speed system that we modeled for assessing factory-installed heat pumps, with the added benefit of reducing duct leakage for the portion of the home’s space-conditioning load shouldered by the ductless system. Combining our variable-speed heat pump and duct-leakage assessment models, we estimate the energy-cost savings from an integrated ductless system that shoulders between a quarter and half of the home’s total space-conditioning load at about $70 to $125 per year.[16] As with the other heat pump innovations, these savings estimates exclude homes that are already installed with a heat pump as well as those heated with natural gas that would see no savings from a ductless system.

The associated break-even incremental cost for these savings is roughly $1,000 to $1,800. Since the ductless system would likely be supplemental to a primary ducted system, full cost of the ductless unit would need to be supported by the energy savings. Contractor-installed single-head ductless systems typically cost between $3,000 and $6,000, while do-it-yourself systems can be purchased for less than $1,500. A factory-supported integrated ductless system would likely fall somewhere between these extremes, making it possible, but by no means likely, that this approach could pencil out to be cost-effective from an energy-savings standpoint. The need for integration controls would also add a minor amount to the overall cost of the system.

Market Motivators and Barriers

The most cost-effective ductless heat pump installation is a single compressor connected to a single indoor head. It delivers very good space conditioning in the zone where the indoor head is located, but one major manufacturer of ductless systems expressed concern about the ability to effectively distribute conditioned air from a centrally-located single-head ductless unit to

[16] This range also incorporates uncertainty in the average duct-leakage level among new manufactured homes.

other parts of the home in the manner described above, especially in cooling climates where adequate dehumidification is often an issue. Those concerns may limit this strategy to heating climates where summer dehumidification is less of a concern and would still require a primary heating system for winter design conditions. Such a hybrid "dual system" approach may also be limited to certain floor plans where secondary zones are not too far removed from the indoor head, and for certain homeowners who are willing to accept lesser cooling performance in bedrooms.

At the same time, many homeowners and home retailers who have experience using ductless heat pumps routinely describe how quiet and comfortable they can make a home. One Oregon home retailer commented that a few years ago his display home with a ductless heat pump would get dubious comments from customers unfamiliar with the system, but now he gets calls from customers who are seeking homes with one.

Ductless systems are likely to remain an important aftermarket bridge technology for electrifying and reducing space conditioning energy, so developing integration controls and application guidance for ductless heat pumps in manufactured homes could still be valuable. Homeowners need education on how to use ductless systems as well.

Market Readiness

Ductless heat pumps themselves are a mature technology. The main product development needed here would be controls and sensors to appropriately integrate control of a centrally located ductless heat pump and a main ducted heating system. Such controls already exist but are not necessarily optimized for the manufactured housing market.

(H3) Quick connect fittings for ductless heat pumps

Description

A licensed HVAC installer is required to set-up a split-system heat pump when new manufactured homes are set-up. The HVAC installer adds an indoor coil to the "heat pump ready" furnace, installs the outdoor unit, and then connects and charges the system with a measured amount of refrigerant. Using pre-charged line sets is not typically current practice for ductless or centrally ducted heat pumps.

This innovation examines how a high-efficiency heat pump could be installed with the outdoor unit mounted and the line pre-charged with a quick-connect fitting that would allow someone other than a licensed HVAC contractor to make the connection during home set-up. This innovation considers how this approach compares to current practice requiring a licensed HVAC installer onsite at the time of home setup, along with the regulatory hurdles, with impacts on cost, supply chain, labor, and the current industry business models.

Retailers did not have any strong reaction to this innovation which was seen as a benefit to local HVAC contractors they work with rather than as a method of eliminating or reducing that expense. Most home installers interviewed viewed this innovation favorably. As noted above, the attention of HVAC-manufacturer R&D departments is focused on the coming phase-out of HFC refrigerants and the need to meet safety standards for new refrigerants with higher flammability potential. HVAC manufacturers are less interested in fittings right now. However, as noted above, Excel Air offers a flexible line set that comes pre-charged and has "Plug & Play" fittings that can be removed and reconnected without refrigerant loss. The company claims that the system can be installed without needing a refrigeration-certified technician. If true, this product could potentially simplify heat pump installation to such an extent that home setup crews might be able to do the work, with a modest amount of training.

Savings Potential and Cost Effectiveness

Our estimated savings for this innovation are the same as for the prior innovation (H2 — Advanced Controls and Distribution for Ductless Heat Pumps). This innovation is possibly cost-effective. However, by reducing field labor, quick-connect fittings have the potential to reduce the incremental cost associated with the system. This would increase the probability of the innovation proving cost-effective from an energy-cost savings standpoint.

Market Motivators and Barriers

Simplifying ductless heat pump installation so that a properly trained home setup crew can take the place of a licensed HVAC contractor could streamline the home setup process. One fewer contractor would need to be managed (e.g., scheduling visits to align with sitework, inspections, times with other trades inside the home and competing for access, etc.). Home manufacturers could profit from supplying the ductless heat pump equipment, performing pre-installation of the indoor head(s), running piping for condensation drains, and providing the electrical disconnect for the outdoor compressor. The home manufacturer would then also be able to appropriately size any secondary heating system supplied with the home, especially if such a system were treated similarly to packaged units in the HUD code (where the home is considered to have a complete heating system by virtue of the equipment being shipped loose in the house for field installation by the setup crew).

Setup contractors would need to be properly trained in completing the ductless heat pump systems on site. Even though the specialized skills for refrigerant handling would be eliminated, some technically critical details would remain. Home manufacturers seeking to purchase ductless heat pump equipment would need to establish relationships with HVAC equipment manufacturers and/or distributors that resolve how best to handle warranty issues that will occur in states where installation work is performed by several home installation contractors.

Market Readiness

The manufactured housing industry has experience using some types of pre-charged refrigerant line sets and purchasing heat pump equipment for factory-installed systems. Manufacturers report challenges with equipment servicing and dealing with refrigerant leaks from faulty connections. Any quick connect fittings identified for use in this application would need to demonstrate the ability to reliably be connected and re-connected, without refrigerant loss or other damage to the system. A non-licensed HVAC contractor would not be allowed to complete the ductless heat pump setup today, but if rules change to allow it in the current market it could reduce time and labor costs, with some limitations. Changes to the HUD code language might be required to specifically call out a ductless heat pump system with shipped-loose equipment and quick-connect refrigerant fittings as being considered a complete heating system.

(H4) Heat pump ready furnace

Description

With some exceptions, HUD code requires manufactured homes to be shipped with a heating system, which is typically a low-cost, single-stage electric or gas forced-air furnace. The limited capabilities of these systems are a barrier to the installation of advanced variable-speed or multi-stage heat pumps, which require a wider airflow range and better control over system airflow. At the same time, the recent federal efficiency standard for furnace fans has resulted in a general migration to electronically commutated motors (ECMs) for furnaces and air handlers, including those meant for manufactured homes. These ECM-based furnaces and air handlers *could* readily meet the airflow needs of advanced heat pumps, but only if the equipment is simply designed with the ability for external controls to adjust airflow.

This innovation would develop electric and gas forced-air furnaces that are factory ready for multi-stage and variable-speed heat pumps. It is premised on using the full capabilities of existing ECM blower motors for external control, as well as providing a ready means to transition a factory-shipped furnace from a primary heating role to being secondary to a heat pump.

The first aspect of this innovation involves relatively minor furnace control-board changes so that a field installer could select any of the (typically five) available ECM blower airflow settings for each of up to three heat pump heating and cooling stages, with the staging determined by an advanced thermostat. In addition, the furnace should have the ability to receive a DEHUM signal from a humidity-sensing thermostat and reduce airflow by one speed setting during cooling calls to improve dehumidification.

The second aspect of the innovation involves modifying electric furnaces so that in northern climates, electric-resistance heat can be switched on in banks (or modulated) to serve as an as-needed supplement (rather than alternative) to the output of a heat pump. The heat pump can continue to operate—and thus more efficiently offset electric-resistance heat—at low temperatures where the heating load for the home exceeds the output capacity of the heat pump.

The overall idea is to produce a furnace that is fully functional as a primary heating source but is also flexible enough to efficiently serve a field-installed multi-stage heat pump or cooling system. This would reduce equipment-specification complexity for manufactured-housing manufacturers while also allowing for buyer, retailer, and HVAC installer flexibility in specifying field-installed heat pumps and cooling systems without having to replace factory-installed systems.

Savings Potential and Cost Effectiveness

Since the main focus of this innovation is to make it easier to install multi-stage and variable-speed heat pumps, we take the energy-cost savings potential and break-even incremental cost to be the same as those calculated above for factory-installed two-stage and variable-speed heat pumps (see Figure 17 and Table 18 on pages 5353 5353and 31 respectively54). On a national basis, this implies roughly 45 to 55 percent HVAC energy-cost savings potential and a break-even incremental cost in the range of $6,000 to $7,000 against electric and propane furnaces. As discussed on Page 5151, we judge the likely incremental cost of field-installing an advanced heat pump (over a furnace and central air conditioner) to be in the range of $2,000 to $4,000, so this innovation is likely cost effective, even if a few hundred dollars of additional controls are needed to make a conventional manufactured-home furnace more heat-pump friendly.

Market Motivators and Barriers

While there are clear market drivers in favor of multi-stage and variable-speed heat pumps that a universal furnace/air-handler would help support, there are some barriers. First, current variable-speed and multi-stage products tend to be oriented toward the higher end of the market and require matched indoor and outdoor units with proprietary communications between the two for airflow. These products would not interface well with the universal manufactured home furnace innovation described here. However, one manufacturer (Bosch) already offers an inverter-driven, variable-speed heat pump that can work with a standard residential furnace, and Mitsubishi has been working on a product along the same lines. Given the large installed base of standard furnaces in U.S. homes, it seems likely that the suite of multi-stage heat pumps that can interface generically with furnaces will increase in coming years.

Second, the flexibility of a universal furnace also comes with risk. While manufactured home manufacturers may appreciate less complexity in specifying the factory-installed equipment, some have already expressed a concern that mis-sized or improperly installed HVAC equipment on the part of local installers result in a comfort complaint directed at the manufactured home manufacturer. Putting even more flexibility in the hands of local contractors may not be seen as a desirable goal by these manufacturers. Training and education supported by both manufactured home and HVAC manufacturers would likely be needed for a flexible manufactured home furnace product.

Third, HVAC manufacturers reportedly use inexpensive electric and gas furnaces as loss leaders in the manufactured home industry in the hope that local contractors will select an A/C system or heat pump of the same make and thus generate additional revenue for the company. This could make HVAC manufacturers reluctant to produce a product that works well with many brands of heat pumps.

Finally, there is the near-term issue that introducing such a product would require engagement with one or more HVAC manufacturers, who, as noted previously, are currently overwhelmed with COVID-related supply-chain issues as well as upcoming refrigerant phaseouts.

Market Readiness

The product described here does not currently exist but could likely be developed through relatively minor revision of existing furnace products.

(V1) Smart ventilation control with heat pump water heater

Description

HUD requires the presence of a whole-house ventilation system capable of providing 0.035 cfm per square foot of floor area. In practice, this is often a simple roof vent ducted to the return side of the main air handler that provides fresh air only when a call for heating or cooling causes the air handler to operate. In some areas, a dedicated continuously operating exhaust fan is used to meet the HUD whole-home ventilation requirement. In addition to whole-home ventilation, new manufactured homes are provided with manually operated exhaust ventilation in the form of kitchen range hoods and bath fans. Smart ventilation controls are an emerging technology with products just beginning to come into the market. These have not been deployed in new manufactured housing to our knowledge.

This innovation explores reinventing the ventilation system to meet ASHRAE standard 62.2 equivalent ventilation requirements and help resolve large challenging operations, maintenance and commissioning issues related to manufactured home ventilation systems. Smart ventilation control may help improve the operation and maintenance of home ventilation systems and help occupants better understand the importance of ventilation. Smart ventilation control algorithms may adjust operation based on home occupancy, outdoor temperature, and/or outdoor air quality.

A heat pump water heater located inside the home could prove useful for adding heat recovery or dehumidification to a home’s ventilation system. When the heat pump water heater runs, it takes care of ventilation in one of two ways. In heating-dominated climates, the water heater would have its exhaust air ducted to the outside (interior air exhausted out), and in cooling-dominated climates, the unit would have its intake air ducted from the outside (supplying cooled and dehumidified ventilation air). We would want to modify a typical heat pump water heater by adding to it the ability to control an external 120-volt AC load, so that the unit would be able to power the other components of the home's ventilation system and shut off that equipment when the water heater runs and takes over ventilation during its duty cycle.

Johnson Controls (JCI) is a major HVAC manufacturer who expressed initial interest in smart ventilation control. However, like other HVAC manufacturers, they are currently focused on transitioning to a new class of low-GWP refrigerants. JCI stated that they are willing to be consulted on this innovation but cannot actively pursue it at this time. The project team has also engaged with LBNL and DOE to consider this innovation. We learned during an interview with staff from the EPA's ENERGY STAR team for new manufactured housing that they are looking at heat pump water heaters as they plan for a future iteration of ENERGY STAR requirements. A heat pump water heater that can bring heat recovery and humidity control to a home's ventilation system could prove very useful.

Savings Potential and Cost Effectiveness

We estimated the savings for this innovation as a combination of the direct domestic hot-water savings from the heat pump water heater itself, plus a 4 percent reduction in space-cooling energy in cooling-dominated climates (Study Regions 1 and 3).[17] For the rest of the country, we judged the innovation to be neutral in terms of space-conditioning impacts.

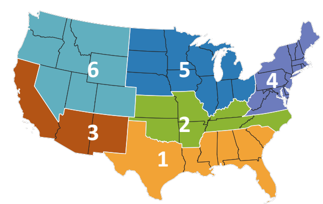
Table 19 on page 62 shows our estimates of the direct domestic-hot-water savings associated with installing a heat pump water heater in lieu of a conventional water heater of different fuel types in this population. The addition of some space-cooling benefit in warmer climates results in the total estimated annual energy-cost savings and break-even incremental cost for the innovation shown in Table 20. As is the case elsewhere in this report, the innovation shows good energy-cost savings against electric-resistance and propane conventional water heaters, but not against natural gas. The break-even incremental cost over conventional electric and propane water heaters is well above the typical $1,000 to $1,500 upgrade cost for a heat pump water heater in all regions. This innovation is likely cost-effective.

[17] This estimate is derived from a recent FSEC lab study (Colon et al. 2016).

Table 20. Annual energy-cost savings and break-even incremental cost for smart ventilation control with heat pump water heater, by region and baseline water-heater fuel.

	Annual energy-cost savings over a conventional...			Break-even incremental cost[a] vs. a conventional....		
Region	...Electric water heater	...Propane water heater	...Nat gas water heater	...Electric water heater	...Propane water heater	...Nat gas water heater
1[b]	$170	(c)	(c)	$1,800	(c)	(c)
2	$165	$230	$5	$1,850	$3,400	$300
3[b]	$190	$135	$20	$2,100	$1,950	$250
4	$270	$305	-$10	$3,250	$4,400	-$250
5	$255	$155	-$55	$2,700	$2,600	-$350
6	$185	$225	-$10	$2,100	$3,400	-$50
National avg.	$185	$215	-$25	$2,050	$3,200	-$150

Notes:
(a) assumes 15-year life for a water heater
(b) Includes 4% space-cooling savings in addition to direct energy savings for domestic hot water
(c) fuel-fired water heaters not modeled for Region 1 due to low market share



Market Motivators and Barriers

The HUD code requires homes to include a mechanical ventilation system, but the commonly employed systems either operate only when the air handler operates for space conditioning or are often turned off by homeowners who do not believe that they need ventilation. A home manufacturer would enjoy the reduced risk of customer complaints from the ventilation and/or dehumidification that a heat pump water heater could be configured to provide to the home. While some homeowners view mechanical ventilation as a cost to operate (and thereby deactivate it), they likely will view heat pump water heater-induced ventilation as a value, since the heat pump is providing energy-efficient water heating. In addition, operation of a heat pump water heater tends to be coincident with production of indoor humidity from showering activity: this could be another perceived benefit from this innovation.

Heat pump water heaters are considerably more expensive than conventional electric water heaters, which creates an immediate challenge to implementing this concept. However, they also considerably reduce water heating costs, and could be part of a larger "electrification" package involving heat pumps for both space-conditioning and water heating, with the ability to eliminate the need for natural gas—and its associated fixed service charges—entirely for the one in six new manufactured homes that uses this fuel.

Since water heaters are commonly installed inside manufactured homes, noise from the heat pump water heater needs to be managed to prevent occupant dissatisfaction. At the same time, homeowners will need to be made aware that the filter needs to be cleaned at regular intervals, which may prove to be more of a challenge than one might expect.

Market Readiness

Heat pump water heaters have been improving rapidly over the past several years. They now commonly support some options for ducting the process air, noise levels have decreased, and equipment reliability appears to have improved from earlier equipment releases. Water heaters in manufactured homes are often electric storage tank units, and they can be located in bedroom closets, utility rooms, or even hallways. Heat pump water heaters may not be suitable for all locations currently employed by the industry, and some work would be needed to modify some home floor plans to isolate the sound from living spaces and to control where the cooled air gets introduced into the home. Rheem supplies much of the water heating equipment to the industry, and their installation instructions allow for minimum clearances around the equipment, which would reduce the extent to which water heater cabinets might require enlarging to accommodate the equipment.

In addition, new controls would be needed to integrate operation of the whole house supply, exhaust or balanced heat or non-heat/energy recovery whole house and intermittent ventilation system(s) and the ventilation provided by the heat pump water heater.

CONCLUSIONS

A pandemic, and labor and materials supply chain issues affecting the manufactured home and HVAC industries combined with the HFC refrigerant phase out impacted the project team's ability to work with industry partners to consider some innovations for new manufactured homes. Industry partners are focused on working through challenges to their day-to-day operations and have limited time to focus on research and development, which influenced the innovations selected to move into the second phase of this project (innovation testing).

The project team selected four innovations to move into the innovation testing phase based on their feasibility for industry adoption and potential energy savings. Innovations focused on increasing the adoption of heat pumps that provide good potential energy savings and support the project's HVAC-energy-reduction goal were considered. We narrowed the heat pump related innovations to innovation H1a. This innovation provides big savings potential, seems feasible by working with heat pump equipment currently available, is likely cost-effective, and supports DOE's beneficial electrification goals.

> **(H1a) Partial Factory-Install of Ducted Heat Pumps:** The feasibility assessment identified several technical and market barriers to full factory installation of high-efficiency heat pumps. This innovation tests a potential near-term solution to these issues in the form of partial factory installation in which the air handler, refrigerant lines, and indoor heat-pump coil are installed at the factory and the outdoor unit is

shipped loose for field installation during siting. Field testing of this concept will focus on home manufacturers and installers in the Northwest and include performance monitoring in one home in the Northwest and one home in the Southeast to demonstrate the comfort and energy benefits of the system.

Ductwork is a known area of concern impacting resident comfort and energy usage. The manufactured home industry is motivated to look at duct related innovations that could solve resident comfort and energy issues. Three ductwork focused innovations (D1, D2, and D2a) are immediately feasible, address a well-known issue in the manufactured home industry, offer medium savings potential, are likely or possibly cost-effective, and support both the project's duct-leakage-reduction and the HVAC-energy-reduction project goals.

(D1) Improved HVAC QA Protocols: This innovation seeks to streamline quality-assurance protocols for proper HVAC-system assembly and operation in the factory, at siting, and/or inspection. We will field test improved in-factory protocols to test for duct leakage, as well as rapid field diagnostics for duct leakage, airflow, and other HVAC-related issues during home siting or inspection. The goals will be to refine the protocols and obtain manufacturer, installer, and inspector feedback and document the final protocols for wider adoption.

(D2) Improved Cross-Over Duct Designs: This innovation strives to improve the design of the crossover duct connection required for multi-section homes by employing metal elbow connectors and a super-insulated flex duct-in-duct approach. Homes in the Northwest have adopted the metal elbow connectors, but we will be testing the ability to build a super insulated flex duct in this region. This innovation will be refined and tested with manufactured home retailers in the Northwest. If successful, the technique will be documented for national applicability for homes with belly crossovers.

(D2a) Comparative Testing of Different Cross-Over Approaches: The feasibility assessment showed that manufacturers, installers, and dealers are long on opinion but short on hard data regarding the strengths and weaknesses of through-the-rim versus traditional flex-duct crossovers for multi-section homes. If through-the-rim designs can be shown to be less prone to leakage and field degradation, it could spur wider adoption by the industry. For this innovation, we will identify and test homes with both types of duct systems for leakage in the Northwest, Midwest and Southeast, and compare field air delivery with factory duct design calculations. This activity will also synergistically serve as a test vehicle for the improved HVAC QA protocols in D1 above.

Not all innovations considered through the feasibility assessment had traction to move forward into the next project phase due to the industry's focus on managing day-to-day operations through supply chain disruptions, as well as project budget limitations. These innovations were not recommended to move into the second phase of the project because they were unlikely to be cost-effective, involve challenges in engaging with industry stakeholders, or are further from market readiness for adoption. These innovations could be considered in future research efforts as market conditions and industry motivations change over time.

(D3) Demonstrate AeroSeal in a factory setting

(D4) Interior duct designs to eliminate leakage

(H1b) Revive the "Insider" ASHP

(H1c) Air Source Integrated Heat Pump (ASIHP)

(H2) Advanced controls and distribution for ductless heat pumps

(H3) Quick connect fittings for ductless heat pumps

(H4) Heat pump ready furnace

(V1) Smart ventilation control with heat pump water heater

Manufactured homes provide an important source of affordable housing to American communities and their residents. The four innovations selected to move into the second phase of this project take steps forward on the pathway to improving resident comfort and energy usage in new manufactured homes.

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