# High Performance Manufactured Homes Field and factory results from 8 demo homes built in 6 factories

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#### ABSTRACT

This paper presents the findings from the construction of eight prototype high performance manufactured homes built by six factories located throughout the Pacific Northwest (PNW). Each home was designed to achieve a 60% reduction in space conditioning and water energy while utilizing the factories' existing construction processes and home designs. Homes were equipped with a data acquisition system monitoring key branch circuits, total hot water use and both indoor and outdoor environmental conditions at a one minute intervals. This paper presents the costs, factory construction impacts, energy and comfort impacts observed in the two years since the homes were built. This 4-year research and demonstration effort is informing the development a new cost effective voluntary efficiency standard, improved factory construction practices, and region wide utility program offerings intended to redefine consumer expectations of what manufactured homes can be.

### Background

#### History of NW Utility Support of Manufactured Homes

The Bonneville Power Administration (BPA) and its partner utilities have strong prior and continuing efforts to improve the energy efficiency of manufactured homes. Between 1992 and 1995, approximately 50,000 homes were built under the Manufactured Housing Acquisition Program (MAP). *The program cost utilities about \$100,000,000, and the PNW realized almost 30 average annual megawatts of savings. Given the measure's 45-year life, the program's levelized cost was about \$2.2M per aMW (Baylon, et al, 1995).* 

When MAP ended in 1995, the state energy offices joined with the manufactured housing industry to establish a self-supported certification program for the industry. This new effort became known as the Northwest Energy Efficient Manufactured Housing Program (NEEM), which adopted specifications at the MAP level of energy efficiency. Northwest Energy Works (NEW) administers NEEM as an industry-supported voluntary program, providing third party certification to homebuyers and verification for utility programs. NEEM homes are branded as ENERGY STAR<sup>®</sup> or Eco-rated<sup>™</sup> (a brand developed by the NEEM program). The underlying energy efficiency specifications have been expanded over time to cover items like duct testing, lighting, higher efficiency equipment and better windows; the core building shell requirements remain largely unchanged.

#### **Renewed Interest in Manufactured Home Efficiency**

The Summary of NEEM Manufactured Home Field Data and Billing Analysis (Baylon, et al,. March, 2009), and "Strategic Recommendations to Improve Energy Efficiency in Manufactured Housing" (Eklund, K.; et al,. January, 2011) confirmed that it was a good time to advance efficiency standards of both federal and voluntary program manufactured home efficiency standards. In 2010, the Northwest Energy Efficiency Alliance (NEEA) contracted the Washington State University Energy Extension (WSU) to participate in and support the work of HUD and the DOE to raise the federal minimum efficiency standard (aka. HUD Code) to be more consistent with site built home efficiency requirements.

In 2011 the BPA began evaluating possible improvements to the NEEM core specification and what a "High Performance Manufactured Home" (HPMH) might include. This research effort was informed by work conducted through a collaborative research project sponsored by the Building America Partnership for Improved Residential Construction, which resulted in three published reports: *Northwest Energy Efficient Manufactured Housing Program Specification Development* (Hewes and Peeks, 2013), *Northwest Energy Efficient Manufactured Program: High Performance Manufactured Home Prototyping and Construction Development* (Hewes and Peeks, 2013), and *Northwest Energy Efficient Manufactured Housing Program High-Performance Test Homes* (Hewes and Peeks, 2015).

#### **HPMH Specification Development**

Central to consideration of creating a HPMH program with the industry is demonstrating that such a home can be built, transported and installed reliably, and produce expected savings. To this end, NEW worked closely and collaboratively with manufacturers, BPA, its partner utilities, and NEW's contractors and partners to investigate, assemble and test available technologies to determine the potential for a HPMH. This was a joint effort to set specifications and measure achievable energy savings without requiring major changes in manufacturing processes (Hewes and Peeks, 2013). Table 1 presents a comparison between current HUD code requirements, NEEM program requirements and the High Performance Manufactured Home requirements.

Component	HUD Code	NEEM	HPMH		
Ceiling	R-22	R-40	R-49 (R-45 net)		
Floor	R-22	R-33	R-38		
Wall	R-11	R-21	R-26		
Window	U=1.10	U=0.35	U=0.22		
Door	R-22	R-5	R-5		
Duct Leakage	n/a	6% of Supply	No ducts		
Target Uo	(nominal 0.079)	0.054	0.040		
Heating System	Electric FAF	Electric FAF	Mini-split HP w/zonal ER		
Lighting	n/a	1.4 W/ft2	0.7 W/ft2		
Infiltration	7.0 ACH50	5.0 ACH50	2.5 ACH50		
Ventilation	0.035 cfm/ft2	0.035 cfm/ft2	0.035 cfm/ft2		
DHW	0.90 EF	0.93 EF	2.00 EF		
Appliances	n/a	ENERGYSTAR dishwasher	All ENERGYSTAR		

#### Table 1. Manufactured Home Efficiency Requirements

The Northwest Regional Technical Forum approved a HPMH Uniform Energy Savings (UES) measure that utilities could use to claim savings for manufactured homes built to the HPMH specifications (Ecotope, 2012). Figure 1 shows the annual energy use comparisons developed by Ecotope Inc. between the baseline performance levels of the HUD (with 0.35 U-value windows), NEEM and the HPMH specification. This information suggested that roughly 8,000 kWh/yr could be saved in heating, and an additional 1,000+ kWh could be saved by a cold climate heat pump water heater (HPWH).



Figure 1. SEEM modeled use of HPMH in heating zones in the PNW. Source: Ecotope, 2013.

#### **Questions Identified**

Development of the specification for a High Performance Manufactured home prompted a series of important cost, buildability, performance and comfort questions that framed additional research was needed.

- 1. Could ductless heat pumps (DHPs) be reliably installed and commissioned in the factory?
- 2. Would a single indoor head DHP with zonal heating in secondary zones ensure comfort?
- 3. Could cold climate heat pump water heaters be integrated into house design such that they do not adversely impact comfort, create pressure imbalances or generate unacceptable levels of noise inside the house?
- 4. Could the HPMH measures be added without factory disruption and at minimal cost?
- 5. What would the HPMH package cost at the wholesale and retail levels?

These questions prompted the formation of an applied research project that succeeded in building a series of eight demonstration home projects at multiple manufacturing facilities. The goal of these demonstration projects was to determine whether the HPMH measure package could be readily incorporated into typical manufactured home designs and whether the homes would achieve the expected levels of energy performance while also delivering acceptable comfort.

# **Eight High Performance Demonstration Home Projects**

The project team for this research consisted of Northwest Energy Works (NEW), Bonneville Power Administration (BPA) and the Northwest Energy Efficiency Alliance NEEA). The project was jointly funded by BPA and NEEA. The project received additional support from the Building America Partnership for Improved Residential Construction. Four projects were built in the fall of 2013, with the other 4 built in the fall of 2014. Seven of the eight homes were double wide construction with only one single wide. Site selection was done quickly due to end of year funding availability challenges, and limited to homes already sold to homebuyers who agreed to receive the HPMH measures as no-cost upgrades to their homes.

Design and construction of the HPMH projects followed the same approval process as a HUD code home. Each plant submitted upgraded energy measures and any corresponding design changes to the plant's designated Design Approval Primary Inspection Agency (DAPIA) for approval. Once the HPMH measures were approved, they were included in each plant's DAPIA manual. The plant's In-plant Primary Inspection Agency (IPIA) is then required to inspect the home to the HPMH spec that was entered into the DAPIA manual for that plant.

NEW staff worked with six factories to build the HPMH. Training at each workstation was provided by NEW as well as in-plant monitoring of the entire construction of all eight HPMH prototype homes.

#### **Unique Construction Elements**

The following are brief descriptions of the construction details that were installed to meet the HPMH specification:

- R-5 High Performance **Windows** The windows were all triple-pane, low-e, argon/krypton gas filled vinyl windows with a U-factor U = 0.20-0.22, SHGC = 0.26-0.28, VLT = 0.45
- **Floors** Full Depth Insulation The floor has no duct system so up to 25% more insulation was installed in the floor system. Enough insulation was added to ensure contact the floor deck in the area between the chassis I-beams, instead of installing all the insulation below the floor framing and ductwork, typical of manufactured homes.
- Walls Exterior Rigid Insulation HPMH were built using 2 × 6 wall framing with R-21 insulation. House wrap was installed and then R-5 foam sheathing was installed over the house wrap requiring longer fasteners for siding installation.
- **Roof** Maximum Depth Insulation Insulation baffles were used to fully pack insulation at the eaves. Insulation bag counts were developed that allowed for packing the eave area and achieving the R-49 target insulation depth.
- Heat Pump Water Heater Inlet air was ducted to the heat pump from the crawlspace and exhaust air was ducted to either a wall vent or roof vent. The goal was to reduce interaction with the interior, reduce noise and use the ground-tempered crawlspace air to enable the heat pump to operate with a higher COP, compared to using outdoor air. Equipment installation required enlarging the water heater closet, adding an exterior door to the HPWH closet, and interior wall insulation (sound attenuation).
- **Minisplit Heat Pump** and Secondary Zone Heating The hybrid zonal system eliminated the electric forced-air furnace and duct system from the home. A single

ductless heat pump (DHP) outdoor unit was connected to one indoor head as the primary space conditioning system, along with electric wall heaters for secondary heating. Ceiling paddle fans were installed in the living room and master bedroom or rooms were made paddle fan ready as a means to increase air mixing in the home.

• **Durability** improvements - Each home included house wrap on the walls. All windows and doors were installed over a peel-and-stick flashing on the sill and sides of the door and window openings. An additional layer of self-adhesive flashing was then installed over the top and side nail fins.

#### **Commissioning and Data Acquisition System Installation**

The project team worked with NEEA's Next Step Home pilot project team to ensure data was collected consistency with NEEA's site-built homes program. This system consists of a power-monitoring computer connected to current transducers located in the main breaker panel. This device connects wirelessly to a gateway device that connects to the Internet and sends 1-minute interval data to the SiteSage servers, where those data become available to the project team through a dedicated Web portal. Temperature, relative humidity and volatile organic compounds (VOCs)/CO<sub>2</sub> were measured in the living room, master bedroom, master bath and hall bathrooms. Water flow rate and temperatures to and from the heat pump water heater were measured. Power measurements were made on the DHP, HPWH, outdoor power, one or more major appliance and lighting/plug circuits.

## **Results and Findings**

#### **Construction Findings**

Once each home was constructed, the project team assisted with the site commissioning of systems and installation of data logger as well as completing a final onsite blower door test. Table 3 building design details. Only two of the projects met the intended target of 2.5 ACH50 for infiltration. The relatively high 3.57ACH value of the project in Pullman Washington was at least in part due to post setup impacts of poorly implemented add-on electrical circuits, extensive computer network cabling and radio systems installed by the owner.

			Area	UA	HP	
Home	Manufacturer	Location	(ft2)	(Btuh/F)	(Btuh)	ACH50
1	Fleetwood Homes of Oregon	Toledo, WA	1279	187	18,000	3.02
2	CMH - Golden West Homes	Pullman, WA	1296	193	18,000	3.57
3	Skyline	Otis, OR	1404	207	12,000	2.86
4	Palm Harbor Homes	Bothell, WA	1137	169	12,000	2.75
5	Fleetwood Homes of Oregon	Chehalis, WA	1492	223	12,000	2.4
6	Palm Harbor Homes	Sixes, OR	587	112	12,000	1.17
7	Marlette Homes	Siletz, OR	2100	286	18,000	not tested
8	Kit Homebuilders West	Boring, OR	1138	187	12,000	3.99

Table 3. Project Locations, Heat Loss Rate, HP Capacity, and Air Leakage Test Results

Five of the projects received a 66 gallon AirGenerate heat pump water heater (HPWH) and projects 5, 6, and 8 received a General Electric Geospring 50-gal non-vented HPWH. The installation required redesigning all of the floor plans to accommodate the larger 66 gallon tank and the clearance requirements for both 50 and 66 gallon HPWH in a modified utility room or dedicated water heater closet. Installing and insulating the 6-in. intake and exhaust metal ducting made the HPWH one of the more time-consuming measures to install. Rooms with the GE HPWH recorded and showed a significant temperature drop when the HPWH was operating. The room recovered relatively quickly when the HPWH shut down.

The ductless mini-split heat pump proved more challenging to incorporate into some of the homes. Prior work with the plants to install DHPs already had found that some home floor plans do not lend themselves to in-plant DHP installation. The home sections typically are built at the maximum width that can be transported on public roads, which means that mounting a DHP compressor on the long side walls of the home is not an option. Similarly, the homes have a trailer hitch on one end, which precludes installing the compressor on hitch end of the house. That leaves the "rear" non-hitch end wall of the home as the location for the outdoor compressor. If the end wall has a window (particularly an emergency egress window), then it may not be possible to mount the compressor on the end wall of the home.

Another design limit is that the indoor head needs to be located in the same home section as the outdoor compressor in order to complete the installation in the plant. The indoor head also needs to be located on a wall with a closet behind it, so the refrigerant piping can be run up the wall to the indoor head while remaining accessible. Thus, three of the eight project homes required DHP installation on site. Where the home floor plan allowed for in-plant DHP installation, doing so challenged the plant staff but proved to be within their capabilities. One plant has continued with installing DHPs as a customer option for some of its home designs, and the staff have become much more adept at the installation process. In all cases, a licensed refrigeration technician is required to make all the lineset connections, evacuate and charge the systems. Since not all homes can reasonably have a DHP installed at the factory, this measure requires coordination with contractors on site to ensure that properly sized equipment is selected and correctly installed on a significant fraction of the homes produced.

The project team found 1,000-W heaters to be a versatile size that works well for many rooms. Fan/light/heater combo units were installed as an effective solution for providing heat in bathrooms. Bathroom heat light fan units were installed and wired to allow independent operation of each function. Some small bathrooms used a heat lamp, so in those cases separate low-wattage lighting was included in the bathroom for illumination purposes.

Incremental costs were provided by each manufacturer. Internal accounting and tracking method differences and differences in the house design and sourcing of materials used, a direct apples-to-apples comparison is not possible. Because the HPMH package incorporates technologies that are not currently being used in manufactured homes the plants relied on their own suppliers and construction approaches to build each HPMH. Table 4 provides an average incremental cost of the efficiency measures normalized to a standard 1600ft<sup>2</sup> double wide design and rounded to the nearest \$100. The average reported incremental cost of Energy Efficiency Measures was \$12,700 with a low of just over \$9,000 and a high of nearly \$14,000. The retail price for the HPMH package is likely to be \$18,000 to \$24,000 if no cost reductions are realized through bulk purchasing or standardized processes.

System	Average Cost
HPWH with ducting, room changes, etc	\$1,500
DHP with Zonal Heating	\$3,800
Triple pane glazing package	\$4,000
Wall, Floor, Ceiling	\$2,300
Air Sealing and Flashing	\$300
Chassis and Axle changes	\$400
Parts and supplies not otherwise identified	\$400
Total	\$12,700

Table 4. Average Incremental Cost (normalized to 1600 ft<sup>2</sup>)

### Heating and Cooling Performance

Annual heating and cooling energy use was adjusted to local TMY weather conditions and used to calibrate a building simulation model (SEEM). Table 5 presents the annual and estimated energy consumption for seven of the eight projects compared to the projected energy use estimates. Model calibration was done by adjusting internal gains. The calibrated model was use to estimate the energy use of the home had it been built to the HUD code levels of efficiency. Savings estimates are the difference between TMY adjusted actual energy use and the calibrated home built to HUD code efficiencies. The average heating energy savings of the seven modeled homes is an impressive 80%. Cooling savings estimates are not comparable as they are relatively small and highly dependent on internal gains and if the windows were opened.

	Heating Energy use (kWh/yr)				Cooling (kWh/yr)				
Site	Location	UA (Btuh/F)	Metered (w/TMY adj)	Modeled	HUD	% Savings	Metered	Modeled	
1	Toledo, WA	187	3,368	3,365	13,778	76%	231	108	
2	Pullman, WA	193	Incomplete - see Pullman home discussion						
3	Otis, OR	207	2,030	2,024	9,220	78%	73	17	
4	Bothell, WA	169	-	1,008	5,953	83%	-	246	
5	Chehalis, WA	223	-	3,989	17,433	77%	-	77	
6	Sixes, OR	112	1,470	1,477	7,452	80%	26	16	
7	Siletz, OR	286	1,903	1,901	10,714	82%	-	307	
8	Boring, OR	187	1,192	1,188	6,635	82%	786	538	

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Table 5 Project	annual	heating	energy	1160	comparison
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Unfortunately, the Pullman home (#2) did not result in useful data. The home turned out to be used not as temporary housing, but as a 24hr "waiting room" for emergency helicopter pilots at the Pullman airport. Additional electronics, and aviation lighting was attached to the building and the "residents" spent time eating pizza, watching TV or playing video games, and as the data shows, never showered. Both the Bothel (#4) and Chehalis (#5) homes encountered

data collection challenges that prevented a whole year of energy data from being gathered. Future data gathering and analysis is anticipated in 2017.

The single DHPs located in the living room proved capable of meeting over 95% of the heating needs of these homes. Figure 3 is representative the mild climate projects (#1, and #3-#8) where little supplemental electric resistance heating was needed during the heating season. The red color indicates when the bathroom electric resistance heating was from the use of the heat lamp fan assembly that was used by the homeowner in the morning to warm of the bathroom prior to taking a shower. The green indicates when the electric backup heater was used. In each home electric heater use didn't show up until outdoor temperatures dropped well below freezing.



Figure 3 - Less than 2% of heating provided by backup electric resistance sources. *Source*: Northwest Energy Works 2015.

Several of the DHPs demonstrated short cycling behavior during moderate or low load conditions. Figure 4a shows an example of this a behavior. Figure 4b shows the typical behavior of a DHP when there is enough load for the machine to operate continuously. Under moderate load conditions (which is common in these homes) the DHP cycles on at full power (~900 watts) for a few minutes, and then shuts off when air temperature near the DHP reaches set point.

This short-cycling behavior has been confirmed by manufactures as a controls problem, intended to ensure rapid response to a call for heating or cooling. The fact that the DHPs were set in "Auto" mode only partially explains for this as it is not present for all makes, and more prevalent in homes with larger 18kBtu rated heat pumps.



Figure 4a and 4b - DHP operation under low load (left) high load (right) operation.

#### **Comfort Performance**

Exit interviews were conducted by NEW staff. Homeowners were universally satisfied with the comfort of their homes. Typical thermostat settings were 70F daytime and 68F nighttime. The homeowners generally kept the doors opened between bedrooms and main living space, and allowed the master bedroom and second bedroom temperature to cool down at night. Most homeowners claimed to use the installed ceiling fan when cooling was needed. The installed compact fluorescent light was "tolerated", but not well liked.



Figure 7. Winter room air temperature comparison (HPMH Site #1). Source: Northwest Energy Works.

Figure 7 shows room temperatures comparison typical bedrooms compared to living room and exterior temperatures. Data from these homes showed a typical 2-3 degrees spread when doors open, and a 5-6 degree spread when a bedroom door was closed when outdoor temperatures were near freezing. Those places farthest away from the DHP (commonly the master bathroom) did tend to be colder than other parts of the home, but home owners reported that the electric resistance heating in such zones provided satisfactory supplemental heating. In cooling mode however, the open door approach may not provide adequate air circulation to satisfy occupant comfort.

#### Water Heating Performance

In homes #1, #2, #3, #4, and #7, the heat pump water was located inside a closet with supply air ducted from the crawlspace and exhaust air ejected out the side of the building. In homes 6, and 8 HWPW was located inside the utility room. In home #5 the HPWH was moved to the garage upon request by the client to make room for a large refrigerator. Figure 5 the shows the total house energy for the five homes with complete and year round how water use.



Figure 5 – Total house consumption by end use.

Ducting air to the heat pump from the crawl space enabled the heat pump to operate without electric resistance backup in all but high load conditions and when outdoor air temperatures dropped below about 15°F. None of the homeowners complained about the heat pump noise, likely because care was taken to insulate the walls around the closet. In two homes with non-ducted heat pumps, the utility rooms got considerably cooler than the rest of the home.

Figure 3 shows the difference in water heater inlet air temperature to outdoor air temperature as a function of outdoor air temperature. When outdoor air temperature is below 58 degrees the crawlspace provides 2-15 degrees warmer than outside air. This allows the HPWH to operate at a higher COP for the majority of the year. Lab test results of the Air Generate HPWH show that a 10 degree rise in inlet air temperature the HPWH COP by about 0.5 (*NEEA 2012*). Earlier whole building analysis (Ecotope, 2014) indicates that the buffering value of drawing air from the crawlspace in these homes is a 10-12% reduction in energy use.

The impact of cooler draw temperatures in the summer is minimal because of the limit water heating hours when the outdoor air temperature is above 80 degrees and that COP is fairly flat above 60 degrees Fahrenheit.



Figure 6. Buffering impact of crawlspace air temperature. Source: Ecotope analysis.

## Conclusions

Overall the primary project goals were achieved. The analysis of energy use data from the monitored homes appears to agree well with early estimates of the savings from the proposed specification.

- 1. The project demonstrated that DHPs could be reliably installed and commissioned on the production line in many but not all floor plans.
- 2. The DHP proved capable of provide space heating in mild climates of western Oregon and Washington. Transfer fans are not needed to meet heating loads.
- 3. Triple pane windows were too expensive to be viable in manufactured homes
- 4. Added flashing details for windows and doors could easily be accommodated in the factory and can be expected to improve home durability.
- 5. Foam sheathing proved valuable in maintaining good interior temperatures, but a challenge in the plant construction because of physical plant layout, flashing details and attachment of the wood and cement board siding typically used in PNW homes.
- 6. The ducted HPWH Installed in four of the HPMH homes proved to be one of best energy saving solutions, though also most challenging from a construction perspective.

Additional areas where research is needed include:

1. Exploring the potential to use a roof assembly with only vapor diffusion venting along the ridge. This would accommodate fuller depth insulation at the eves and remove the need for baffles and perimeter screening.

- 2. Coordinate with the industry's window suppliers to acquire a more cost effective window package that can be bulk purchased. A U=0.25 Btuh/ft2-F double pane window is now possible from a major industry supplier, but was not available at the time of this project.
- 3. Refine a method to simplify and streamline the installation of the heat pump water heater. Specifically the dual ducting and acoustical isolation. This measure offered the best efficiency gains for the least cost, but proved challenging for the assembly line process.
- 4. Identify a low cost mini-split heat pump that can be factory installed that can provide serve climates where cooling is needed remote rooms.

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