Reimagining HVAC for New Manufactured Housing
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Energy Modeling and Cost Effectiveness Report

slipstream

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EXECUTIVE SUMMARY

To determine the potential energy savings of HVAC innovations for new manufactured homes, a number of potential HVAC improvements were modeled against two baselines:

1. An original baseline that represents the 1994 HUD envelope code level with a few exceptions and some assumptions made previously by others along with current minimum federal efficiency levels of HVAC equipment.
2. An efficient baseline broadly meant to represent a typical ENERGY STAR qualified home, a tighter duct system, and regional thermostat set points.

Each of these baselines were run for eight cities, chosen to represent the shipment-weighted climate midpoint by region and HUD thermal zone:

HUD Zone 1: Houston, Texas and Atlanta, Georgia

HUD Zone 2: Raleigh, North Carolina and Phoenix, Arizona

HUD Zone 3: Baltimore, Maryland; Chicago, Illinois; Denver, Colorado; and Seattle, Washington

Improvement analysis focused on HVAC solutions that included high-efficiency heat pump systems and improved duct systems including reducing leakage, improving crossover insulation, eliminating crossovers outside conditioned space, and reducing or eliminating duct leakage. Energy savings for key improvements over the original baseline are shown in Table ES-1. As shown, heat pumps can save a significant amount of energy relative to the electric furnaces with central air conditioning systems that currently dominate the national market. Reductions in duct leakage show lower—but noticeable—savings potential.

Table ES-1. Modeled energy savings for a double-wide home with an electric furnace and SEER 14 central air conditioner (original baseline).

	Conventional Heat Pump		**Variable-Speed Heat Pump**		**75% Reduction in Duct Leakage**	
City	kBtu/yr	%	kBtu/yr	%	kBtu/yr	%
Houston	5,800	25%	12,300	53%	1,760	8%
Atlanta	12,200	41%	18,200	61%	2,030	7%
Raleigh	15,500	45%	21,500	62%	3,120	9%
Phoenix	3,000	12%	10,600	41%	1,490	6%
Baltimore	19,100	48%	24,900	63%	4,230	11%
Chicago	27,700	49%	34,200	60%	6,440	11%
Denver	21,200	49%	26,700	62%	5,300	12%
Seattle	19,600	60%	23,100	71%	4,920	15%

Note: Color-codes here represent the three HUD climate zones, yellow-Zone 1, green-Zone 2 and blue-Zone 3

If modeled under the efficient baseline, kBtu per year savings above are reduced by roughly 15 to 30 percent for the heat pump measures and 5 to 60 percent for the duct-leakage measure. Percentage savings remain relatively unaffected.

The modeled energy savings estimates were translated into annual cost savings using regional fuel prices. Life-cycle cost analysis was also used to calculate the break-even incremental cost for various innovations; that is, the maximum up-front incremental cost that could be supported by the innovation’s discounted lifetime energy savings. These results were then weighted to regional and national average values using estimates of the regional distribution of heating fuels and HVAC system types.

Table ES-2 shows heat pumps are estimated to provide substantial energy-cost savings capable of supporting at least several thousand dollars in up-front incremental cost over the conventional forced-air furnace and split-system central air conditioner that currently dominates the market. At current fuel prices, heat pumps are not cost-effective against natural gas in most areas, and in fact produce negative energy-cost savings. This excludes 10 to 15 percent of the national market for new manufactured homes, but more than 50 percent of homes destined for the Midwest. The economics of heat pumps versus natural-gas heat is sensitive to the price of natural gas, however, and depend on whether the home can be fully electrified and thus entirely avoid natural gas service and its associated fixed monthly charges.

Table ES-2. Weighted-average regional energy-cost savings and break-even incremental cost for heat pumps and duct-leakage reduction (original baseline). Heat pump results exclude gas-heat shipments where energy-cost savings would be negative.

	Conventional Heat Pump[a]		**Variable-Speed Heat Pump**[a]		**75% Reduction in Duct Leakage**	
Region	Annual energy-cost savings[b]	Break-even incremental cost[c]	Annual energy-cost savings[b]	Break-even incremental cost[c]	Annual energy-cost savings[b]	Break-even incremental cost[cc]
1	$185	$2,850	$355	$4,450	$40	$500
2	$345	$5,550	$495	$7,250	$60	$750
3	$100	$1,750	$355	$3,100	$50	$600
4	$675	$13,850	$885	$16,900	$130	$2,050
5	$575	$10,200	$730	$12,100	$85	$1,200
6	$520	$8,650	$625	$10,050	$90	$1,300
National	$310	$5,350	$475	$6,900	$65	$900

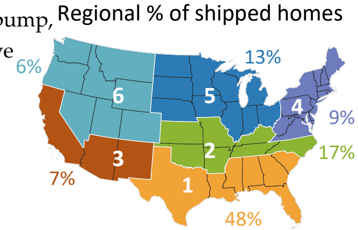
Notes:

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

b) rounded to the nearest $5

c) rounded to the nearest $50

Regional % of shipped homes



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

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INTRODUCTION

Roughly ten million manufactured homes have been built since federal regulation of the industry under HUD began in 1976 and about 100,000 homes were shipped nationwide in 2021 according to the Manufactured Housing Institute. While highly affordable, these homes often lack the energy efficiency and performance mandated by local codes for site-built homes. The HUD code, which regulates the industry nationwide, has not been updated since 1994. This report supports a DOE Advanced Building Consortium project focused on improving the energy efficiency of new manufactured homes through innovations related to space heating and cooling.

The DOE ABC project has identified 13 innovations for heating, ventilating, and air conditioning (HVAC) systems installed in manufactured homes, covering two broad categories: duct-system improvements and increased adoption of heat pumps for space conditioning (Table 1). By modeling site energy[1] savings, estimating energy-cost savings and exploring life-cycle cost impacts, this report supports a broader feasibility assessment of these innovations (Stendel, et. al, 2021), and is meant as a companion to that effort.

This report has two major sections: 1) Energy Modeling, and 2) Cost Savings and Cost Effectiveness. The Energy Modeling section includes a description and basis for the baseline models used for the analysis, simulation procedures, limitations and results for the baseline and innovation models. Results from the energy modeling feed into the Cost Savings and Effectiveness section where methods and assumptions are described, and annual and discounted life-cycle cost are provided. In this section, results are weighted up to the regional and national level using regional fuel prices and the estimated market share for different HVAC fuels and system types.

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

Table 1. List of potential innovations. See Stendel et al. (2021) for details.

ID	Name	Description
D1	Improved Duct Testing Protocols	Protocols and toolkit for more efficiently measuring duct (and envelope) leakage in the factory and HVAC system airflow, in the yard or after siting
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 linesets, 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 MH market
H3	Quick connect fittings for ductless heat pumps	NREL quick-connect concept applied to ductless mini-splits for MHs
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

ENERGY MODELING

Energy models were developed to examine the potential of HVAC improvements. Modeling was performed with EnergyPlus, a detailed whole-building energy modeling tool. Two manufactured-home prototypes (single-wide and double-wide) were chosen to represent the majority of the manufactured homes purchased in the US based on previous research related to HUD-code home energy analysis and rule-making activities. As described in more detail in the sections that follow, two sets of baseline assumptions were developed, each with regional variation. Savings for innovations were obtained by comparing models that were adjusted to reflect various innovations to the results for the baseline runs.

BASELINE MODELS

To determine the potential energy savings of HVAC innovations a number of baselines were modeled and a number of HVAC energy improvements to those baselines were modeled. The baseline modeling consisted of two efforts:

1. An original baseline that represents the 1994 HUD envelope code level with a few exceptions and some assumptions made previously by PNNL and others[2] along with current minimum federal efficiency levels of HVAC equipment.
2. An efficient baseline that represents Energy Star packages prevalent by region, along with reduced duct leakage and regional thermostat setpoints.

Our initial baseline-home modeling assumptions started with inputs used in a Pacific Northwest National Laboratory (PNNL) study (PNNL 2014). That effort was intended to explore savings from what was believed to be the homes built by many manufacturers. The research team decided that builders were typically putting in some slightly more efficient walls and windows and thus created this baseline with U_0 and infiltration values that were slightly better than what was used in an ASHRAE study (Lucas et al. 2007). Equipment efficiencies were brought up to current federal minimums. The thermostat set points were changed to 72ºF and 75ºF consistent with all recent DOE/PNNL building code simulation efforts. The original baseline assumptions are shown in Table 2 along with differences from the 2007 simulations.

[2] Lucas, Robert, Philip Fairey, Robert Garcia, Michael Lubliner. 2007. "National Energy Savings Potential in HUD-Code Housing from Thermal Envelope and HVAC Equipment Improvements," ASHRAE Transactions, Volume 113, Part 2.

Table 2. Original-baseline Model Assumptions. Baseline values from the prior (Lucas et. al. 2007) study shown in *red italics*)

HUD model geometry	**Double-wide (DW)**	**Single-wide (SW)**
Floor/ceiling area (ft^2)	1568 (56x28)	924 (66x14)
Wall area (ft^2)	1344	1280
Window area (ft^2)	188	111
[12% glass-to-floor ratio]	Equal area per facade	Equal area per facade

Envelope and Equipment Parameters

Envelope Component	**HUD Zone 1** (Houston/Atlanta)	**HUD Zone 2** (Raleigh/Phoenix)	**HUD Zone 3** (Baltimore/Chicago Denver/Seattle)
Wall (framing / batt insulation)	2x4 / R-11		2x6 / R-19
2006 study baseline insulation	*R-11 all zones*		
Ceiling (blown insulation)	R-30		
Floor (batt insulation)	R-11		R-22
Window U-val/SHGC	0.52/0.60		
2006 study baseline windows	*1.10/0.70*	*0.52/0.60*	
Infiltration (ACH_{50})	8.0		
2006 study baseline infiltration	*9.0*		
Duct Leakage (Qn)	0.12		
Duct Leak % Supply/Return	0.67/0.33		
Equipment	HUD Zone 1	HUD Zone 2	HUD Zone 3
AC + Electric Furnace	SEER 14 + Elec Resistance		SEER 13 + Elec Resistance
AC + Gas Furnace	Not modeled	SEER 14 + AFUE 80%	SEER 13 + AFUE 80%
AC + Heat Pump	SEER 14 + HSPF 8.2		
2006 study baseline equipment	*All zones 13 SEER/7.7HSPF/0.78AFUE*		
Duct Location	Ceiling or Belly	Belly only	
Crossover Duct area & R-value	63 ft^2 / R-8 (Double-wide only)		
Total Duct Area (ft^2)	DW-423 / SW-249		
Setpoint Heat/Cool	72ºF / 75ºF		
2006 study baseline setpoint	*68ºF / 78ºF*		
Whole-house Ventilation (continuous)	DW – 55 CFM / SW – 32 CFM (exhaust)		
Water Heater (electric resistance)	UEF 0.94		
2006 study baseline water heater	*EF 0.90*		
Interior Lighting	34% high-efficacy		
Appliance & Misc. Equip. (kWh/yr)	Misc./Refrig./Range/Dishwash. 2085/718/500/111		
Occupancy	3BR + 1 = 4		

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

Mechanical systems are primarily modeled as split systems with an interior mounted air handler and outdoor unit. The primary air distribution system has ducts located in the belly above the floor insulation such that they are insulated from below and considered inside conditioned space. Return ducting is minimal and also considered inside conditioned space. All double-wide models include a small length of R-8 flex duct (64 ft^2) located in the crawlspace for the crossover connection between the two halves.

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

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

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

In addition to the original baseline, we also considered modifications to the baseline inputs intended to reflect the possibility that a large number of new manufactured homes are already being built more efficiently than assumed in our original baseline. In fact, the market share for ENERGY STAR® certified homes has grown appreciably in recent years: in 2019, one in five new manufactured homes in the U.S. was ENERGY STAR certified across the nation (SBRA 2020). To provide some notion of the savings implications among this more-efficient subset of the market, we developed a second “efficient” baseline intended to broadly reflect ENERGY STAR level performance and other aspects of more efficient home construction. (

Table 3 shows the efficient-baseline assumptions.

The prescriptive requirements for ENERGY STAR qualification comprise three packages (electric heat pump, high-efficiency furnace and envelope-only) that differ in their requirements: we chose regional values that we believe broadly represent the packages most used in the respective region.

Some of the other efficient-baseline inputs warrant additional discussion. For windows, beyond ENERGY STAR requirements for U-value and solar heat gain coefficient, there is good evidence that the manufactured-home market has at least partly shifted to low-E window products, which reduce heat loss in the winter and solar gain during the summer. Two major manufacturers make low-E windows standard for all their homes, and others offer it as part of an efficiency-package option.

Duct leakage under the efficient baseline is half that of the original baseline. ENERGY STAR does not have a quantitative requirement for duct leakage. The duct leakage assumption for the efficient baseline is instead mainly based on field measurements of duct leakage from a Minnesota field study (Pigg et al. 2016) suggesting that actual duct leakage among newer manufactured homes is less than assumed previously.

The efficient baseline also uses regional estimates of setpoints that differ from the national values used in prior energy modeling for manufactured housing. These derive from recent analysis of data from connected thermostats around the country that suggest regional differences in preferred setpoints. Specifically we used two data sources to develop regional average setpoints for the analysis: (1) Ueno and Meier (2020) provide regional average indoor temperatures on days with heating or cooling operation; and, (2) materials from an EPA working group on connected thermostats (EPA 2018) shows regional average “comfort” temperatures, which are defined as the 90th percentile of indoor temperature during the heating season and the 10th percentile during the cooling season.

Table 3. Parameters for alternative (efficient home) baseline. Strike-through text denotes original baseline values; *blue italics* denotes efficient-home baseline values).

	HUD Zone 1 (Houston/Atlanta)	**HUD Zone 2** (Raleigh/Phoenix)	**HUD Zone 3** (Baltimore/Chicago Denver/Seattle)
Envelope Component			
Wall (framing / batt insulation)	2x4 / R-~~11~~ *13*	2x4 / R-11	2x6 / R-19
Ceiling (blown insulation)	~~R-30~~ *R-38*	~~R-30~~ *R-33*	~~R-30~~ *R-38*
Floor (batt insulation)	~~R-11~~ *R-22*	~~R-11~~ *R-22*	~~R-22~~ *R-30*
Window U-val/SHGC	~~0.52/0.60~~ *0.35/0.34*		
Infiltration (ACH_{50})	8.0		
Duct Leakage (Qn)	~~0.12~~ *0.06*		
Duct Leak % Supply/Return	~~0.67/0.33~~ *0.95/0.05*		
Equipment			
AC + Electric Furnace	SEER 14 + Elec Resistance		SEER 13 + Elec Resistance
AC + Gas Furnace	Not modeled	SEER 14 + ~~AFUE 80%~~ *AFUE 95%*	SEER 13 + ~~AFUE 80%~~ *AFUE 95%*
AC + Heat Pump	SEER 14 + HSPF 8.2		
Duct Location	Ceiling or Belly	Belly only	
Crossover Duct area & R-value	63 ft^2 / R-8 (Double-wide only)		
Total Duct Area (ft^2)	DW-423 / SW-249		
Thermostat Setpoints	~~72ºF / 75ºF~~ ***City*** / ***BA region*** / ***Heating (F)*** / ***Cooling (F)*** *Houston* / *Hot-humid* / *70.5* / *74.0* *Atlanta* / *Hot-humid* / *70.5* / *74.0* *Raleigh* / *Mixed-humid* / *69.5* / *72.5* *Phoenix* / *Hot-dry* / *70.5* / *75.5* *Baltimore* / *Mixed-humid* / *69.5* / *72.5* *Chicago* / *Cold* / *68.5* / *73.0* *Denver* / *Cold* / *68.5* / *73.0* *Seattle* / *Marine* / *69.0* / *73.0*		
Whole-house Ventilation (contin.)	DW – 55 CFM / SW – 32 CFM (exhaust)		
Water Heater (electric resistance)	UEF 0.94		
Interior Lighting	34% high-efficacy		
Appliance & Misc. Equip. (kWh/yr)	Misc./Refrig./Range/Dishwash. 2085/718/500/111		
Occupancy	3BR + 1 = 4		

The Ueno and Meier data reflect actual average temperatures but are likely somewhat biased toward increased setback behavior because they are rooted in data from advanced connected thermostats. The EPA comfort temperatures are meant to reflect people's preferred setpoints when awake and at home and can be taken as a rough proxy for setpoints in the absence of any setback behavior. We averaged the two for each region as an approximation of average regional indoor temperatures reflecting some setback behavior but not as much as would otherwise be suggested by the Ueno and Meier data. There is additional uncertainty here in the fact that all of this derives from connected-thermostat data for the general population of connected-thermostat owners, and preferences and behavior could be different among households in new manufactured homes.

REPRESENTATIVE CITIES

Weather characteristics from eight cities were chosen to represent a combination of HUD thermal zones and Building America climate zones, as shown in Figure 1 and Table 4. Cities were chosen based on the mid-point of the shipment-weighted annual temperature for each region. The eight regions represented by these cities constitute 94 percent of annual new manufactured home shipments.

Figure 1. HUD thermal zones and Building America climate zones

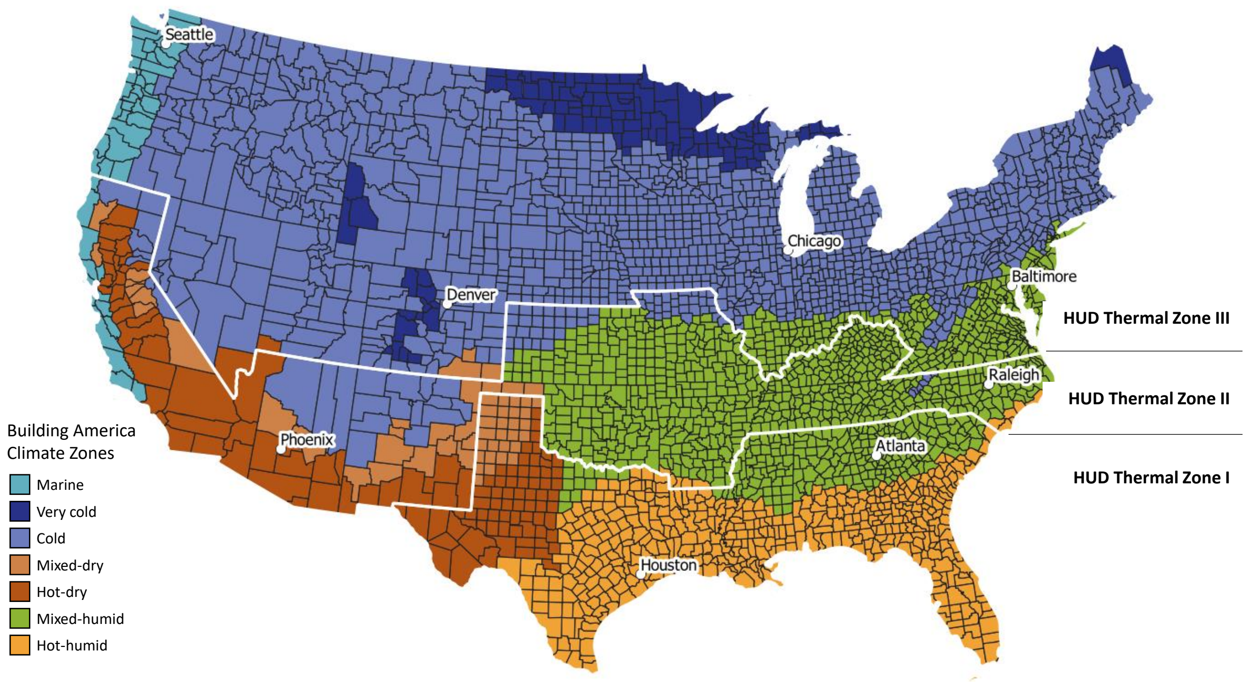


Table 4. Selected cities to represent HUD thermal zones and Building America climate zones.

Weather Region #	City	HUD Thermal Zone	BA Climate Zone	Estimated % of annual new manufactured-home shipments (floors)
1	Houston TX	I	Hot-humid	34%
2	Atlanta GA	I	Mixed-humid	11%
3	Raleigh NC	II	Mixed-humid	16%
4	Phoenix AZ	II	Hot-Dry	6%
5	Baltimore MD	III	Mixed-humid	5%
6	Chicago IL	III	Cold (humid summers)	15%
7	Denver CO	III	Cold (dry summers)	4%
8	Seattle WA	III	Marine	3%
			Total	**94%**

SIMULATION MODEL AND LIMITATIONS

The energy-modeling process began by entering the house into EnergyGauge® to run ACCA Manual J© and determine system loads and select a capacity for the system. Then the home was entered into BEopt. The BeOpt Energy Plus version 8.8 input deck was then run through Energy Plus 9.5, which generated annual output results. These results were written to files for comparison analysis. This process is shown in Figure 2.

Simulation procedures

1. **System Sizing Used for Modeling**

For each baseline model we determined Manual J8 loads using EnergyGauge®, an ACCA approved software. The software offers two options for sizing, using the ACCA 99 percent peak temperatures or using the TMY3 99 percent peak temperatures. For cooling these are often the same but for heating the TMY3 peak tend to be lower providing larger temperature difference. The TMY3 was chosen. Also, if there were two climatic data locations for the city in the software the one with the colder winter temperature was chosen. The software follows ACCA procedures, fixing the interior temperatures at 70^{o}F for heating and 75^{o}F for cooling. We decided to err on the size of larger capacities, consistent with observed practice. The results are shown in Table 5. In each case the heat pump size meets or nearly meets the heating load for most cities because of the cooling load. However, in Chicago, the heat pump size is purposely larger than the straight cooling system in order to better handle the heating requirement.

Figure 2. Simplified diagram of simulation process employed for this project.

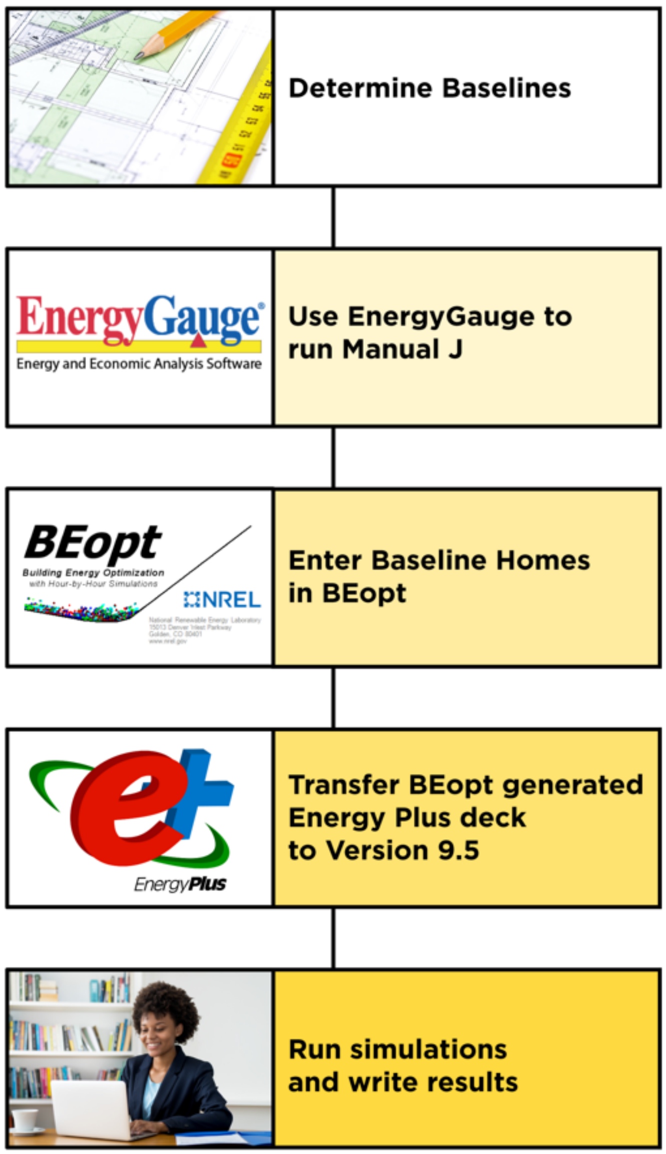


Table 5. Calculated heating and cooling loads and furnace, central air conditioner and heat pump sizes used for simulation, by home type, location, and equipment type.

Single-Wide - Duct in belly								
HUD Region	**City**	**Htg/Clg Design Temp ºF**	**Manual J Load** (kBtu per hour)		**Size used in simulations**			
			Heating	Cooling Total	Electric Furnace	Central AC	Heat pump Size	Gas Furnace
1	**Houston**	27/97	13.3	14.6	2 ton	1.5 ton	1.5 ton	NA
1	**Atlanta**	20/93	15.5	13.0	2 ton	1.5 ton	1.5 ton	NA
2	**Raleigh**	18/93	16.2	13.3	2 ton	1.5 ton	1.5 ton	2 ton
2	**Phoenix**	38/109	9.9	16.0	1.5 ton	2 ton	2 ton	1.5 ton
3	**Balti-more**	10/93	16.5	11.7	2 ton	1.5 ton	1.5 ton	2 ton
3	**Chicago**	-6/90	20.8	10.9	2.5 ton	1.5 ton	2 ton	2.5 ton
3	**Denver**	6/95	17.1	10.4	2 ton	1.5 ton	1.5 ton	2 ton
3	**Seattle**	25/82	12.4	7.8	2 ton	1.5 ton	1.5 ton	2 ton
Double-wide - Duct in belly								
HUD Region	**City**	**Htg/Clg Design Temp ºF**	**Manual J Load** (kBtu per hour)		**Size used in simulations**			
			Heating	Cooling Total	Electric Furnace	Central AC	Heat pump	Gas Furnace
1	**Houston**	27/97	19.1	20.3	2.5 ton	2 ton	2 ton	NA
1	**Atlanta**	20/93	22.1	17.7	2.5 ton	2 ton	2 ton	NA
2	**Raleigh**	18/93	23.0	18.3	2.5 ton	2 ton	2 ton	2.5 ton
2	**Phoenix**	38/109	14.2	21.9	2 ton	3 ton	3 ton	2 ton
3	**Balti-more**	10/93	24.0	16.5	2.5 ton	2 ton	2 ton	2.5 ton
3	**Chicago**	-6/90	30.2	15.2	3.0 ton	2 ton	2.5 ton	3.0 ton
3	**Denver**	6/95	24.6	14.4	2.5 ton	2 ton	2 ton	2.5 ton
3	**Seattle**	25/82	18.1	10.5	2 ton	1.5 ton	1.5 ton	2 ton

For consistency, we kept the system size the same for both the baselines and the innovation runs. Note that there were only mild envelope efficiency improvements incorporated in either the efficient baseline or the innovation with the exception of improved duct leakage. Units with ducts in attic used the same sizing except for double-wide homes with attic ducts in Houston. There we required a 2.5-ton cooling/HP system to avoid a high number of unmet hours.

2. Input file generation using BEopt

Using parameter values determined in the baselines, we generated baseline inputs using BEopt (Building Energy Optimization Tool). BEopt[3] developed by NREL provides capabilities to evaluate residential building designs and identify cost-optimal efficiency packages at various levels of whole-house energy savings along the path to zero net energy. The latest version is 2.8 and the program is currently not being updated. Considerable work went into BEopt as a front end for Energy Plus for residential buildings. The most important feature for us was to generate EnergyPlus input files from the baseline parameters described in Tables 3 and 4. A sample input diagram is provided in Appendix A.

3. Version update into 9.5

BEopt generates EnergyPlus input files with Version 8.8. The latest public release version of EnergyPlus is 9.5[4]. In order to use the latest features of EnergyPlus for the present project, we updated the EnergyPlus input file version from 8.8 to 9.5. IDFVersionUpdater.exe was used to update the input file version. The tool is provided in the EnergyPlus installation package.

4. Add output variables to meet project requirements

EnergyPlus has a number of output variables available for users to select. The output variables have to be defined in the input files. In order to meet the project analysis requirements, specific outputs were needed. They consisted of annual input energy[5] use for heating and cooling coils, and associated fan energy use, separated by cooling and heating. In addition, output energy for coils was also required. These required output variables were added to the EnergyPlus input files, so that each simulation would provide valuable outputs for analyzing simulation results further.

5. Perform simulations using group files

After adding the required outputs to the input files, multiple runs can be accomplished using group files. Since the present project requires a parametric study with multiple runs, several group files were created based on selected parameters, such as baselines, duct leakage

[3] https://www.nrel.gov/buildings/beopt.html
[4] https://energyplus.net/
[5] All references to energy use and savings represent site energy rather than source energy throughout the report

variations, highly efficient HVAC systems, etc. Then, groups of simulations were performed using the Group of Input Files from EP-Launch[6] feature.

EP-Launch is an optional component of the EnergyPlus Windows installation (it is not available for Linux and Mac platforms). For users that want a simple way of selecting files and running EnergyPlus, EP-Launch provides this and more. In addition, EP-Launch can help open a text editor for the input and output files, open a spreadsheet for the postprocessor results files, a web browser for the tabular results file, and start up a viewer for the selected drawing file.

6. Process outputs for data analysis

An Excel file using VBA was created to process all outputs. A sample is provided in Appendix A.

Model assumptions and limitations

There are some noteworthy assumptions and limitations associated with some aspects of the modeling, particularly the modeling of the belly area of manufactured homes and the nature of air leakage from ducts. The "belly" area of a manufactured home is the area below the floor but above the ground. This is the typical location of the ductwork for HVAC system, with the ducts located above a road barrier and layer of insulation (Figure 3). In theory, the space containing the main duct system is close to the temperature of the conditioned space and is isolated thermally from the outside in the same manner as the rest of the home.

However, in practice, the thermal dynamics of the belly area are far more complex—and often change over time. The road barrier and belly insulation can be compromised as early as during initial installation of the home and are commonly seriously degraded over time by vermin and access for plumbing repairs. Structural members and even the duct system itself compresses the belly insulation in areas and reduces its insulating value. Plumbing and other penetrations through the flooring create infiltration pathways between the living space and the belly area that affect both the temperature of the space in which the duct system resides, and dynamics related to what happens to leaks of heated or cooled supply air from the duct system.

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

[6] https://bigladdersoftware.com/epx/docs/8-3/getting-started/ep-launch-program.html

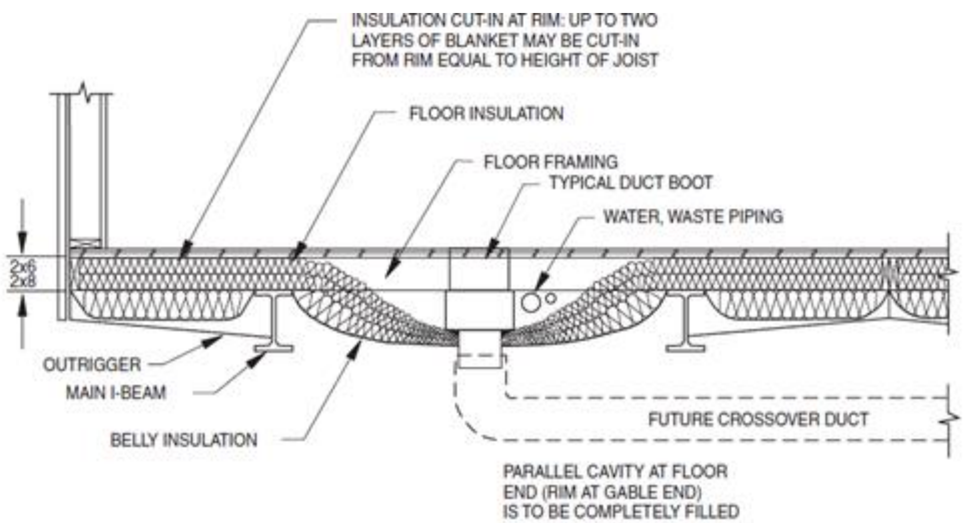
None of these important factors are well addressed with current modeling tools, though some work in the direction has been done in the past (e.g. Francisco and Palmiter, 2007), and the Project Team is aware of an effort currently being undertaken by LBNL to model indoor air quality in manufactured housing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

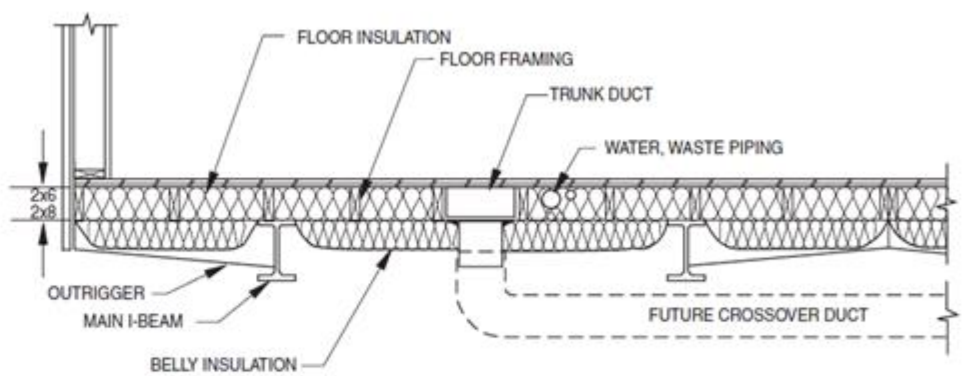
Developing better models of the belly area and duct-leakage dynamics is sorely needed for the manufactured-housing industry but was deemed beyond the scope of the first phase of this project. Here, we rely on a combination of simplifying assumptions and a probabilistic approach for some key assumptions:

- The main duct system is assumed to be "inside" and not subject to conductive losses.
- Belly insulation is modeled at nominal R-values without adjustment for compression or compromise.
- Duct leakage under actual operating conditions is assumed to be the same as that measured under a standard duct-pressurization test level of 25 Pascals.
- Due to issues related to the highly unbalanced nature of duct leaks in manufactured homes, the modeling for duct leakage uses a less-refined, mass-conservation approach for duct leakage instead of EnergyPlus's more-refined airflow-network model.
- For assessing potential innovations that rely on the average level of duct leakage to the outside for new homes, we consider the uncertainty range to be from 6 to 12 cfm per 100 ft^2 of floor area (these values are built into the efficient and original baselines, respectively).
- For assessing energy savings for innovations that seek to reduce the degradation of duct systems over time, we take an approach that defines scenario uncertainty ranges for incidence and magnitude of degradation in a population of homes, and then probabilistically combines these to produce ranges for savings from mitigating degradation.

Some of these assumptions and limitations could potentially be addressed in later phases of the project if warranted.

Figure 3. Belly sections showing insulation and routing of HVAC ducts, water, and waste pipes. Longitudinal section at top shows main duct trunk running the length of floor causing insulation compression. Transverse section at bottom shows floor framing where short trunk or branch ducts run with full insulation thickness.





BASELINE MODEL RESULTS

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

All equipment consisted of a centrally ducted air conditioner with one of three heating types: 1) electric resistance, 2) gas furnace, 3) electric heat pump. The vast majority of manufactured homes utilize split-refrigeration systems with separate indoor and outdoor components, but a significant number of packaged systems (evaporator and condenser co-located in a single outdoor unit) are prevalent in hot-humid climates along the gulf coast. Packaged systems thus require a portion of both supply and return ductwork located in the crawlspace to route air from the outdoor air handler to indoor duct systems. Table 6 shows which mechanical systems were modeled by HUD Climate Zone and which were excluded from analysis due to low incidence of use in those regions. A total of 28 simulations were required for each home type (single/double-wide) resulting in 56 total baseline runs.

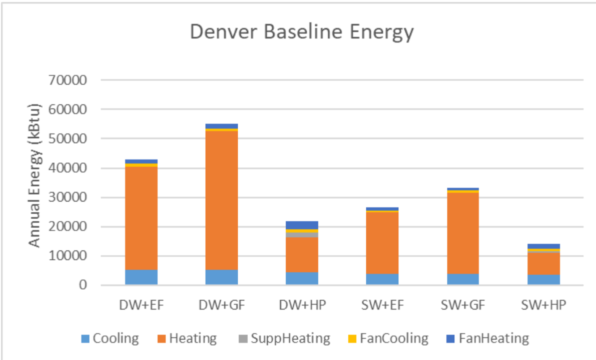
Table 6. Mechanical equipment modeled for each city

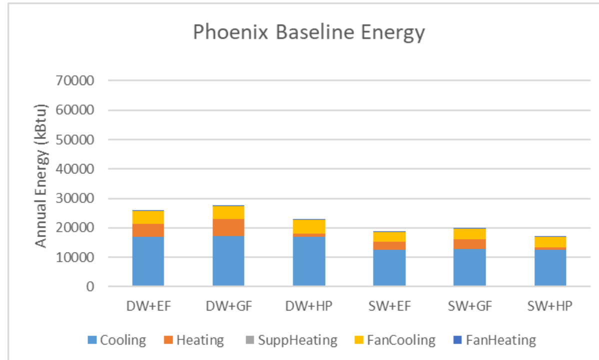
Mechanical Equipment	HUD Zone 1 (ATL, HOU)	HUD Zone 2 (RAL, PHX)	HUD Zone 3 (BAL, CHI, DEN, SEA)
Split-system AC + Elec.Resistance Heat	All cities	All cities	All cities
Split-system AC + Gas Furnace	Not modeled	All cities	All cities
Split-system Heat Pump	All cities	All cities	All cities
Packaged AC + resist. heat or heat pump	Houston only	Not modeled	Not modeled
Floor supply air (ducts in belly)	All cities	All cities	All cities
Ceiling supply air (ducts in attic)	All cities	Not modeled	Not modeled

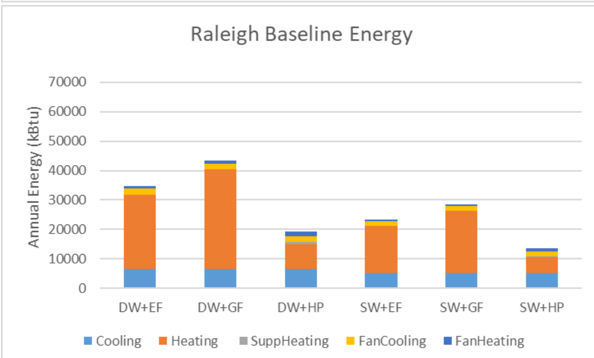
Modeling results from the original baseline (as defined in Table 2) are presented in Figure 4 for each city showing annual heating and cooling energy use. Energy units of kBtu allow side-by-side comparison of electric and gas fuel sources. Each bar represents mechanical system types for double-wide (DW) and single-wide (SW) models with colored segments showing proportions of heating, cooling, and fan energy use. Supplemental heating is also included for heat pumps representing second stage electric resistance heating. All ducts are below the floor in the belly space unless otherwise noted in each bar chart.

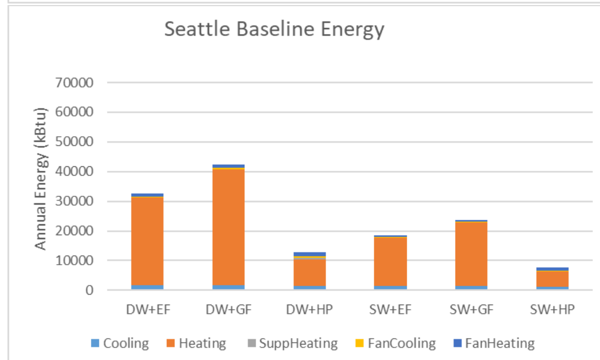
A considerable number of manufactured homes in the warmest climates are constructed with attic-mounted ducts which are represented here in Atlanta and Houston only. Models show the energy penalty for placing ducts in the vented attic versus the belly zone was 7 to 9 percent in both cities for AC+EF systems but significantly higher at 15 to 20 percent for heat pump systems. The simulation of outdoor-mounted packaged systems with both attic and crawlspace ducts was only modeled in Houston and showed a higher penalty of 11 to 18 percent over standard floor ducts.

Figure 4. Modeled HVAC energy use (original baseline) for single-wide (SW) and double-wide (DW) homes by location and mechanical system type (EF = electric furnace, GF= gas furnace, HP = heat pump) All ducts in belly unless otherwise noted. “Attic/Crawl” denotes a package system.









Comparison of original baseline annual energy use of heat pump systems in all cities for single and double-wide homes are presented in Figure 5 and Figure 6.

Figure 5. Original-baseline energy use of heat pump systems in eight cities for single-wide homes

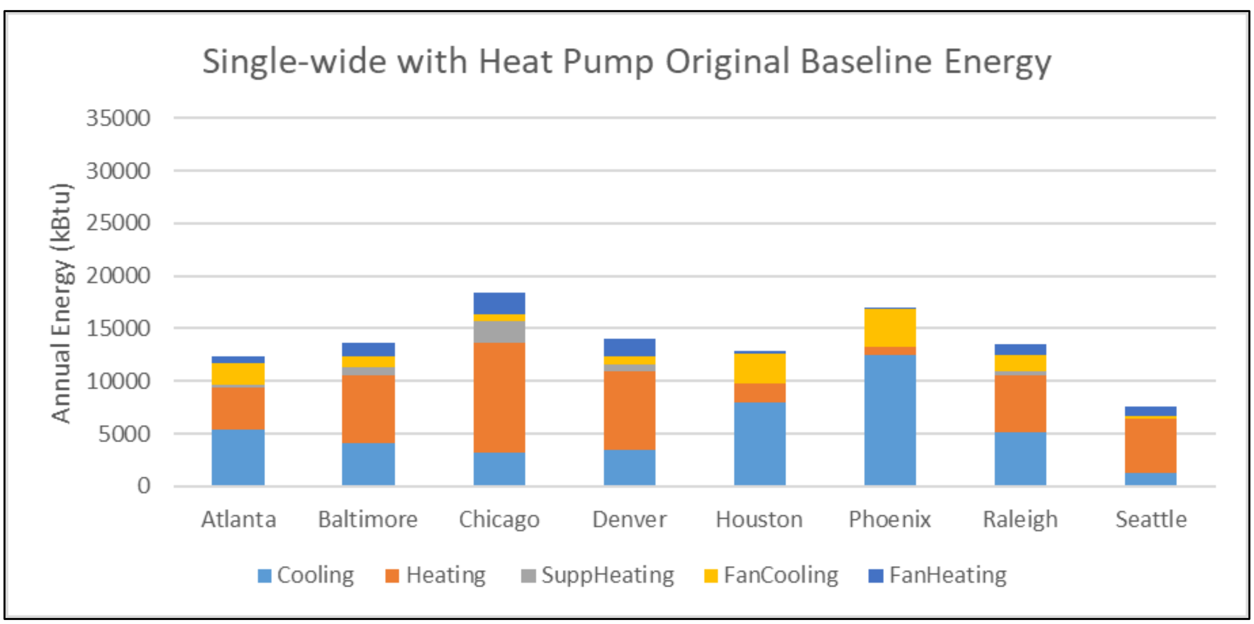
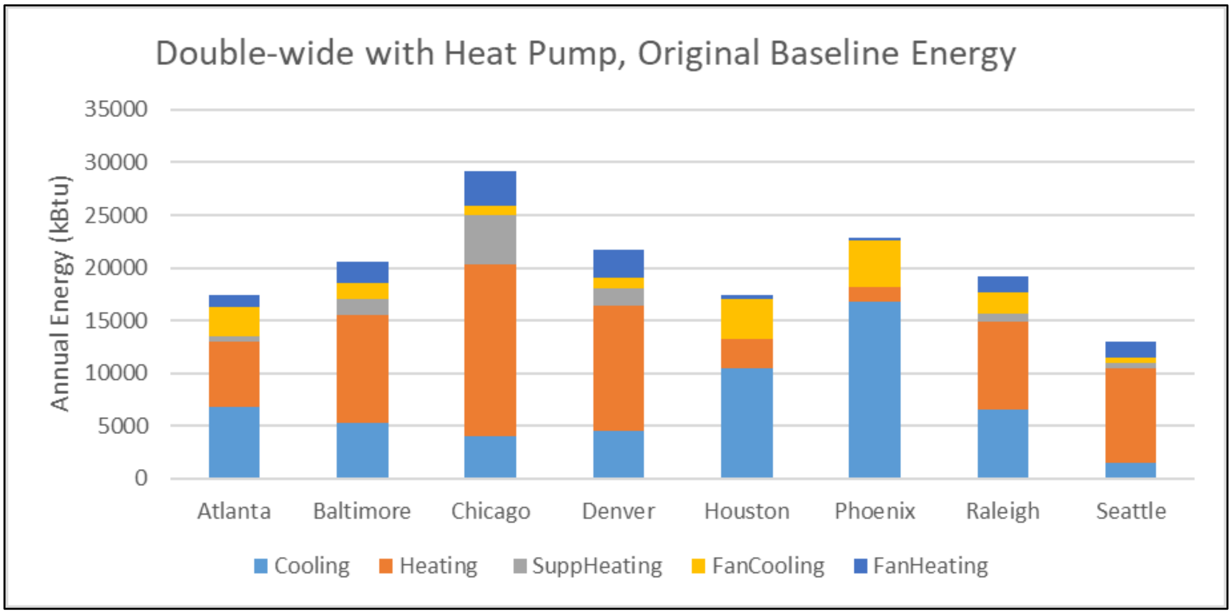


Figure 6. Original-baseline energy use of heat pump systems in eight cities for double-wide homes



Manufactured homes built with ducts in the attic are typically found in cooling dominated climates, thus these were only modeled in HUD Zone 1 (Atlanta and Houston). Figure 7 and Figure 8 provide a comparison of each of three mechanical system types with ducts in the belly versus the attic for single and double-wide homes in Atlanta and Houston.

Figure 7. Belly versus attic duct comparison of original-baseline energy use for three mechanical system types in single and double-wide homes in Atlanta.

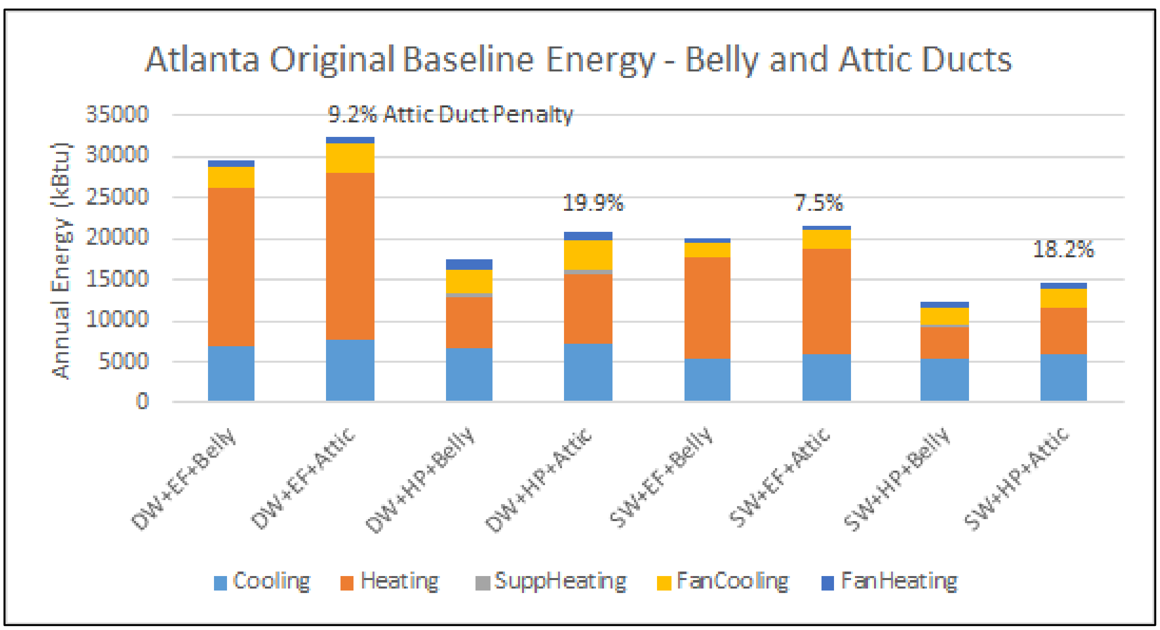
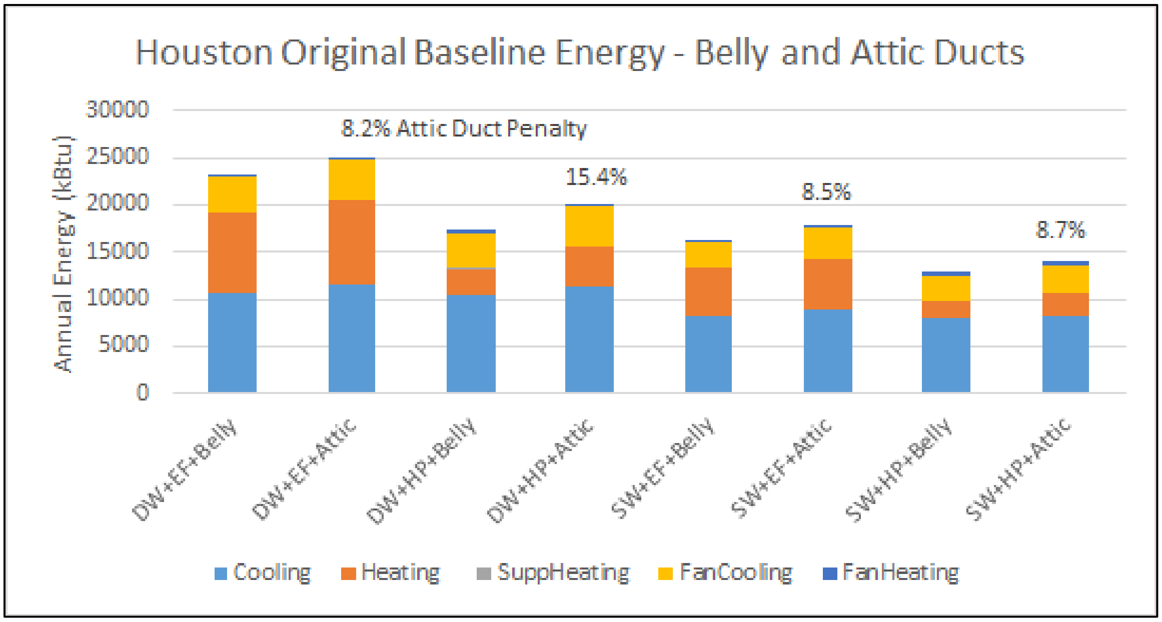


Figure 8. Belly versus attic duct comparison of original-baseline energy use for three mechanical system types in single and double-wide homes in Houston

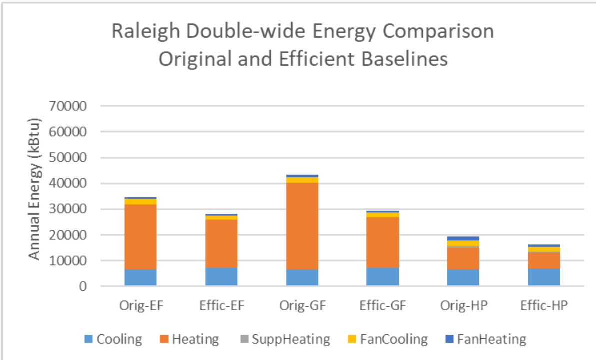


Full modeling results for the original baseline are included in Appendix B.

Modeling results from the efficient baseline (as defined in Table 4) represent a more efficient reference point for manufactured homes, such as those that meet ENERGY STAR specifications. Full modeling results for the efficient baseline are also included in Appendix B. An example comparison of the two baselines for double-wide homes is presented in Figure 9 for each city and mechanical-system type and summarized in Table 7.

The two baselines differ primarily in envelope construction with the efficient version having greater insulation levels throughout. The efficient baseline includes only one equipment improvement over the original, a 95 AFUE furnace in place of the minimum 80 AFUE furnace. Greater savings are most evident in colder, heating-dominated climates and especially where gas heating is utilized.

Figure 9. Comparison of baseline modeling results between the Original (“Orig”) and Efficient (“Effic”) baselines for double-wide homes, by city and mechanical system type (electric furnace, gas furnace, heat pump).



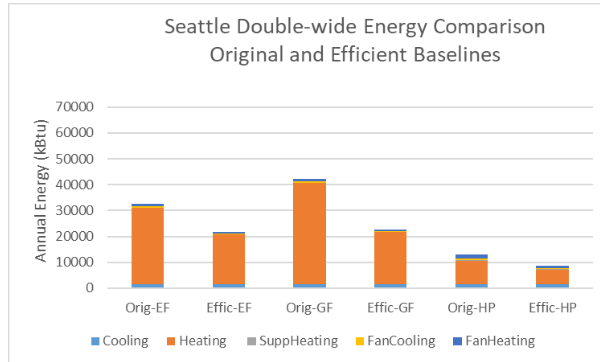


Table 7. Efficient-baseline total HVAC energy use compared to the original baseline, by city and mechanical-system type.

(Double-wide home with floor ducts)

City	Electric Furnace	Gas Furnace	Heat Pump
Atlanta	-19.0%	N/A	-16.8%
Baltimore	-19.0%	-34.9%	-20.1%
Chicago	-26.3%	-41.6%	-28.6%
Denver	-28.2%	-41.7%	-28.9%
Houston	-16.4%	N/A	-12.6%
Phoenix	-21.2%	-25.5%	-19.9%
Raleigh	-18.8%	-32.6%	-15.0%
Seattle	-33.2%	-46.2%	-33.0%

SAVINGS FOR HEAT PUMPS

Heat pumps provide a large opportunity for energy savings for residents of manufactured homes. There are several possible solutions for what is often a cost-effective option. One simple thing that manufactures can do is make the system *heat pump ready* by installing a heat pump equipped air handler in the factory instead of an electric resistance furnace. Since matched systems are rated, this may mean specifying the outdoor system to be installed. Other options include installing heat pump systems at the factory including multi-split options which have variable speed compressors. Cold climate heat pumps are designed to operate in heat pump mode at lower temperatures, reducing the amount of supplemental electric resistance heat. Sizing of heat pumps can also impact the amount of backup heat required although larger systems may consume more fan power and run in non-steady state more often. Variable speed systems overcome some of these issues. In this section we explore savings from standard heat pumps, two-speed high-efficiency units, and variable speed high-efficiency units. We then explore what sort of difference sizing variable speed units may have, how much some of the newer heat pump units designed for cold climates may save relative to standard units and similarly the savings of not having a compressor lock out set where a unit can still provide some efficient heating.

Baseline heat pump savings relative to electric resistance

Table 8 shows electric energy savings for a conventional (HSPF 8.2) heat pump over an electric furnace with standard central air conditioning under the original baseline models. Relative savings for space heating are large everywhere, but since space heating loads are small in Phoenix and Houston, overall savings there are small. Homes with ceiling ducts show somewhat reduced savings in this comparison.

Table 8. HVAC energy savings for a conventional heat pump over an electric-resistance furnace with standard central air conditioning in a double-wide home.

Electric Savings (Conventional Heat Pump vs Resistance Heat)		
City	**Floor Ducts**	**Ceiling Ducts**
Atlanta	41.3%	35.5%
Baltimore	48.2%	
Chicago	48.8%	
Denver	49.3%	
Houston	24.8%	19.8%
Phoenix	11.7%	
Raleigh	44.6%	
Seattle	60.2%	

Two-Stage and Variable Speed Heat Pump Systems

In addition, we modeled the energy savings over conventional systems for higher efficiency two-stage and variable-speed heat pumps (Table 9)

Table 9. Efficiency inputs for two-speed and variable-speed heat pumps.

	Number of speeds	SEER	HSPF
2 stage	2	19	9.5
Variable speed	4	22	10

Figure 10 illustrates the modeled energy HVAC energy use of various mechanical systems in Baltimore, including the three types of heat pumps and two levels of gas-furnace efficiency. The two-stage heat pump saves 15 percent of the energy used by the standard heat pump and the variable speed heat pump saves 28 percent relative to the standard heat pump. For the sake of comparison, we also modeled a 90 percent efficient gas furnace: it shows about 15 percent less energy compared to the standard 80 percent AFUE furnace.[7]

[7] The BEOpt model reduces the infiltration rate when the furnace efficiency improves, likely due to reduced combustion exhaust gas, this reduction in energy use is a little larger than just the AFUE ratio.

Figure 10. Annual HVAC energy use for single-wide (SW) and double-wide (DW) homes for three types of heat pump (base, two-stage, and variable-speed) and two levels of gas-furnace efficiency (AFUE80 and AFUE90), for Baltimore with the original baseline.

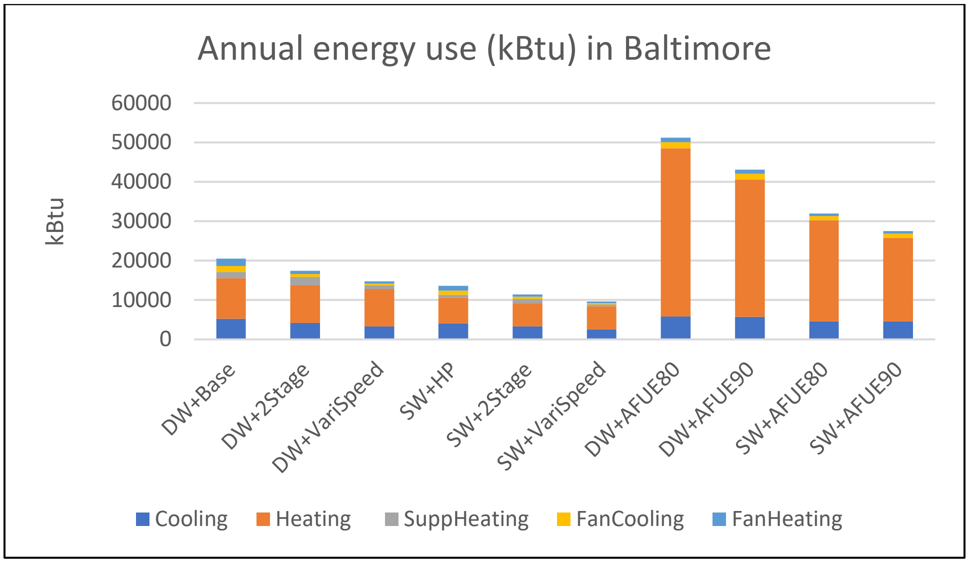


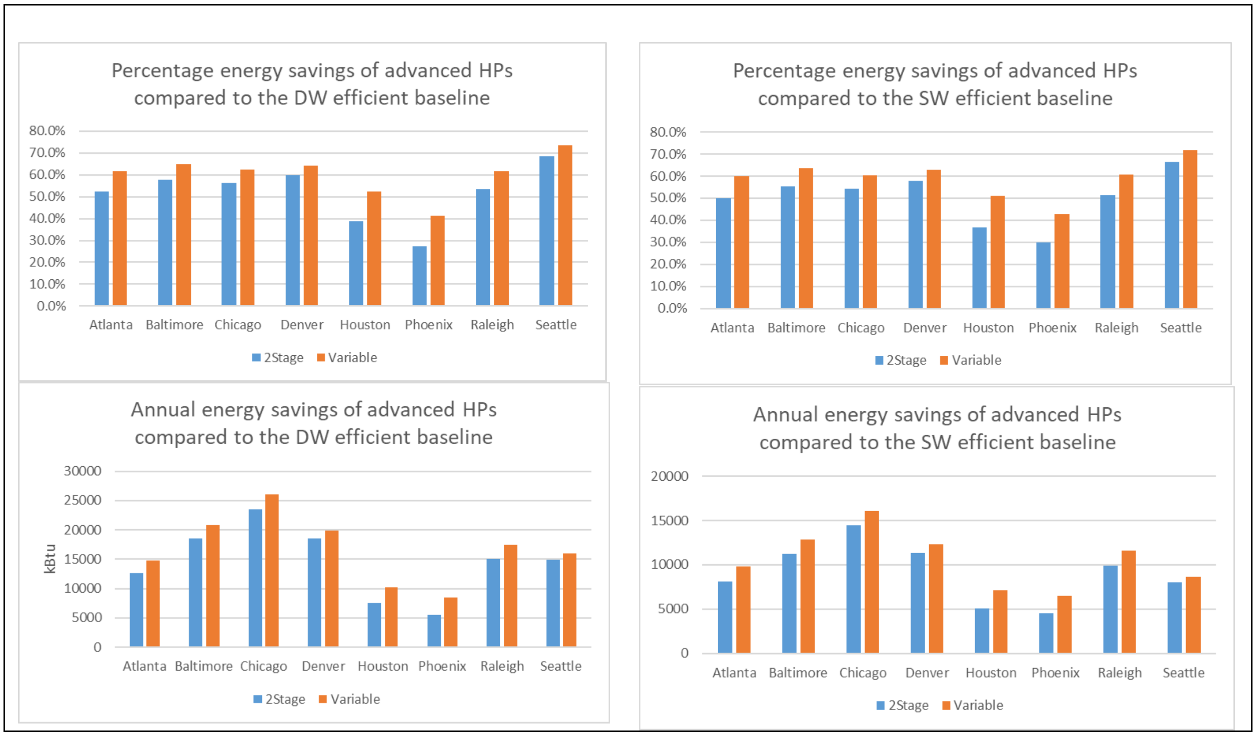
Figure 11 shows the annual energy savings for the improved heat pump systems relative to an electric furnace with conventional central air conditioning in each climate. Savings are largest in heating-dominated climates (where heat pumps are relatively rare) and generally above 50 percent in both double-wide and single-wide units.

Savings compared to the efficient baseline are presented in

Figure 12 with the same advanced heat pump systems relative to an electric furnace with conventional central air conditioning. The efficient baseline represents Energy Star packages prevalent by region, along with reduced duct leakage and regional thermostat setpoints. This results in a smaller amount of absolute savings than the original baseline but a similar amount of percentage savings.

Figure 11. Two-stage and variable speed heat pump savings relative to an electric furnace with conventional central A/C under the original baseline assumptions.

Figure 12. Two-stage and variable speed heat pump savings relative to an electric furnace with conventional central A/C under the efficient baseline assumptions.



Air Source Integrated Heat Pump (ASIHP)

One of the considered innovations in the study is to employ an integrated heat-pump that serves space conditioning and domestic hot water loads, as well as providing energy-recovery ventilation. EnergyPlus Version 9.5 has an ASIHP model, developed by ORNL[8]. The model was determined to have some bugs[9] and although the bugs have been fixed by authors, the fix is not available in the public release 9.5 version. The ORNL ASIHP model may be included in future simulation work under this project.

As a fallback, we approximated the savings from an ASIHP as the sum of separately calculated HVAC savings for the variable-speed heat-pump model discussed above, plus typical savings from a heat pump water heater, as shown in

[8] Bo Shen*, Joshua New, Van Baxter, Air source integrated heat pump simulation model for EnergyPlus, Energy and Buildings 156 (2017) 197-206

[9] Communication with Bo Shen at ORNL on 10/14/21, by Lixing Gu.

Table 10.

Table 10. Estimated energy savings for an air-source integrated heat pump as the sum of savings for a variable-speed heat pump (ASHP) plus the savings for a heat pump water heater (HPWH), by home type and city.

	Single-Wide (kBtu/yr)			**Double-Wide** (kBtu/yr)		
City	ASHP	HPWH	Total	ASHP	HPWH	Total
Atlanta	12,100	5,550	17,600	18,200	5,550	23,700
Houston	8,400	4,700	13,100	12,300	4,700	16,950
Raleigh	14,200	5,850	20,050	21,550	5,850	27,400
Phoenix	7,800	3,900	11,700	10,650	3,900	14,500
Baltimore	15,700	6,300	22,000	24,850	6,300	31,150
Chicago	21,050	7,000	28,050	34,200	7,000	41,200
Denver	16,200	6,800	23,000	26,700	6,800	33,500
Seattle	13,400	6,600	19,950	23,150	6,600	29,700

Reference case is electric furnace with central A/C and electric water heater, using original-baseline assumptions.

SAVINGS FOR DUCT-LEAKAGE REDUCTION AND DUCT-SYSTEM IMPROVEMENTS

Reductions in duct leakage have the potential for non-trivial savings in new manufactured homes, and there are several possible solutions. These include manufacturing ductless homes that use room conditioning, mini-splits, or radiant heating. Potential solutions also include better construction and duct leakage testing during manufacturing at the factory. See Table 1 for a brief description of duct leakage reduction innovations.

Duct leakage is typically measured by pressurizing the duct system to 25 Pascals and measuring total leakage and leakage to the exterior of the home. We focus on the latter leakage rate here, normalized by the conditioned floor area of the home (Qn). Our original baseline assumes that the average new manufactured home has leakage to the outdoors of 12 cfm per 100 ft^2 of floor area, or Qn=12 percent (the efficient baseline assumes a Qn of 6 percent). In this section we explore the energy-savings potential by modeling the limits of duct leakage from the baseline assumption of 12 percent down to zero duct leakage, as well as from insulating cross-over ducts to R16.

Duct Leakage Savings

Figure 13 (kBtus) and Figure 14 (percent) show modeled savings for different levels of duct leakage for double-wide homes under the original baseline. Note that the relative savings between heating dominated climates and cooling dominated climates appear larger in kBtus. This is because we are showing the electric resistance furnace runs for heating whereas the cooling efficiency is much greater and thus kBtus savings in those cities dominated by cooling are smaller.

Figure 13. Energy savings (kBtu/yr) associated with 50%, 75% and 100% reduction in duct leakage for a double-wide home with an electric furnace and central A/C, by city.

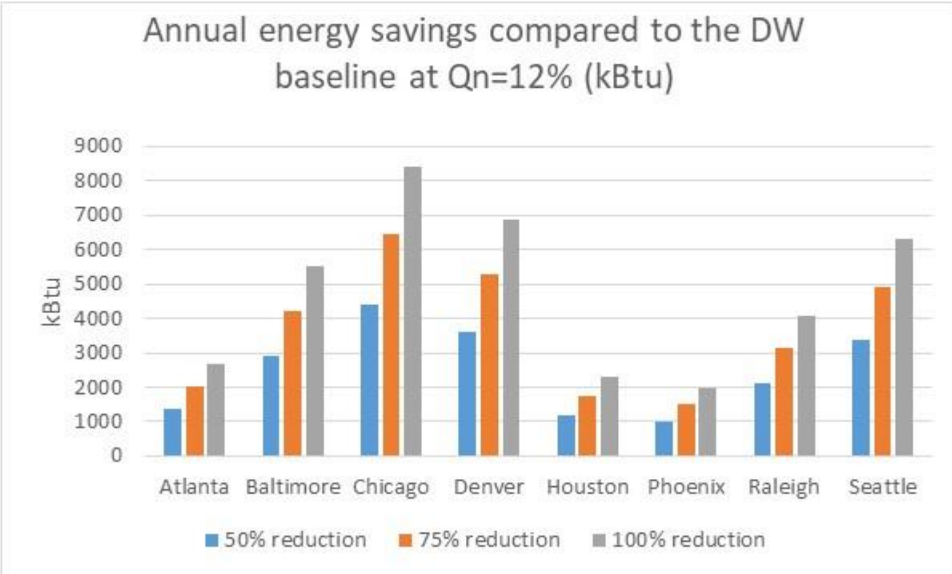
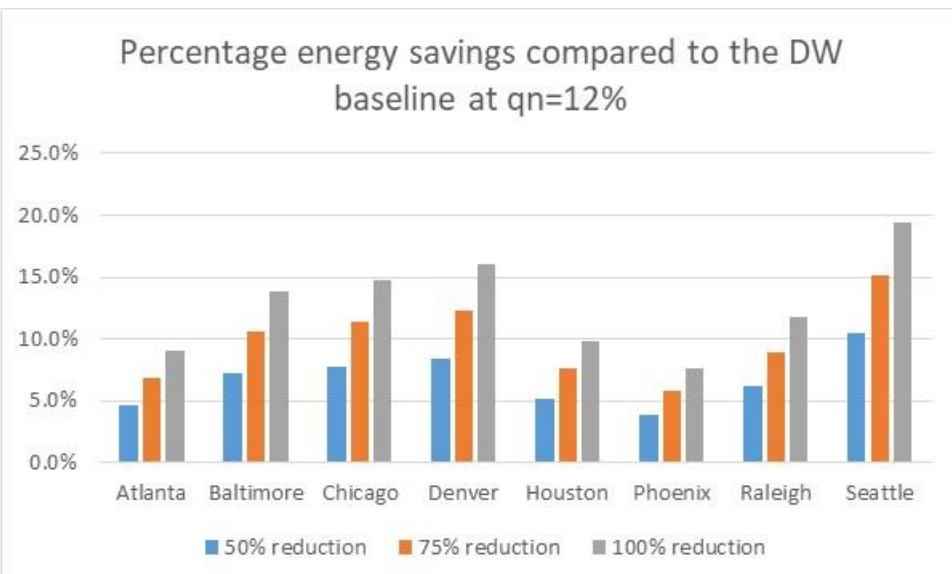
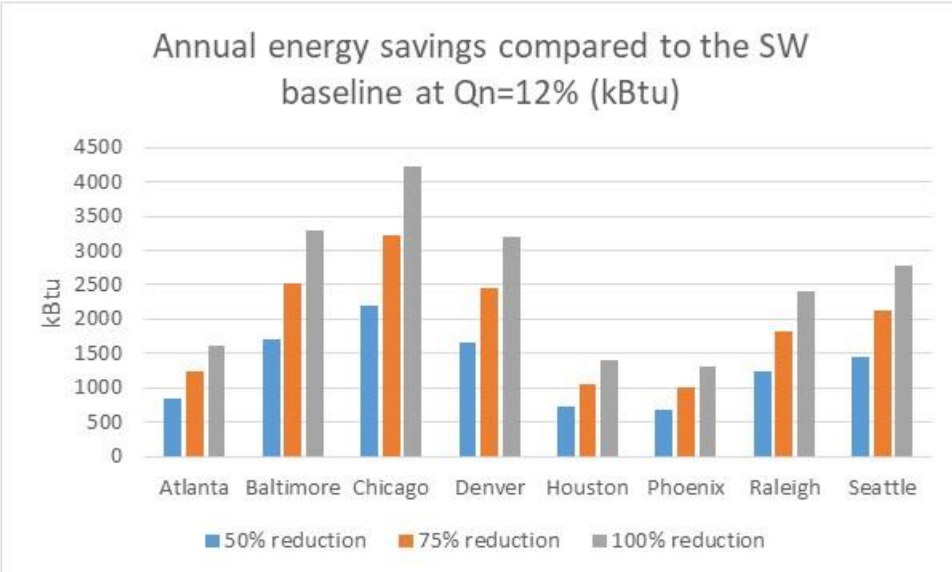


Figure 14. Energy savings (percent) associated with 50%, 75% and 100% reduction in duct leakage for a double-wide home with an electric furnace and central A/C, by city.



Similarly, Figure 18 shows kBtu/year duct-leakage-reduction savings for a single-wide home in each location. Since there is no crossover duct connection, leakage should be less in single-wide units if factory duct installation is done well. Percentage savings remain similar to double-wide construction.

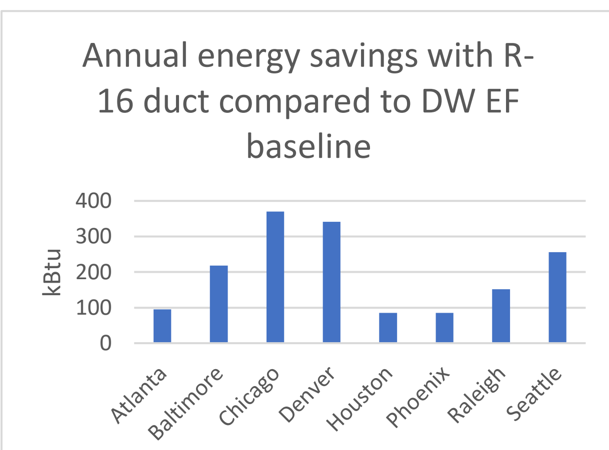
Figure 15. Energy savings (percent) associated with 50%, 75% and 100% reduction in duct leakage for a double-wide home with an electric furnace and central A/C, by city.

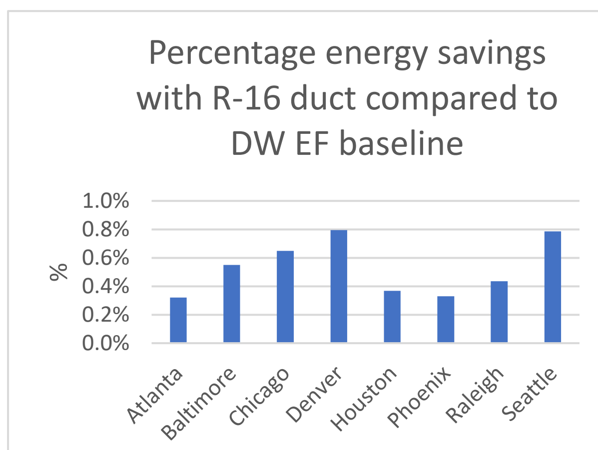


R-16 Duct Insulation

Improved crossovers for double-wide homes can also involve upgraded duct insulation. The baseline home assumes that the crossover is insulated to R-8. We modeled the impact of upgraded R-16 insulation for the crossover (Figure 16). (Due to limited duct area outside the conditioned space, this improvement has limited savings.)

Figure 16. Annual energy savings for upgraded R-16 (vs. R-8 baseline) cross-over insulation for a double-wide home with electric furnace.





Advanced controls and distribution for ductless heat pumps

Controls to better integrate ductless heat pumps with central forced-air systems could help offset at least part of the load imposed on these systems with an efficient ductless system. We estimated the potential savings by combining the variable-speed heat pump model (which has similar performance characteristics to a ductless system) and adding savings from reduced duct losses to account for the reduced duct losses associated with the central forced-air systems. Since the degree to which a ductless system would offset the central system can be flexible, we considered two levels offset: 25 and 50 percent. The estimates for energy savings relative to an electric furnace with conventional central air conditioning are shown in Table 11.

Table 11. Estimated energy savings for ductless heat pump offset of central space-conditioning system, by level of assumed offset, home type and city.

	Single-Wide (kBtu/yr)		**Double-Wide** (kBtu/yr)	
City	25% offset	50% offset	25% offset	50% offset
Atlanta	3,450	6,950	5,250	10,550
Houston	2,500	5,000	3,750	7,450
Raleigh	4,200	8,400	6,450	12,950
Phoenix	2,350	4,650	3,250	6,450
Baltimore	4,800	9,550	7,650	15,300
Chicago	6,350	12,700	10,700	21,400
Denver	4,850	9,750	8,450	16,850
Seattle	4,050	8,100	7,400	14,800

Reference case: electric furnace with central A/C under original-baseline assumptions.

SAVINGS FOR SMART VENTILATION WITH HEAT PUMP WATER HEATER

Heat pump water heaters are considerably more efficient than electric resistance units. A unit located in a manufactured home in northern climates would typically be ducted so that the cold-air exhaust from the heat pump water heater is exhausted outside. Through a smart controller that air could be used to reduce the runtime of the standard bath exhaust fan. In southern climates, the cold air is desired much of the year and may warrant a two-way system to vent from outside to inside during the cooling season and exhausting inside air to outside during the heating season. Even in southern areas, the heat pump water heater's impact in a typical house is small relative to the overall cooling energy use. In a Florida lab study (Colon, et. al. 2016) a system ducted from the interior back to the interior reduced air conditioning load by about 4 percent. Researchers also showed the change in load from outside air by bringing it in through the heat pump water heater, although they did not have a control case of venting the house without the heat pump water heater.

We did not model a smart vent system with a heat pump water heater in Energy Plus; however, we approximated the impact by assigning 4 percent cooling savings in cooling dominated climates (Houston, Atlanta, and Phoenix) to which we added estimated domestic hot water savings from the heat pump water heater. For the latter, we assumed a seasonal energy factor of 2.5 for a heat pump water heater, which yields about 60 percent domestic hot water energy savings relative to the Energy Plus-estimated consumption of a conventional electric water heater. Table 12 shows annual savings of a heat pump water heater over a standard 40-gallon, electric resistance water heater and associated cooling savings in warm climates at an estimated 4 percent of total cooling per the Florida lab study. Savings are with respect to the original baseline for single and double-wide manufactured homes with minimum efficiency air conditioner and floor ducts. The bulk of savings are attributable to the switch to the heat pump water heater. The results vary by city due to differences in incoming water temperature.

Table 12. Heat pump water heater with smart ventilation control energy savings over 40-gallon, electric resistance water heater.

	Double-wide Savings (kBtu/yr)			Single-wide Savings (kBtu/yr)		
City	**HPWH**	**Cooling**	**Total**	**HPWH**	**Cooling**	**Total**
Houston	4,678	570	5,248	4,678	434	5,111
Atlanta	5,536	387	5,923	5,530	298	5,828
Raleigh	5,841	0	5,841	5,835	0	5,835
Phoenix	3,884	858	4,743	3,884	646	4,531
Baltimore	6,305	0	6,305	6,300	0	6,300
Chicago	7,011	0	7,011	7,005	0	7,005
Denver	6,811	0	6,811	6,805	0	6,805
Seattle	6,582	0	6,582	6,576	0	6,576

COMPARISON OF MODELED IMPROVEMENT SAVINGS

Table 13 indicates the savings for key measures under the original baseline for a double-wide home with an electric furnace and conventional central air conditioner, and Table 14 provides the same information under the assumptions for the efficient baseline. Percentage savings values are relatively unaffected by the choice of baseline, but kBtu savings are about 15 to 30 percent lower under the efficient baseline for the two heat pump measures and 5 to 60 percent lower for the duct-leakage reduction measure.

Table 13. Modeled energy savings for a double-wide home with an electric furnace and SEER 14 central air conditioner using the original-baseline assumptions.

	Conventional Heat Pump		**Variable-Speed Heat Pump**		**75% Reduction in Duct Leakage**	
City	kBtu/yr	%	kBtu/yr	%	kBtu/yr	%
Houston	5,800	25%	12,300	53%	1,760	8%
Atlanta	12,200	41%	18,200	61%	2,030	7%
Raleigh	15,500	45%	21,500	62%	3,120	9%
Phoenix	3,000	12%	10,600	41%	1,490	6%
Baltimore	19,100	48%	24,900	63%	4,230	11%
Chicago	27,700	49%	34,200	60%	6,440	11%
Denver	21,200	49%	26,700	62%	5,300	12%
Seattle	19,600	60%	23,100	71%	4,920	15%

Table 14. Modeled energy savings for a double-wide home with an electric furnace and SEER 14 central air conditioner using the efficient-baseline assumptions.

	Conventional Heat Pump		**Variable-Speed Heat Pump**		**75% Reduction in Duct Leakage**	
City	kBtu/yr	%	kBtu/yr	%	kBtu/yr	%
Houston	4,100	21%	10,200	52%	1,600	8%
Atlanta	9,500	40%	14,800	62%	1,900	8%
Raleigh	11,800	42%	17,400	62%	2,300	8%
Phoenix	2,100	10%	8,400	41%	900	5%
Baltimore	15,700	49%	20,800	65%	2,800	9%
Chicago	21,100	50%	26,100	62%	2,800	7%
Denver	15,400	50%	19,800	64%	2,300	7%
Seattle	13,100	60%	16,000	74%	2,600	12%

COST SAVINGS AND COST EFFECTIVENESS

In this section we translate the above energy-modeling results into estimates of annual energy costs and cost savings for the innovations using regional fuel prices and estimates of heating-fuel and equipment-type proportions for new manufactured-home shipments. We also apply life-cycle costing calculations to examine the present value of lifetime energy-cost savings and assess the potential cost effectiveness of proposed HVAC innovations. This section also rolls up results from the eight modeled locations into regional and national estimates of baseline energy costs, energy-cost savings for potential innovations and cost-effectiveness.

METHODS AND ASSUMPTIONS

Assessing the energy-cost savings life-cycle cost-effectiveness of potential innovations requires knowledge of fuel prices and assumptions about factors such as equipment life and discount rates. In addition, developing overall estimates of savings and cost effectiveness at the regional or national level requires data on—or assumptions about—the proportion of new manufactured homes with, for example, different heating-system fuels and types. Here we discuss the methods and assumptions used to translate the energy-modeling results into estimates of energy costs, energy-cost savings and cost effectiveness.

Regions and weighting factors

As discussed above, the team chose eight cities for the energy modeling, representing the three HUD thermal zones as well as differences in Building America climate zones within these. Here, we further intersect these with the six Study Regions for the purposes of developing regional fuel prices (described below) and regional weighting factors.

Figure 17 shows the study regions, climate zones and modeling cities, and Table 15 provides the regional and home-type weighting factors that we used. The weights are scaled to total 100,000 annual shipments of new manufactured homes, which is close to current industry production levels. Note that the Baltimore and Houston modeling results do double duty here, representing the mixed-humid and cold climates respectively for Study Regions 4 and 5. Also, the Phoenix modeling results are used for all of Region 3, though Region 3 actually comprises a diverse range of climate zones.[10] This tends to exaggerate the hot-dry portion of the region, though on a national basis, the entire region represents only 7.5 percent of shipments.

In addition to regional weights, we also developed weighting factors for HVAC system type and fuel, along with (for Region 1) duct location. Heating fuel allocations were derived from Census data; the others are our own estimates based on conversations with industry

[10] By our estimates, new-home shipments to Region 3 by climate zone are: 68% Hot-Dry, 11% Mixed-Dry, 10% Marine and 11 percent Cold.

stakeholders. Appendix C provides a complete listing of the weighting factors used in the analysis.

Figure 17. Study regions, Building America climate zones, and selected energy-modeling locations used in the study.

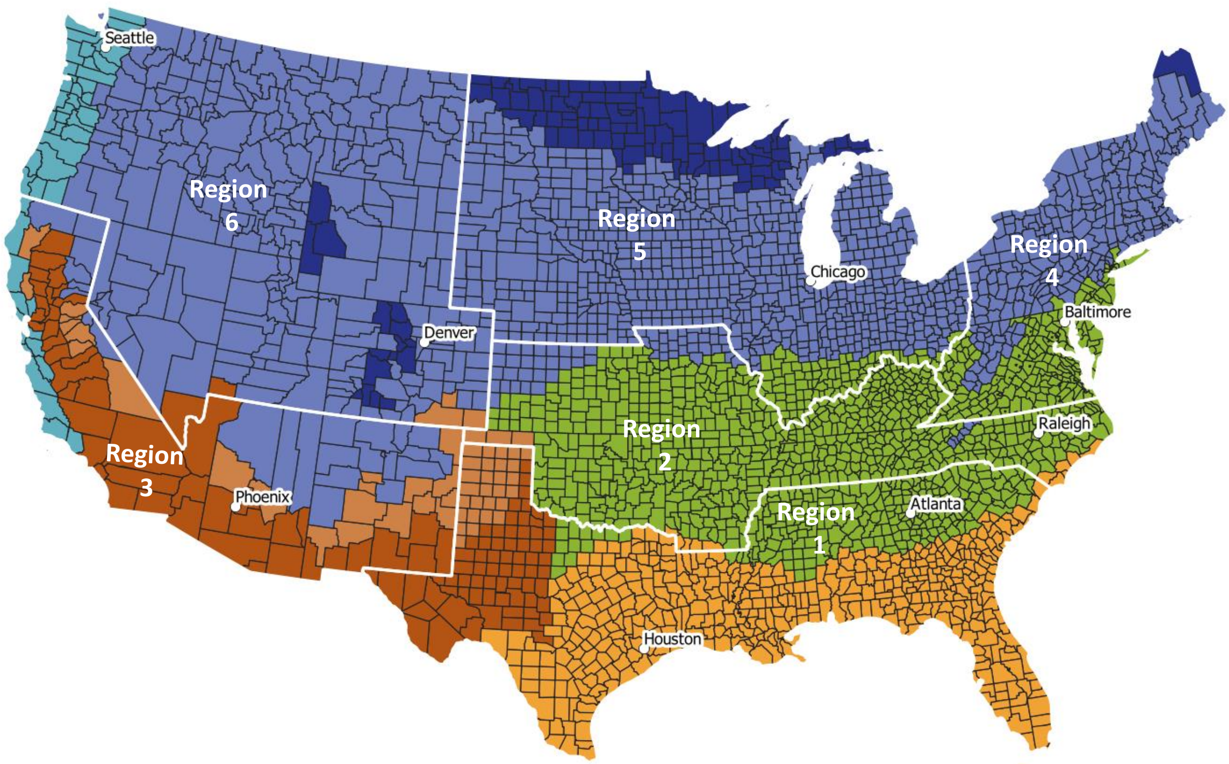


Table 15. Analysis weighting factors, by study region, Building America climate zone and home type.

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

Fuel-prices

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

For electricity and natural gas, we estimated two price components: the variable (per-kWh or per-therm) portion and the fixed (per-month) portion of utility charges. We did this by using published state (for electricity) or regional (for natural gas) estimates of monthly residential fixed charges, then calculating the state-level average variable fuel price by subtracting estimated aggregate annual fixed charges from EIA total residential revenues and dividing the result by EIA total annual kWh or therm sales.[11] On average, this resulted in state per-kWh electricity prices that were about 10 percent less than EIA's published electricity prices, which combine fixed and variable charges into a single per-kWh price. For natural gas, our state per-therm prices averaged about 20 percent less than the EIA values. Table 16 shows the regional fuel prices used in the analysis.

Table 16. Regional fuel prices.

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

Life-Cycle Costing Inputs

We adopted key life-cycle costing assumptions from the current DOE rulemaking related to manufactured-home efficiency standards (DOE 2021), which splits home buyers into three categories depending on their financing option (Table 17). We escalated fuel prices using the latest supplement to NIST Handbook 135 (Lavappa and Kneifel 2021), using listed regional fuel-

[11] Our estimates of state-level fixed charges for electricity came from a public database of electric utility rates, which we combined with EIA data on utility sales to estimate state-average fixed charges (*Electric Utility* Rates. (n.d.). Utility Rate Database. Retrieved November 4, 2021, from https://openei.org/wiki/Utility_Rate_Database. For natural gas we used regional values published in a 2015 American Gas Association study of customer charges (AGA 2015, applying the regional value to each state in the region.

price indices that include an assumed 2 percent inflation. All results presented here are based on a 25-year lifetime.

Table 17. Life-cycle costing factors used in the current DOE rulemaking (DOE 2021) and adopted here.

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

Break-Even Incremental Cost

From a life-cycle energy-savings perspective, a particular innovation can be deemed cost-effective if the discounted present value of its costs—mainly the up-front incremental cost but also any associated ongoing costs—is less than the discounted present value of lifetime energy savings. However, because we do not yet have solid estimates of the incremental cost for some innovations (primarily those related to duct-system improvements), we turn the analysis around and rely on the calculated *break-even incremental cost*. As the name implies, this is the up-front incremental cost that yields a net present value of zero when combined with the discounted life-cycle value of energy savings and additional on-going costs, such as increased property taxes. At the break-even incremental cost, a buyer should be financially indifferent about whether to choose an innovation over the baseline option. If the actual incremental cost is less than the break-even value, it is financially advantageous to choose the innovation over conventional practice. On the other hand, if the actual incremental cost is greater than the break-even value, it is better to stick with standard practice.

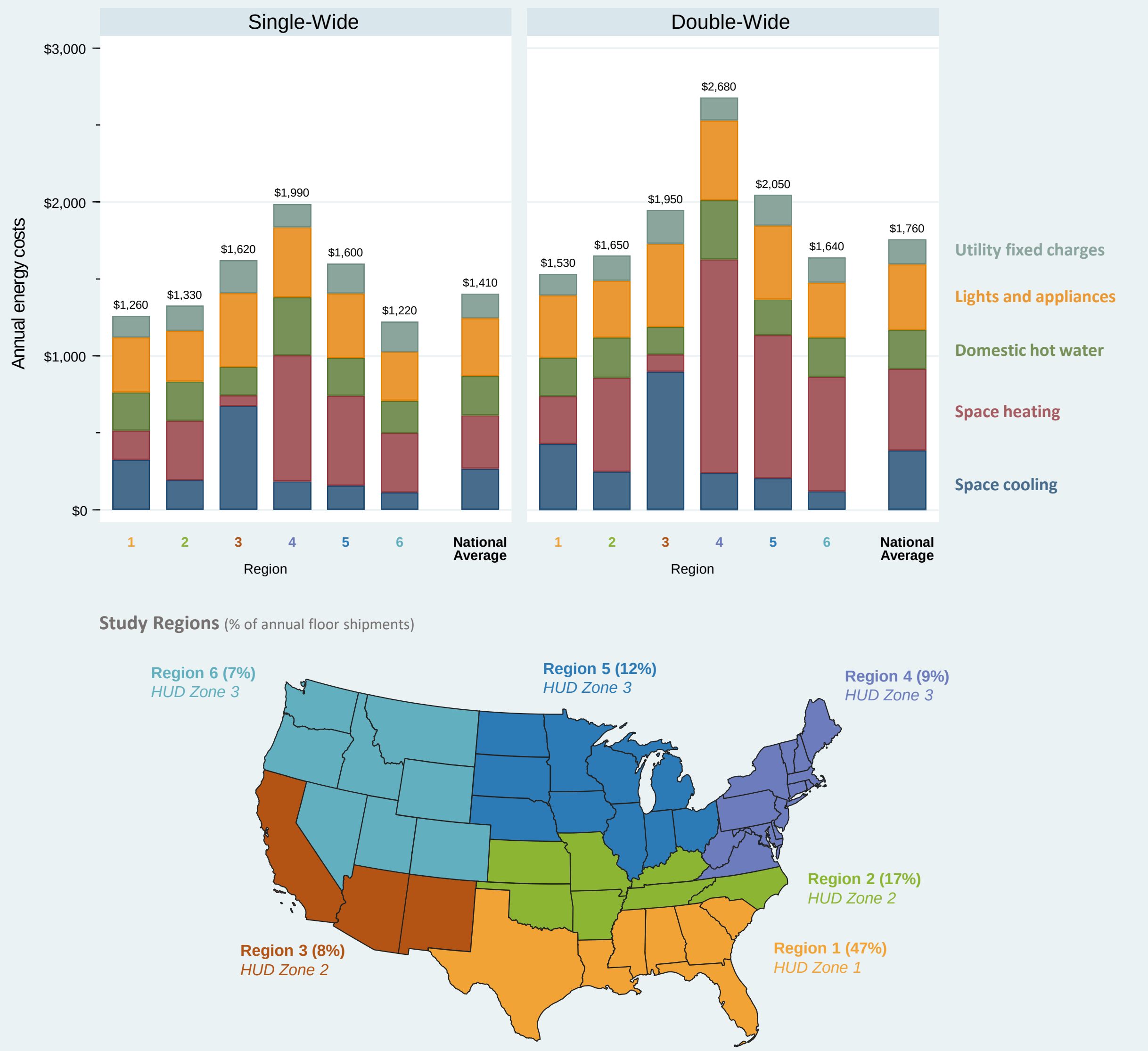
BASELINE ENERGY COSTS

To set the stage for cost savings associated with various HVAC innovations, it is helpful to first look at estimates of annual energy costs among new manufactured homes. Combining the energy-modeling results with regional heating-fuel proportions and fuel prices yields estimated annual energy costs that average $1,410 for a typical single-wide home and $1,760 for a double-wide nationally (Figure 18). Climate, heating-fuel proportions, fuel prices and the number of double- versus single-wide homes all factor into regional energy costs. Region 4 stands out as having notably higher costs, due to nearly half of new manufactured homes in that region being heated with propane or fuel oil, which are relatively expensive fuels.

Nationally, heating and cooling energy costs make up roughly half of total energy costs, for an average of about $775 per year. Regionally, these costs range from $630 in Region 1 to $1,340 in Region 4. Estimated heating and cooling costs vary significantly by system type and location

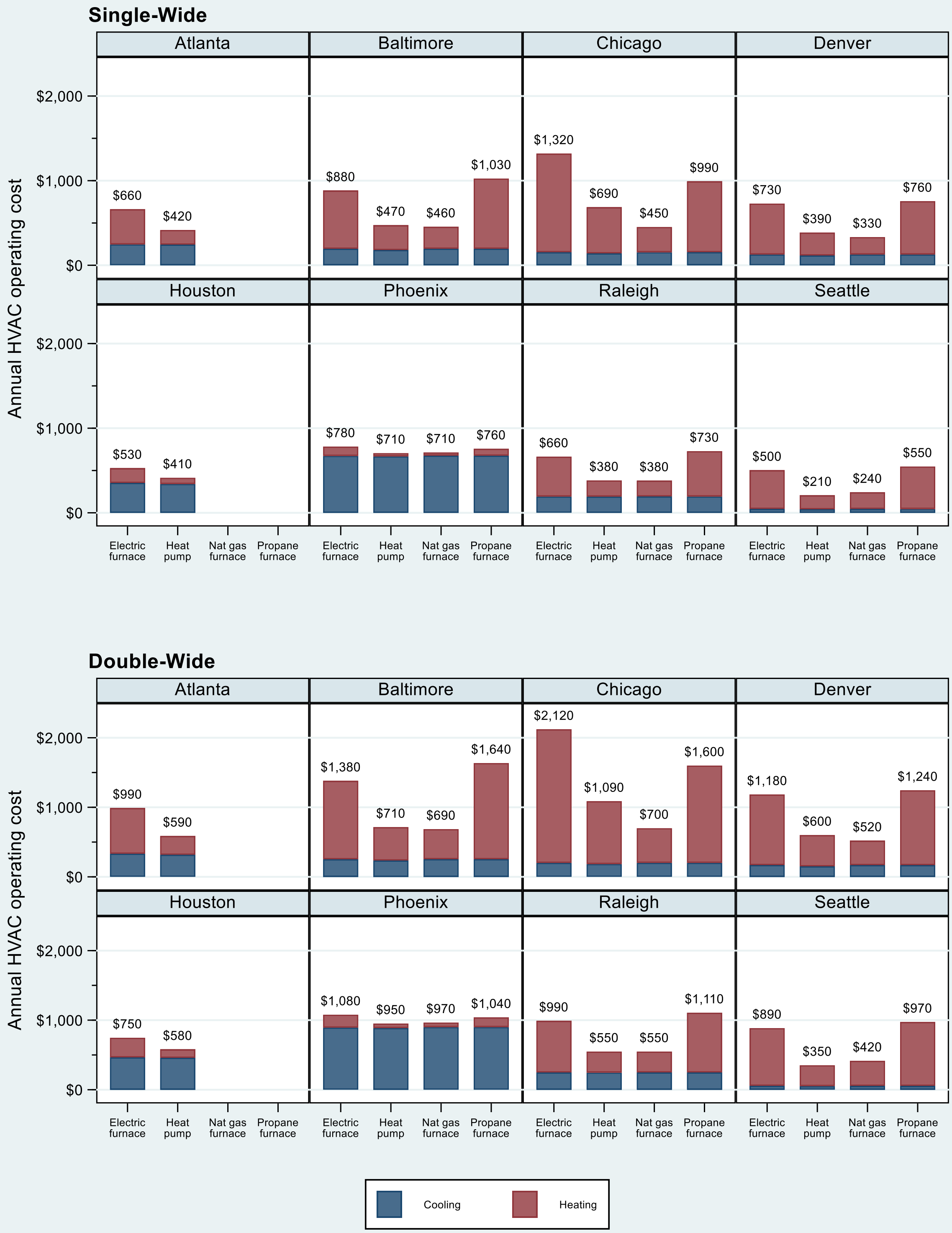
(Figure 19). Costs are highest for homes in cold climates with electric or propane furnaces, and lowest for homes in mild climates with heat pumps, as well as in most regions where natural gas is the heating fuel. Note however, that systems with high operating costs, such as electric furnaces in the North, tend to be rare in the population.

Figure 18. Estimated annual energy costs by type of home and region.



Based on modeled energy consumption, regional heating-fuel proportions and regional fuel prices

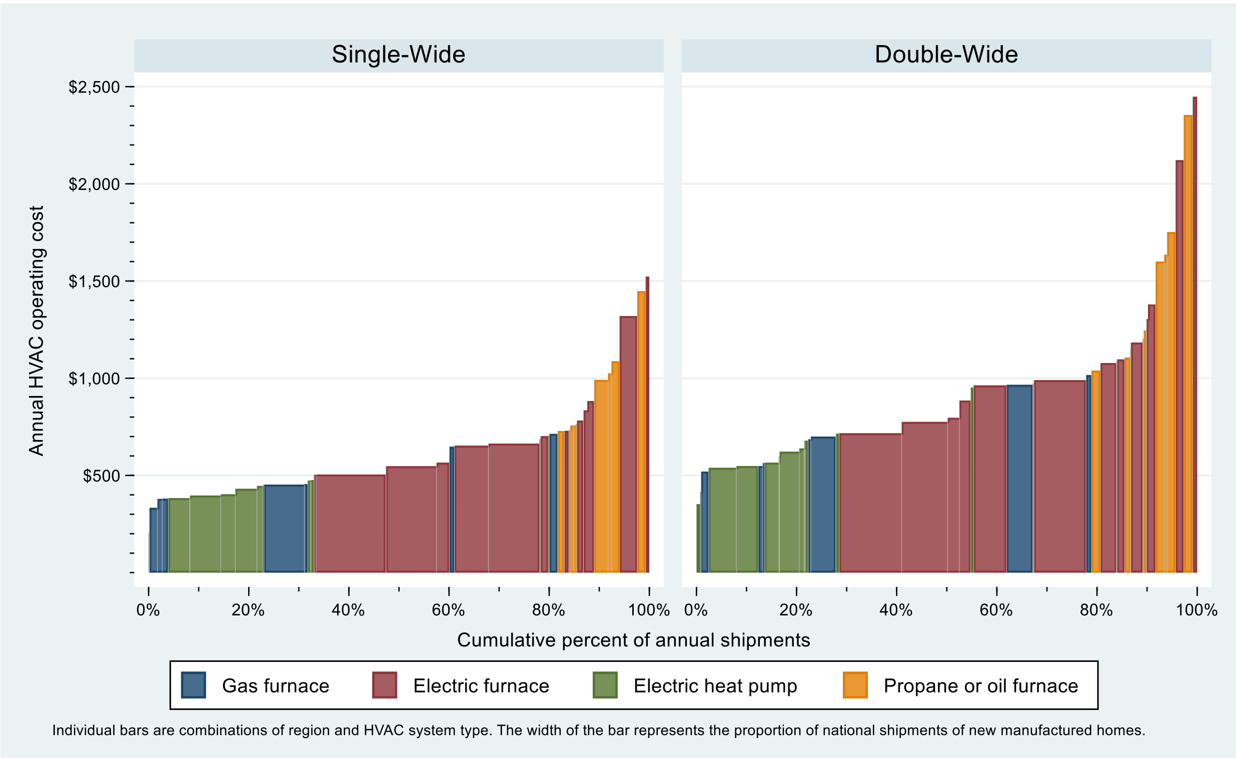
Figure 19. Estimated heating and cooling costs by type of home and modeled location.



Note: fuel-fired furnaces not modeled for Houston or Atlanta due to small market share.

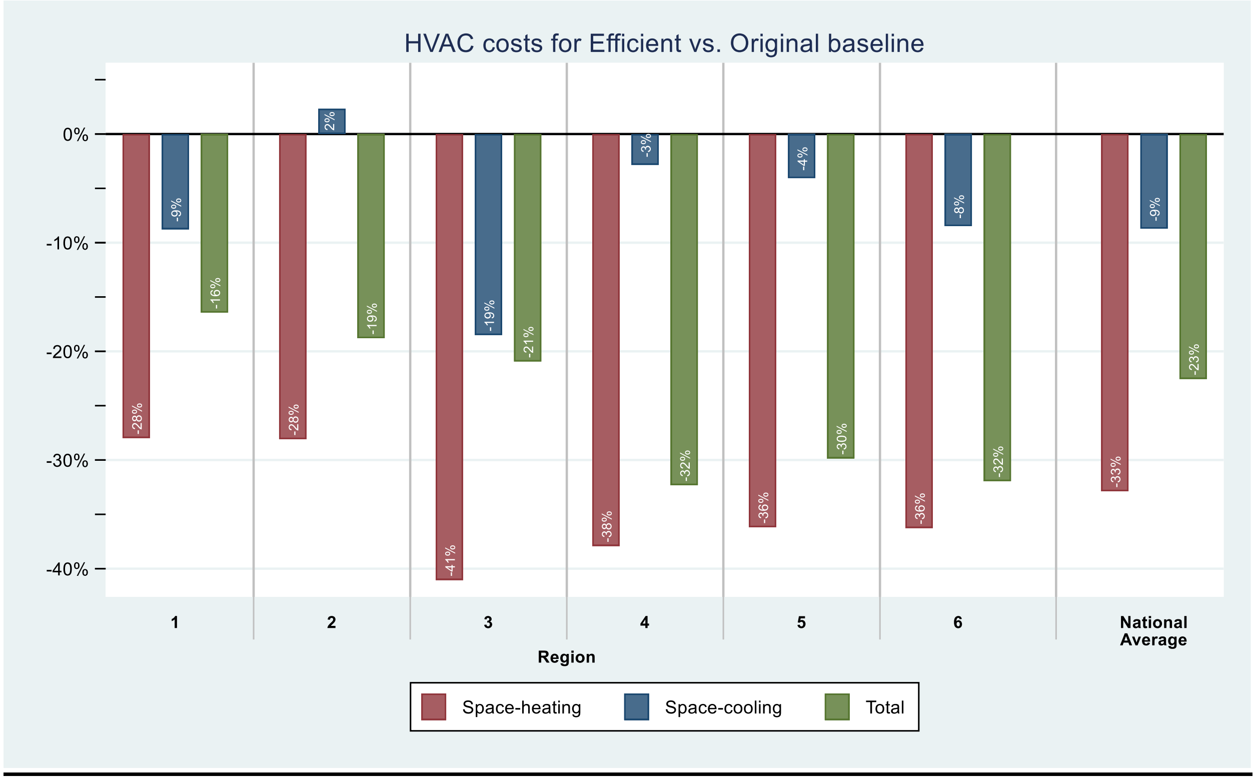
We can also use the modeling results and regional fuel prices to estimate the distribution of annual heating and cooling costs across the country for new manufactured homes. This analysis suggests that most homes have HVAC costs between about $400 and $800 for single-wide homes, and between about $600 and $1,100 for double-wide homes (Figure 20). However about 20 percent of homes are expected to have heating and cooling costs above these ranges: these are homes in colder climates with electric, propane or fuel-oil furnaces.

Figure 20. Estimated cumulative distribution of annual heating and cooling costs, by home type.



All the preceding results are derived from the original baseline. The alternative efficient baseline results in lower space-heating costs (Figure 21). The difference between space-heating and space-cooling impacts is due to the use of regional setpoint temperatures for the efficient baseline. These are generally lower than the original baseline for both space-heating and space-cooling, which has the effect of reducing space-heating costs while increasing space-cooling costs—all within the context of a general reduction in heating and cooling loads due to a more thermally-efficient building shell. The overall effect of the efficient baseline is space-conditioning costs that are 23 percent lower than the original baseline on a national basis.

Figure 21. Space-heating and space-cooling costs for the efficient baseline relative to the original baseline, by region.



HEAT PUMPS

Turning to the question of the savings and cost-effectiveness of heat pumps, we examined the annual energy-cost savings and break-even incremental cost for the three modeled types of air-source heat pumps relative to electric, propane and natural gas furnaces. The analysis shows that for most regions of the country, there is substantial cost-savings potential associated with heat pumps over electric and propane furnaces, especially for high-efficiency variable speed units. Among the 50 percent of new manufactured homes that currently rely on an electric furnace and central air conditioner, a variable-speed heat pump would save roughly $300 to $700 per year in heating and cooling costs for single-wide homes and $400 to $1,200 per year in double-wide homes (Table 18 and

Figure 22). Energy-cost savings are even higher among the one in ten homes that are heated with propane (Figure 23).

Moreover, when compared against electric and propane furnaces, higher-end heat pumps appear to be financially attractive, with a break-even incremental cost that exceeds $3,000 for single-wide homes in warm climates to upwards of $15,000 for double-wide homes in colder areas (see lower half of

Figure 22 and Figure 23). If—as appears to be the case—most new manufactured homes are already provided with central air conditioning, the cost to upgrade to a variable-speed heat pump is likely to be well within these break-even values.

Note that all these results are about 30 percent lower under the efficient baseline compared to the original baseline results above.

Table 18. Annual energy-cost savings and break-even incremental cost for heat pumps compared to an electric furnace with central A/C, by home type and region.

Home type	Region	Current electric-furnace market share	Annual energy-cost savings			Break-even incremental cost*		
			Conventional HP	Two Stage HP	Var Speed HP	Conventional HP	Two Stage HP	Var Speed HP
Single-wide	1	62%	$140	$210	$290	$1,900	$2,400	$3,100
	2	60%	$280	$360	$410	$3,800	$4,500	$5,000
	3	33%	$80	$250	$320	$1,100	$2,500	$3,100
	4	24%	$520	$600	$670	$7,700	$8,600	$9,600
	5	25%	$590	$660	$740	$7,700	$8,400	$9,300
	6	36%	$330	$390	$420	$4,600	$5,300	$5,700
	National	50%	$220	$290	$370	$3,000	$3,600	$4,300
Double-wide	1	63%	$230	$320	$420	$3,000	$3,700	$4,700
	2	62%	$440	$550	$610	$6,000	$7,000	$7,700
	3	30%	$130	$330	$440	$1,800	$3,300	$4,400
	4	27%	$860	$970	$1,090	$12,800	$14,000	$15,600
	5	21%	$970	$1,070	$1,210	$12,700	$13,700	$15,400
	6	58%	$560	$640	$680	$7,800	$8,700	$9,300
	National	52%	$340	$440	$540	$4,700	$5,500	$6,500

*Blended average of 55% of homes financed with a chattel loan, 15% financed with a real-estate loan and 30% purchased in cash.

Figure 22. Energy-cost savings and break-even incremental cost for three types of heat pumps compared to an electric furnace with central A/C, by home type and region.

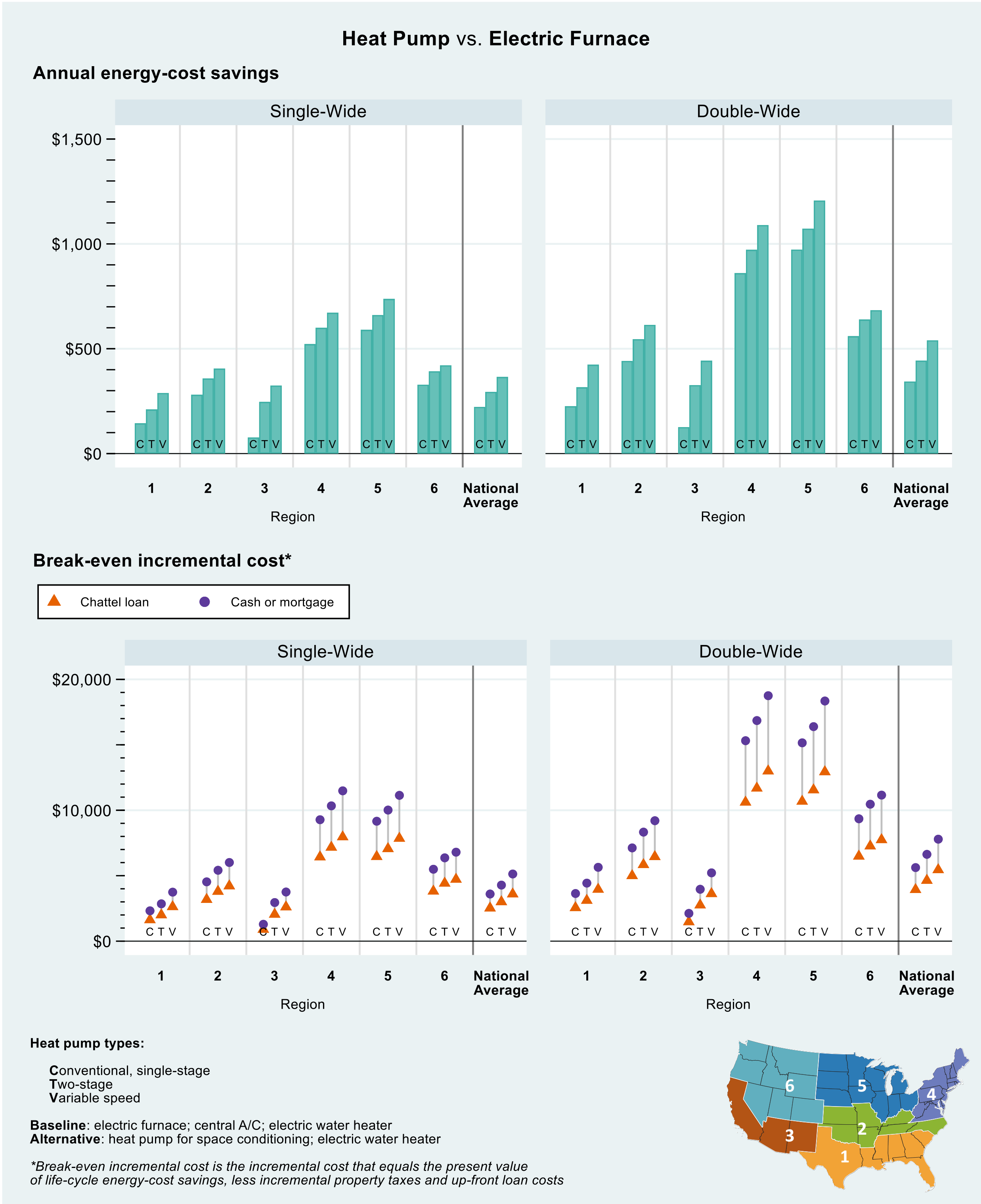
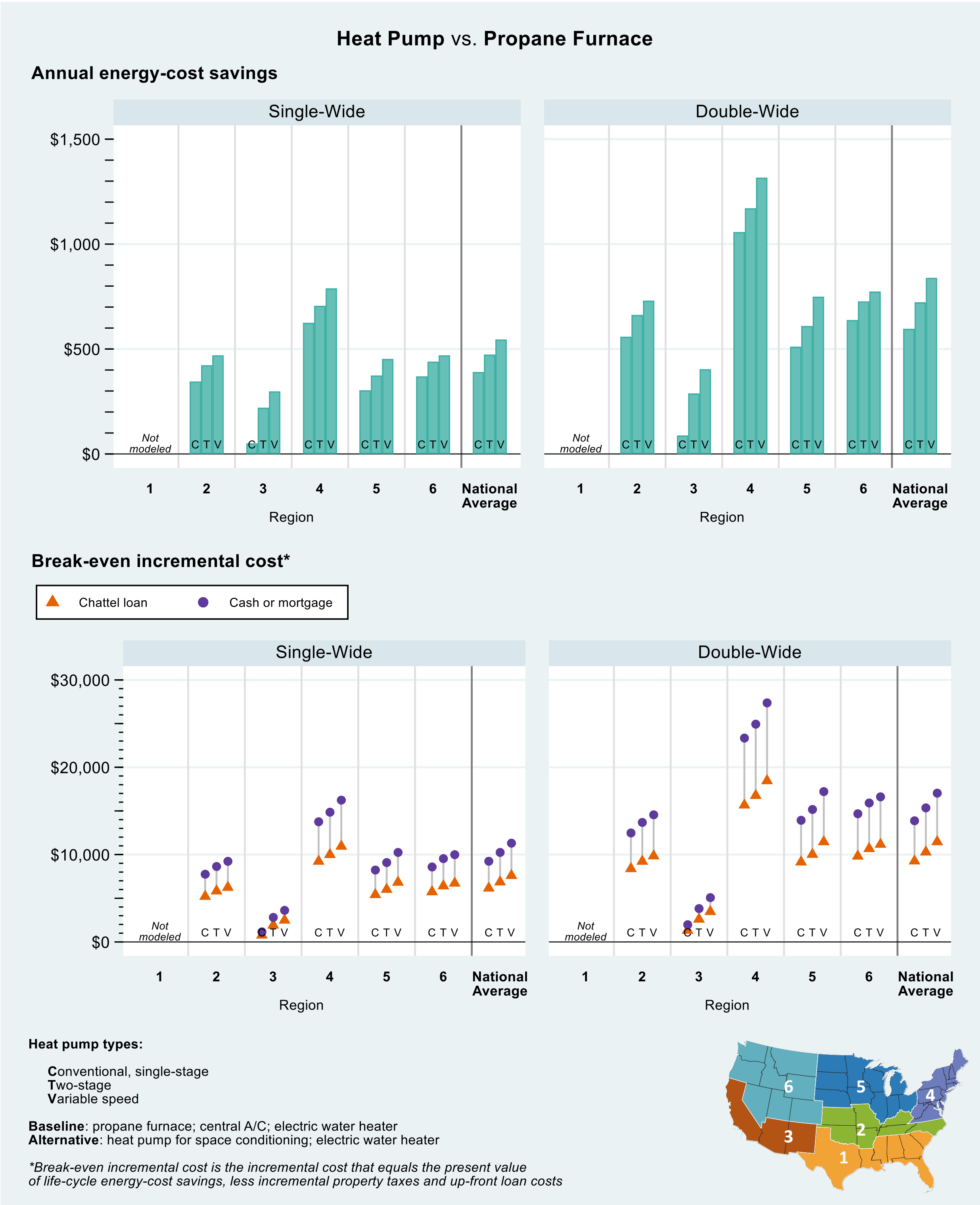
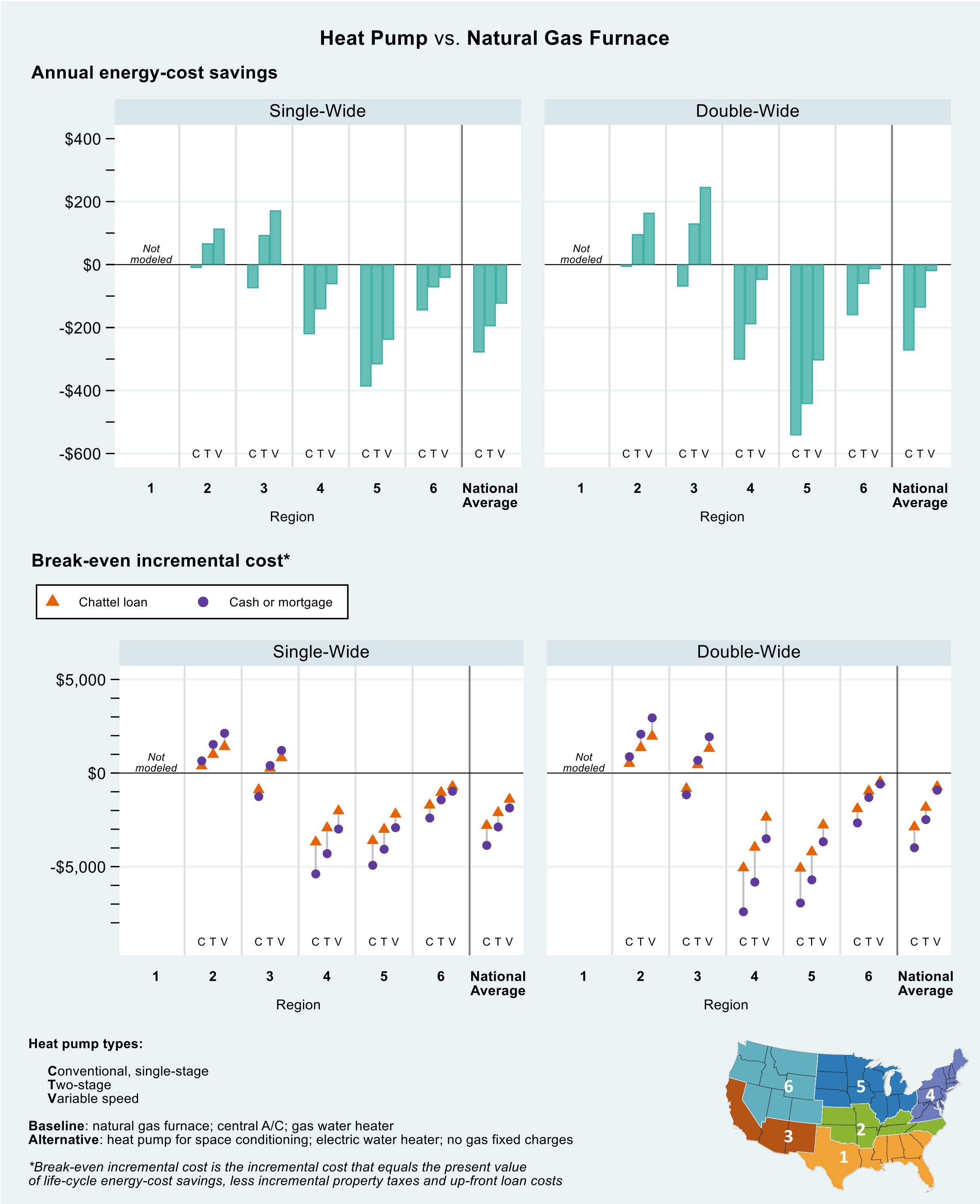


Figure 23. Energy-cost savings and break-even incremental cost for three types of heat pumps compared to a propane furnace with central A/C, by home type and region.



When it comes to the one in six new manufactured homes that heat with natural gas, however, the situation is very different—at least at first glance. At current natural gas prices, in much of the country the operating cost for even a high-efficiency, variable-speed heat pump is actually *higher* than that for a standard-efficiency furnace and central A/C system (Figure 24). The strongly negative energy-cost savings for the Midwest (Study Region 5) are particularly noteworthy, because more than 40 percent of new manufactured homes that heat with natural gas are shipped to this region.

Figure 24. Energy-cost savings and break-even incremental cost for three types of heat pumps compared to a natural gas furnace with central A/C, by home type and region. Assumes a conventional gas water heater for the baseline (gas furnace) case and a conventional electric water heater for the alternative (heat-pump) case.



However, when comparing heat pumps to natural gas furnaces, there is an important additional consideration: the fuel and type of water heater and the presence or absence of natural-gas service in the case of the heat pump. Data from EIA's 2015 Residential Energy Consumption Survey indicate that about 60 percent of manufactured homes with natural gas heat also have a gas water heater, while 40 percent have electric water heaters. A conventional electric water heater is generally more expensive to operate than a gas water heater but shifting to an all-electric home can avoid the need for natural gas service entirely and thus eliminate monthly gas-service charges.[12] Moreover, upgrading to a heat pump water heater can significantly reduce the cost of using electricity to provide domestic hot water—though at the expense of additional up-front investment.

Table 19 shows how heating and cooling, domestic hot water and gas service charges compare for a double-wide home in Chicago when considering a variable-speed heat pump over a natural gas furnace. At current regional energy prices, a heat pump results in lower energy costs only if paired with a heat pump water heater—and only in the case of a home that would otherwise have received a conventional electric water heater.

Table 19. Estimated HVAC, domestic hot water (DHW) and fixed gas-service charges for different DHW configurations when comparing a variable-speed heat pump to a gas furnace for space conditioning for a double-wide home in Chicago.

Baseline (gas furnace)					**Alternative (variable-speed heat pump)**					
	Annual cost*					Annual cost*				**Annual cost savings**
DHW type	HVAC	DHW	Gas Fixed	Total	**DHW type**	HVAC	DHW	Gas Fixed	Total	
Gas	$699	$102	$140	$941	*Gas*	$846	$102	$140	$1,087	-$146
	$699	$102	$140	$941	*Elec*	$846	$422	$0	$1,267	-$326
	$699	$102	$140	$941	*HPWH*	$846	$160	$0	$1,006	-$65
Elec	$699	$422	$140	$1,261	*Elec*	$846	$422	$0	$1,267	-$6
	$699	$422	$140	$1,261	*HPWH*	$846	$160	$0	$1,006	$255

DHW types:

Gas – conventional gas water heater (EF=0.67);
Elec – conventional electric water heater (EF=0.95);
HPWH – heat pump water heater (EF=2.5).

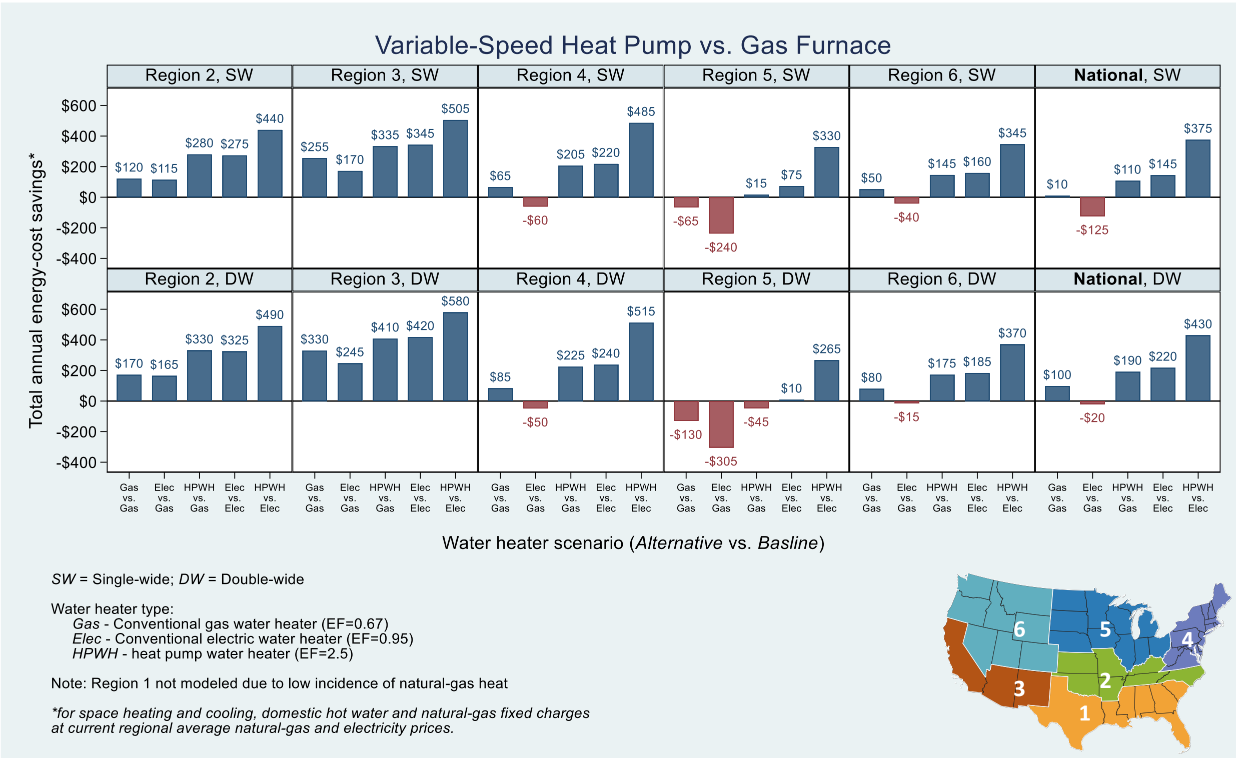
*at current regional average price of 63.5 cents per therm for natural gas and 12.7 cents per kWh for electricity

At the regional level (Figure 25), the analysis suggests generally positive savings against natural gas in Regions 2 and 3 regardless of the water-heater scenario. For Regions 4 through 6, however, the savings range from strongly negative to strongly positive depending on the region

[12]Full electrification also requires the kitchen range and oven to be electric. RECS data indicate that about 75 percent of manufactured homes with gas space heating also have gas ranges. We assume that electrification of cooking would also follow from electrification of space heating and water heating, but we did not calculate the energy-cost impacts of cooking electrification, as these are generally small.

and scenario. Note that these three regions account for about 60 percent of all new manufactured homes with natural gas heat.

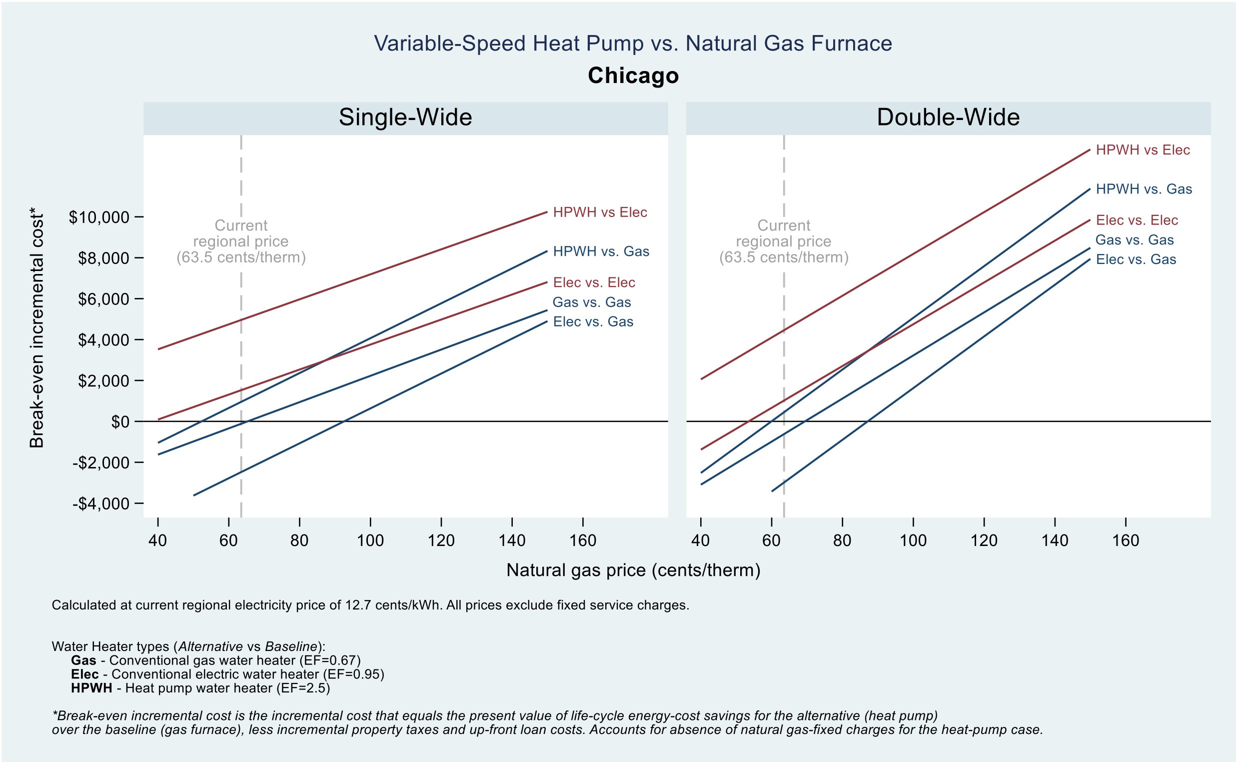
Figure 25. Annual energy-cost savings for a variable-speed heat pump over a natural-gas furnace and central A/C for four water heater scenarios, by region and home type.



It is also important to recognize that these results are sensitive to the price of natural gas, which has been inexpensive for some time but has recently shown signs of increasing. Figure 26 shows how the break-even incremental cost for a variable-speed heat pump over a natural-gas furnace varies with the price of natural gas for a double-wide home modeled for Chicago under different water-heating scenarios. For a home that would otherwise receive a gas furnace and electric water heater, upgrading to the heat pump and heat pump water heater has a break-even incremental cost in the range of $4,000 to the $5,000, even at current natural gas prices. The other water-heating scenarios, however, do not achieve these levels until the price of natural gas is well over $1.00 per therm.

All of these factors make assessing the cost-effectiveness of heat pumps against natural-gas furnaces a complicated endeavor. Policy goals to promote heat pumps and electrification of space heating to mitigate climate change drivers could also lead to incentives that strongly affect the economics of heat pumps versus natural gas.

Figure 26. Break-even incremental cost for a variable-speed heat pump compared to a natural gas furnace in Chicago, for different water heating scenarios.



Air-Source Integrated Heat Pump (ASIHP)

As described previously, we approximated the savings from an ASIHP system as the sum of savings from a separately modeled variable-speed heat pump and those from a heat pump water heater. Figure 27 shows the calculated energy-cost savings and break-even incremental cost for this innovation, by region and home type. Because the innovation involves substantial reductions to both space-heating and domestic hot water energy, the savings are the highest of any of the innovations examined. Even so, the analysis suggests that operating costs will be higher than conventional systems for many homes with natural-gas heat. This reduces the scope of this innovation by about 9 percent nationally but eliminates about half of shipments to Region 5.

Figure 27. Annual energy-cost savings and break-even incremental cost for an air-source integrated heat pump versus conventional space-conditioning and domestic hot water systems, by home type and region. Does not include ventilation savings from heat recovery.

DUCT LEAKAGE REDUCTION

Five of the potential innovations considered here involve reducing duct leakage, which has long bedeviled the manufactured housing industry. Here, the modeling and fuel-price estimates suggest that each cfm of duct-leakage reduction per 100 ft^2 of floor area (that is, each 0.01 reduction in Qn) is worth between about $3.50 and $19 in annual energy cost savings and has a break-even incremental cost of between $35 and $350, depending on the region of the country. A 75 percent reduction in duct leakage under the original baseline would produce a national-average of about $50 per year for single-wide homes and $85 per year double-wides (Figure 28). Because a double-wide home is significantly larger than a single-wide, a given change in Qn has a larger dollar impact in the former. In absolute terms, again on a national basis, our analysis suggests that a leakage reduction of 100 cfm will result in energy-cost savings of about $60 per year in both single- and double-wide homes, with a (blended) break-even incremental cost of about $900.

Translating all of this into savings and break-even incremental cost for specific innovations requires assumptions about the incidence and magnitude of duct-leakage issues that would be resolved by the innovation. Figure 29 shows on a national basis how the break-even incremental cost varies with the assumed percent of homes that have a duct leakage issue and the assumed average leakage reduction achieved when addressed by the innovation: higher incidence rates and higher average reductions mean higher incremental costs that can be supported by energy savings from the innovation.

Figure 28. Energy-cost savings and break-even incremental cost for 75 percent duct leakage reduction.

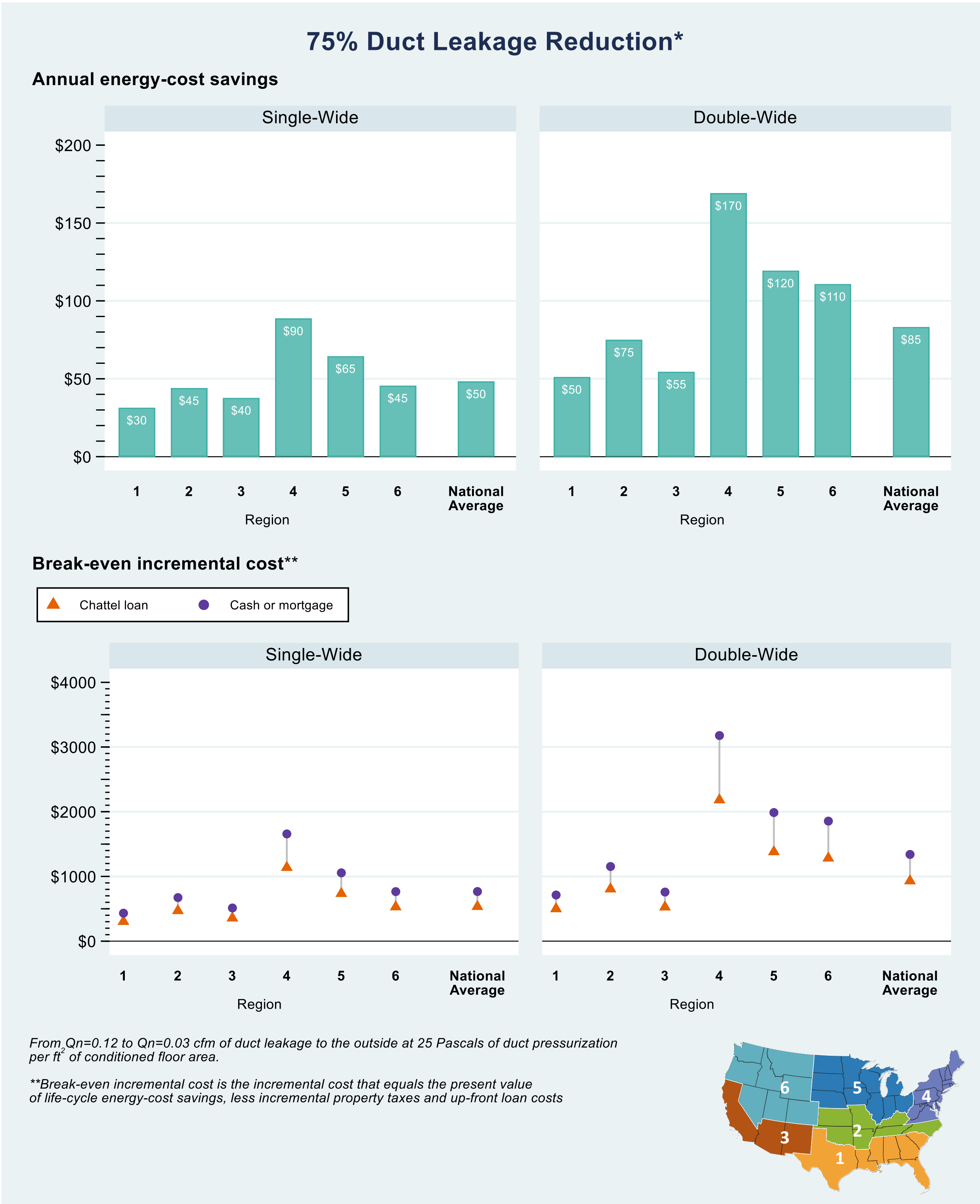
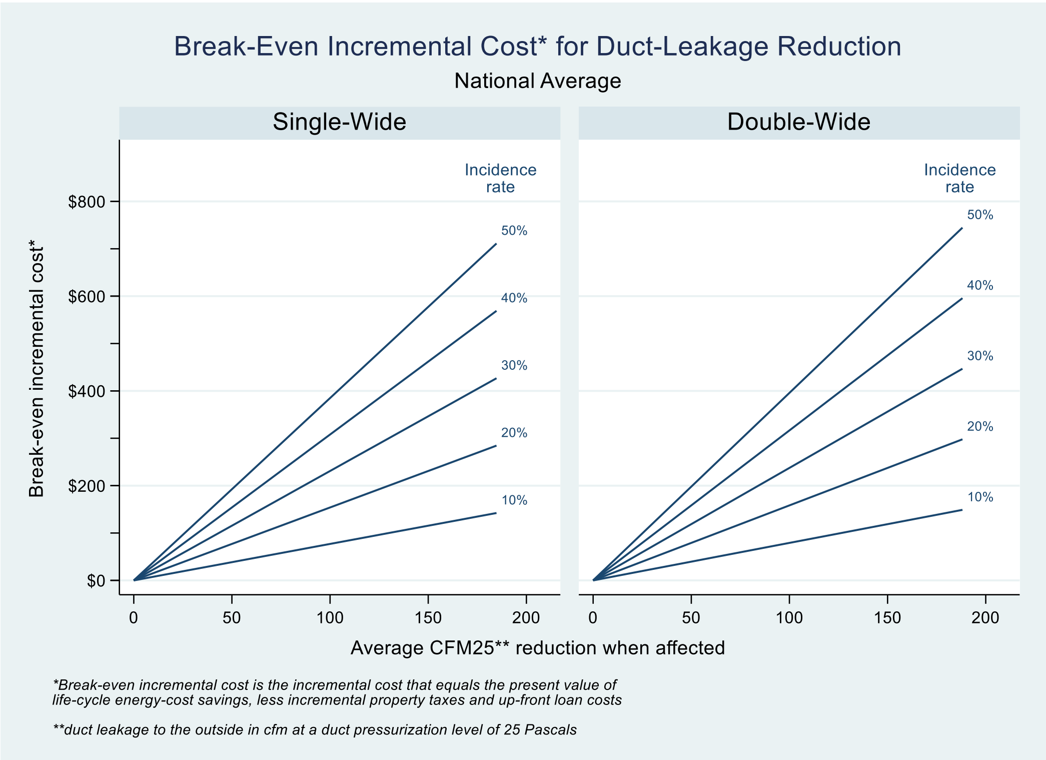


Figure 29. National average break-even incremental cost for resolving duct-leakage issues, by home type.



The actual incidence and magnitude of leakage reductions for the innovations is difficult to know. But given ranges for these, the results above can be used to roughly bound the supportable incremental cost for innovations that seek to reduce duct leakage. Table 20 shows national-average ranges for energy-cost savings and break-even incremental costs for what we consider to be plausible ranges of incidence and magnitude for the innovations that seek to reduce duct-leakage.

Table 20. Approximate national-average HVAC energy-cost savings and break-even incremental cost associated with scenario ranges for duct-leakage related innovations.

Innovation		Scenario Ranges for Innovation Impacts	HVAC energy savings[a]		Break-even incremental cost[a]
			Percent	$ per year	
D1	Improved HVAC Quality Assurance Protocols	Simplified in-plant testing of every home reduces average duct leakage by 70 to 90% relative to baseline of 6 to 12 CFM25 per 100 ft^2 of floor area.	5-10%	\$35 - \$70	\$500 - \$950
		Simplified field diagnostics identifies and remedies an average of 50 to 100 CFM25 of leakage in 5 to 15% of homes tested.	4-8%[b]	\$30 - \$55[b]	\$50 - \$100
D2	Improved Cross-over Duct Designs[d]	Prevents 10 to 40% of homes from developing leaks that average 50 to 200 CFM25 and develop after 1 to 5 years	0.5-4.0%	\$5 - \$30	\$50 - \$400[c]
D2a	Comparative testing of different cross-over approaches				
D3	AeroSeal in a Factory Setting	70-90% reduction in duct leakage relative to baseline of 6 to 12 CFM25 per 100 ft^2 of floor area	5-10%	\$35 - \$70	\$500 - \$950
D4	Interior duct designs to eliminate leakage	100% reduction in duct leakage relative to baseline of 6 to 12 CFM25 per 100 ft^2 of floor area	7-13%	\$45 - \$85	\$650 - \$1,150

Notes
a) Results based on 5th and 95th percentiles from Monte Carlo simulation (n=10,000) using input ranges above (assumed to be uniform distributions) and modeled energy impacts per unit of leak reduction. Uncertainty in fuel costs and other life-cycle costing parameters is not included.
b) For homes where leaks are identified and remediated.
c) Includes effect of reduced present value due to delayed onset of cross-over failure.
d) Does not include savings from improved insulation level (see next report section for combined impact).

IMPROVED CROSS-OVERS

Innovation D2 (improved cross-overs) involves improving traditional under-belly cross-overs to both reduce the potential for later cross-over failure resulting in duct leakage as well as upgrading the level of insulation for the cross-over. In the prior section, we examined the cost-savings potential for reducing leakage associated with down-the-road cross-over failure: here we add in the effect of increasing the cross-over insulation level to look at the cost-savings potential for the package.

Figure 30 shows the energy-cost and break-even incremental cost implications of the modeled energy savings from increasing cross-over insulation from standard practice (R-8) to R-16. The annual energy-cost savings ranges from about \$3 to \$11, with a national average of about \$8. This translates into regional break-even incremental costs of between roughly \$40 and \$210.

On a national basis, the improved cross-over R-value has a break-even incremental cost of about $100. When added to the reduced leakage for this innovation shown in Table 20, the break-even incremental cost range for the package becomes $200 to $550.

Figure 30. Energy cost savings and break-even incremental cost for improved (R-16) cross-over duct insulation, by region.

INTEGRATION CONTROLS FOR DUCTLESS HEAT PUMPS

Innovations H2 (Advanced Controls and Distribution for Ductless Heat Pumps) and H3 (Quick-Connect Fittings for Ductless Heat Pumps) call for integrating a ductless heat pump with a central ducted HVAC system, with the latter innovation also providing a potentially more cost-effective way of installing the ductless system.

For modeling purposes, we assume that the ductless system takes over somewhere between 25 and 50 percent of the total load of the home, with a commensurate reduction in duct leakage. We thus estimate the cost-savings and break-even incremental cost as a combination of half the previously shown savings from a variable-speed heat pump, plus the savings associated with a 50 percent reduction in duct leakage.

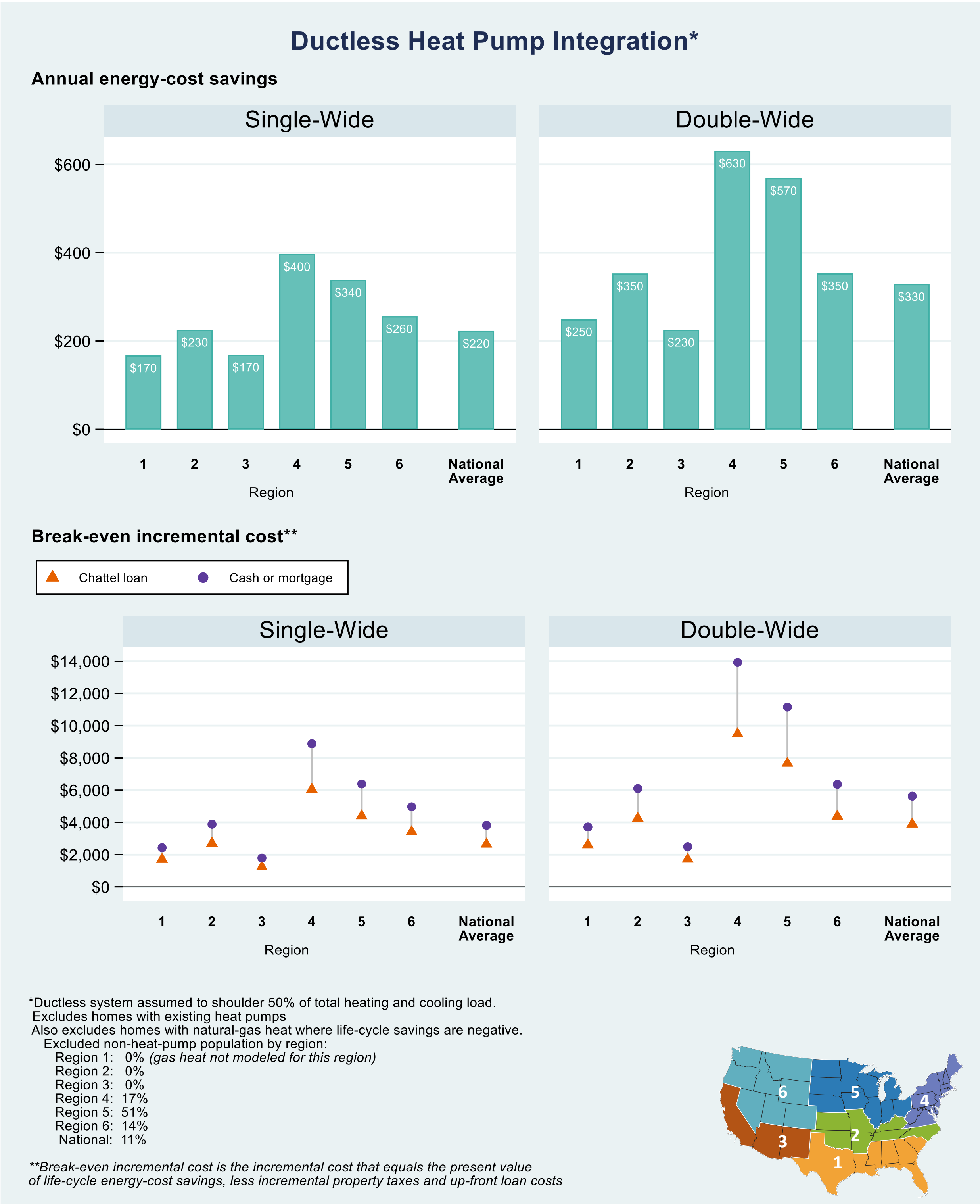
As with the preceding heat pump analysis, energy savings are negative against natural-gas heat in most parts of the country at current fuel prices. Figure 31 shows the regional and national annual energy-cost savings and break-even incremental cost for a 50 percent load offset when cases with negative life-cycle savings are excluded. Nationally, this eliminates only about 11 percent of new-home sales, but more than half of annual new homes in Region 5 are excluded in this analysis. Impacts at the low-end estimate of a 25 percent ductless-heat-pump load offset would be half the values shown in the figure.

In addition to the question of how much of the total heating and cooling load of the home would be taken up by the ductless unit, uncertainty in the average baseline duct leakage level creates some uncertainty in the estimates for these innovations. The preceding analysis uses the original baseline estimate for duct leakage to the outside of 12 cfm per 100 square feet of floor area. If we instead use the leakage estimate under the efficient baseline (6 cfm per 100 ft^2), first-year energy-cost savings and the break-even incremental cost are reduced by about 8 percent.

Combined, uncertainty in the amount of load offset by the heat pump and the duct leakage savings suggests a national average range of energy-cost savings between about $65 and $125 per year (8 to 15 percent of HVAC operating costs), and a break-even incremental cost range of $950 to $1,800.

All these results are about 30 percent lower if calculated with the alternative efficient baseline.

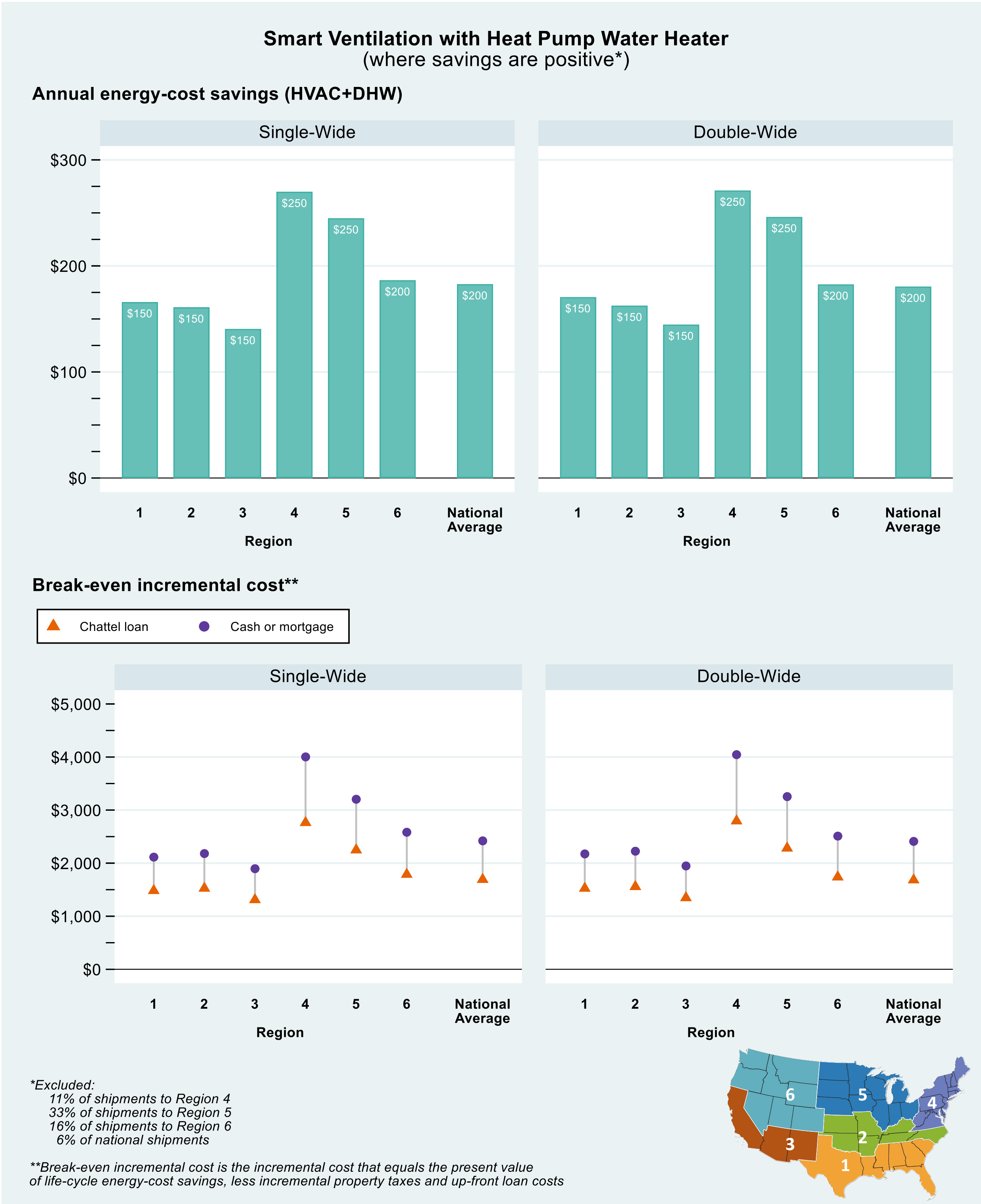
Figure 31. Energy cost savings and break-even incremental cost for integration of a ductless heat pump with central ducted HVAC system.



SMART VENTILATION CONTROL WITH HEAT PUMP WATER HEATER

As described previously, savings for this innovation are based on estimated savings for a heat pump water heater, plus 4 percent cooling savings in cooling-dominated climates (Houston, Atlanta, and Phoenix). The analysis indicates that operating costs are higher for about 6 percent of national shipments that involve homes with natural-gas water heaters where gas prices are low. Figure 32 shows annual energy-cost savings and break-even incremental cost when these are excluded.

Figure 32. Energy cost savings and break-even incremental cost for smart ventilation with a heat pump water heater, by home type and region.



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APPENDIX A DETAILS OF SIMULATION INPUTS

GENERAL MODELING

This appendix provides more detail as to how the modeling was accomplished. This information may prove fruitful to future modelers who may want to duplicate the process.

Sample output

The following formats (partial results presented in the figure) are used to present simulation results. The first column represents case number, and next column lists input file names. The next five columns present input energy values of annual energy use as cooling, heating, supplemental heating, fan separated by cooling and heating times, respectively. The next 3 columns present output energy for heating, cooling and supplemental heating coils. The detailed simulations are summarized in the tables for all cases. All value units are kBtu. The last 3 columns present internal loads of lights and appliances, and electricity energy use of domestic water heater. Supplemental heating is available in heat pumps. It will turn on when outdoor temperature is below the compressor lockout temperature and an HP DX heating coil does not provide enough heating capacity to meet heating loads.

Figure 33. Sample simulation output

Units	kBtu	Input energy					Output energy			Additional input energy		
Num	Name	Cooling	Heating	SuppHeat	FanCoolin	FanHeatir	Cooling	Heating	SuppHeat	Lights	Appliance	DWH
1	DW_EF_Houston.idf	10643.99	6151.333	0	2404.836	201.661	48804.17	6162.489	0	4814.911	8185.604	7554.1023
2	DW_HP_Houston.idf	10482.86	1992.935	6.958806	2426.12	350.9846	48831.97	5955.253	6.958806	4814.911	8185.604	7554.1023
3	SW_EF_Houston.idf	8283.921	3687.009	0	1840.868	121.113	38178.32	3701.427	0	3307.882	8185.604	7554.1023
4	SW_HP_Houston.idf	8132.271	1207.788	5.418016	1853.05	213.191	38179.87	3565.123	5.418016	3307.882	8185.604	7554.1023
5	DW_EF_Phoenix.idf	14378.39	2815.017	0	3107.222	96.39944	56537.98	2822.635	0	4814.911	8185.604	6265.071
6	DW_GF_Phoenix.idf	14378.39	2966.668	0	3107.222	96.39944	56537.98	2822.635	0	4814.911	8185.604	6265.071
7	DW_HP_Phoenix.idf	14169.87	871.9917	0	3118.86	151.1094	56637.17	2763.958	0	4814.911	8185.604	6265.071
8	SW_EF_Phoenix.idf	10937.81	1639.724	0	2587.974	56.43563	44166.88	1646.897	0	3307.882	8185.604	6265.071
9	SW_GF_Phoenix.idf	10937.81	1725.027	0	2587.974	56.43563	44166.88	1646.897	0	3307.882	8185.604	6265.071
10	SW_HP_Phoenix.idf	10814.59	511.8212	0	2593.634	88.6885	44243.26	1609.344	0	3307.882	8185.604	6265.071
11	DW_EF_Atlanta.idf	7127.585	14738.56	0	1624.049	499.061	33215.76	14747.16	0	4814.911	8185.604	8937.9153
12	DW_HP_Atlanta.idf	6985.412	4819.549	147.0122	1625.976	895.217	33125.98	13945.62	147.0122	4814.911	8185.604	8937.9153
13	SW_EF_Atlanta.idf	5601.599	9108.522	0	1274.269	308.586	26407.24	9123.488	0	3307.882	8185.604	8928.4371
14	SW_HP_Atlanta.idf	5497.339	3025.168	93.15067	1275.378	563.3869	26378.58	8628.868	93.15067	3307.882	8185.604	8928.4371
15	DW_EF_Baltimore.idf	6198.724	23932.38	0	1176.322	766.7033	26433.79	23951.94	0	4814.911	8185.604	10189.034
16	DW_GF_Baltimore.idf	6198.724	25192.98	0	1176.322	766.7033	26433.79	23951.94	0	4814.911	8185.604	10189.034
17	DW_HP_Baltimore.idf	5421.514	7863.433	458.4011	1162.437	1481.972	26051.92	21979.65	458.4011	4814.911	8185.604	10189.034
18	SW_EF_Baltimore.idf	4805.433	14198.3	0	862.443	455.0228	20574.95	14225.57	0	3307.882	8185.604	10179.556
19	SW_GF_Baltimore.idf	4824.389	15439.94	0	884.2651	471.1133	20746.87	14691.72	0	3307.882	8185.604	10179.556
20	SW_HP_Baltimore.idf	4246.221	4825.75	216.6374	866.6879	915.2083	20539.1	13268.64	216.6374	3307.882	8185.604	10179.556
21	DW_EF_Chicago.idf	4208.308	35704.27	0	838.6245	1142.313	18474.29	35716.24	0	4814.911	8185.604	11326.414
22	DW_GF_Chicago.idf	4208.308	37580.95	0	838.6245	1142.313	18474.29	35716.24	0	4814.911	8185.604	11326.414
23	DW_HP_Chicago.idf	3819.703	11748.93	2070.241	711.2579	2454.451	18332.23	30832.94	2070.241	4814.911	8185.604	11326.414
24	SW_EF_Chicago.idf	3374.229	21866.14	0	633.9632	702.459	14862.21	21889.91	0	3307.882	8185.604	11326.414
25	SW_GF_Chicago.idf	3374.229	23013	0	633.9632	702.459	14862.21	21889.91	0	3307.882	8185.604	11326.414
26	SW_HP_Chicago.idf	3108.84	7464.801	1131.9	515.5489	1579.127	14961.43	19229.2	1131.9	3307.882	8185.604	11316.936
27	DW_EF_Raleigh.idf	7212.888	18709.91	0	1678.108	606.1312	34076.18	18723.79	0	4814.911	8185.604	9440.2583
28	DW_GF_Raleigh.idf	7212.888	19695.64	0	1678.108	606.1312	34076.18	18723.79	0	4814.911	8185.604	9440.2583

MODELING OF INNOVATIONS

The innovations being considered largely were in two areas: innovations that reduced duct leakage and conduction, and high efficiency air conditioners and heat pumps, and heat pump control strategies as compressor lockout and supplemental heater operation control. Here we present more details about duct and heat pump modeling.

Duct system

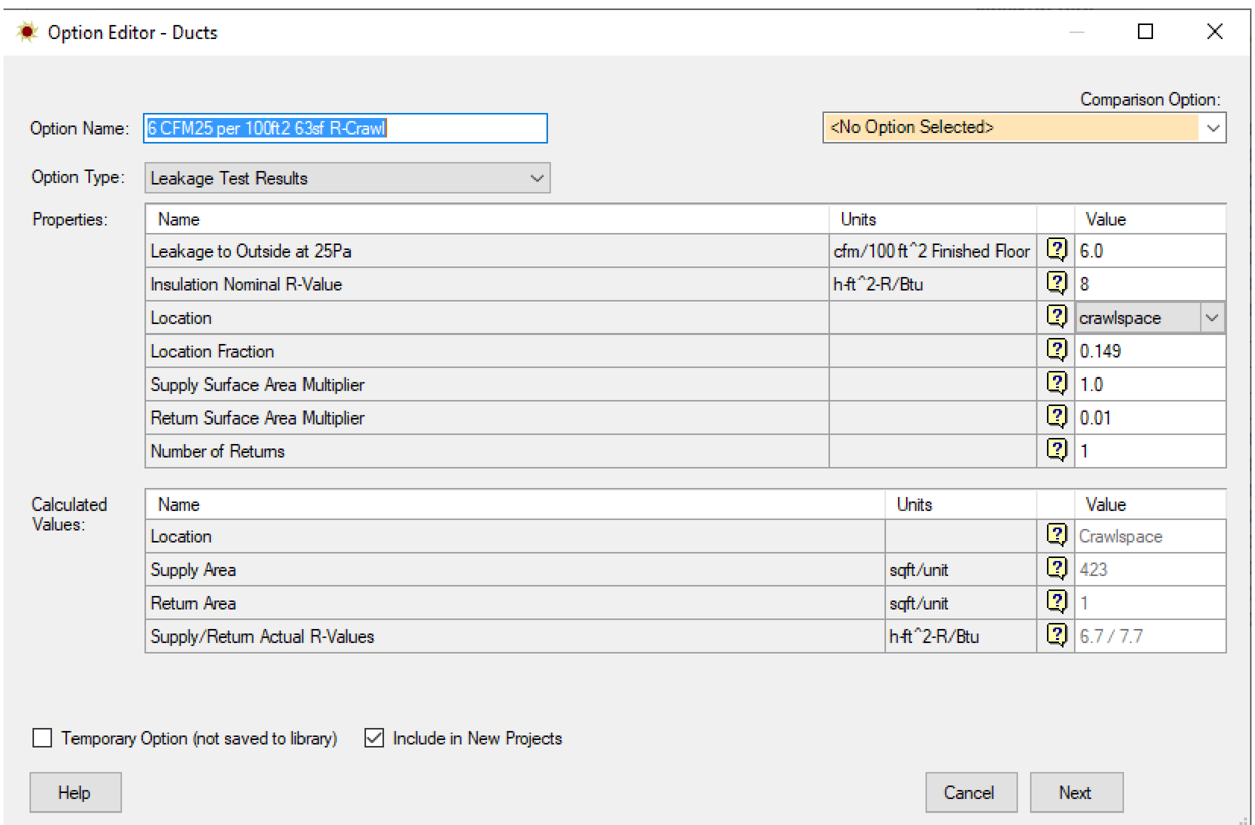
Duct system innovation is composed of leakage reduction and higher crossover duct insulation as R-16, compared to R-8 as baseline crossover duct insulation level.

Duct leakage

1. **Baseline selection**

The following figure presents duct selection for the efficient baseline case using BEopt. The Qn used for the efficient baseline was 6 percent whereas it is 12 percent for the original baseline.

Figure 34. Efficient baseline BEopt entry for ducts



The nominal duct insulation level is R-8. Due to the effects of cylindrical geometry, actual duct insulation will be reduced to 6.7 for supply ducts and 7.7 for return ducts.

The duct leakage is calculated based on floor area at 25Pa pressure difference between indoor and outdoor, and independent of supply flow rate. Since all buildings have the fixed geometry for double and single-wide, variation of system sizes requires different supply flow rates. Therefore, the percentage of duct leaks to supply flow rate varies with system sizes. Since no air handling unit leak is assumed, the 3 EMS variables are used to represent duct leaks in EnergyPlus input files generated by BEopt as fractions of supply leak, return leak and outdoor makeup air to supply flows. In order to keep mass conservation, the following rule is applied:

Supply leak = Return leak + Outdoor makeup air.

2. **Leakage reduction**

It is obvious that Qn=3 percent is a quarter of leakage of original baseline of Qn=12 percent, so that all leakage values are reduced to 1/4 to accomplish Qn=3 percent.

Although BEopt allows leakage rate changes, it is time consuming to use BEopt to generate input files with Qn variation. Instead, we used VBA (Visual Basic Application) script to change values automatically. At the same time, mass conservation is kept.

3. **Leakage innovation with Qn=0 percent**

The supply leak, return leak, and outdoor makeup air values are set to 0.0001, 0.00005 and 0.00005, respectively for modeling Qn =0 percent.

High efficiency HVAC system

The high efficiency HVAC system are composed of cold climate heat pumps, 2 stage and variable speed air conditioners and heat pumps.

Cold climate HP

Heat pump heating mode has higher efficiency than a normal electric furnace. Unfortunately, the heating mode itself has compressor lockout when the outdoor temperature is below -8C. The supplemental electric heater will turn on with relatively low efficiency. This type of behavior blocks a lot of application in cold climate locations. In order to make up a gap, many manufacturers have developed heat pumps to work at very cold outdoor temperatures, so that the compressor lockout temperature is much lower than standard HP system. One of heat pumps is developed by Carrier. This type HVAC system application is one of innovations in the present project.

To simulate such heat pump performance in EnergyPlus, performance curves are essential for simulations. The performance curves are modifiers for system capacities and energy consumption. The curves can be developed based on performance data. The following procedures are used to develop cold climate heat pump model used in EnergyPlus simulations.

The cold climate HP is only applied to HUD Zone 3 locations, such as Baltimore, Chicago, Denver and Seattle in the present project.

1. **Select equipment with performance data**

The team selected 40MBAA Air Handler Unit Ductless System and 38MARB Outdoor Unit Single Zone Ductless System. The Air Handler system, as one of compatible indoor units, is selected. The main reason to select the air handler system is that the system can be used as a central system with ducts. The system has SEER = 20.0 and HSPF = 11.6. Its specification with corresponding indoor and outdoor units is provided in the following figure.

Figure 35. Cold-climate high efficiency heat pump ratings

	Indoor Model		40MBAAQ24XA3
	Outdoor Model		38MARBQ24AA3
Air Handler	Energy Star		YES
	NEEP		YES
	MASSSAVE		YES
	CCHP		YES
	ASHP		YES
	ASHP COLD CLIMATE		NO
	Cooling System Tons		2.0
	Cooling Rated Capacity	Btu/h	22,000
	Cooling Cap. Range Min - Max	Btu/h	7,500~26,000
	SEER		20.0
	EER		12.5
	Heating Rated Capacity (47°F)	Btu/h	27,000
	Heating Rated Capacity (17°F)	Btu/h	16,500
	Heating Maximum Capacity (17°F)	Btu/h	25,000
	Heating Maximum Capacity (5°F)	Btu/h	22,000
	Heating Cap. Range Min - Max	Btu/h	5,600~31,000
	HSPF		11.6
	COP (47°F)	W/W	3.77
	COP (17°F)	W/W	2.60
	COP (5°F)	W/W	1.75

The cooling performance data is provided in the next figure. We select two independent variables as indoor wet-bulb and outdoor dry-bulb temperatures to meet EnergyPlus curve fit requirements. The indoor wet-bulb temperature varies from 59ºF to 73.4ºF, while the outdoor dry-bulb temperature varies from -4ºF and 122ºF.

Figure 36. Cooling performance data used to develop curves for Energy Plus modeling of cold climate high efficiency unit

COOLING PERFORMANCE - AIR HANDLER

Model	COOLING			OUTDOOR CONDITIONS (DB)										
	Indoor Conditions DB			-4°F (-20°C)	0°F (-17°C)	5°F (-15°C)	17°F (-8°C)	47°F (8°C)	77°F (25°C)	86°F (30°C)	95°F (35°C)	104°F (40°C)	113°F (45°C)	122°F (50°C)
	DB	WB												
24K (208-230V)	69.8°F (21°C)	59°F (15°C)	TC	22.81	22.6	22.34	23.12	21.96	24.82	23.92	22.78	21.03	17.97	11.95
			SC	18.09	18	17.8	18.43	17.51	19.52	18.85	18.5	17.4	14.87	11.81
			Input	1.22	1.25	1.29	1.14	1.14	1.87	2.2	2.54	2.54	2.21	1.86
	75.2°F (24°C)	62.6°F (17°C)	TC	24.64	24.41	24.13	24.97	23.72	26.8	25.83	24.6	22.71	19.41	12.9
			SC	19.53	19.44	19.22	19.9	18.91	21.09	20.36	19.98	18.79	16.05	12.75
			Input	1.24	1.27	1.3	1.15	1.15	1.89	2.22	2.57	2.57	2.24	1.88
	80.6°F (27°C)	66.2°F (19°C)	TC	26.47	26.22	25.92	26.82	25.47	28.54	27.75	26.43	24.17	20.84	13.86
			SC	20.98	20.88	20.65	21.38	20.31	22.45	21.86	21.46	20	17.24	13.69
			Input	1.25	1.28	1.32	1.17	1.16	1.91	2.24	2.59	2.6	2.26	1.9
	89.6°F (32°C)	73.4°F (23°C)	TC	27.83	27.57	27.26	28.21	26.79	30.28	29.18	27.79	26.07	21.92	14.58
			SC	22.07	21.96	21.72	22.48	21.37	23.82	22.99	22.57	21.57	18.14	14.4
			Input	1.26	1.29	1.33	1.18	1.17	1.93	2.27	2.62	2.62	2.28	1.92

LEGEND
DB --- Dry Bulb
WB --- Wet Bulb
TC --- Total Net Capacity (1000 Btu/hour)
SC --- Sensible Capacity (1000 Btu/hour)
Input --- Total Power (kW)

The heating performance data is provided in the following figure. We select two independent variables as indoor dry-bulb and outdoor dry-bulb temperatures to meet EnergyPlus curve fit requirements.

Figure 37. Heating performance data used to develop curves for Energy Plus modeling of cold climate high efficiency unit

HEATING PERFORMANCE- AIR HANDLER

Model	HEATING		OUTDOOR CONDITIONS (DB)											
	Indoor Conditions DB		-22°F (-30°C)	-13°F (-25°C)	-4°F (-20°C)	0°F (-17°C)	5°F (-15°C)	17°F (-8°C)	19.4°F (-7°C)	24.8°F (-4°C)	32°F (0°C)	39.2°F (4°C)	44.6°F (7°C)	53.6°F (12°C)
24K (208-230V)	59°F (15°C)	TC	15.79	19.73	22.34	24.18	25.8	27.5	27.69	28.19	32.46	35.84	33.17	31.51
		Input	3.02	3.23	3.45	3.6	3.61	3.57	3.53	3.44	3.01	3.25	2.55	1.9
		COP	1.53	1.79	1.9	1.97	2.1	2.26	2.3	2.4	3.16	3.23	3.81	4.85
	64.4°F (18°C)	TC	15.35	19.19	21.73	23.52	25.09	26.74	26.93	27.41	31.56	34.85	32.26	30.64
		Input	3.12	3.34	3.57	3.72	3.73	3.68	3.64	3.55	3.11	3.36	2.63	1.97
		COP	1.44	1.68	1.79	1.85	1.97	2.13	2.17	2.26	2.97	3.04	3.59	4.57
	69°F (20.5°C)	TC	15.21	18.83	21.32	23.08	24.62	26.24	26.42	26.9	30.97	34.19	31.65	30.07
		Input	3.22	3.45	3.68	3.84	3.84	3.8	3.76	3.66	3.21	3.47	2.72	2.03
		COP	1.39	1.6	1.7	1.76	1.88	2.02	2.06	2.15	2.82	2.89	3.41	4.34
	71.6°F (22°C)	TC	14.48	18.1	20.5	22.19	23.67	25.23	25.41	25.86	29.78	32.88	30.43	28.91
		Input	3.31	3.55	3.8	3.96	3.96	3.92	3.87	3.78	3.31	3.58	2.8	2.09
		COP	1.28	1.49	1.58	1.64	1.75	1.89	1.92	2.01	2.63	2.69	3.18	4.05

LEGEND
DB --- Dry Bulb
WB --- Wet Bulb
TC --- Total Net Capacity (1000 Btu/hour)
Input --- Total Power (kW)
COP --- (W/W)

2. **Develop performance curves using a curvefit tool to meet EnergyPlus requirements**

When EnergyPlus is installed on a local computer, the installer also installs many auxiliary programs. HVAC Performance Curve Fit Tool is one of auxiliary programs, and generates HVAC performance curves in EnergyPlus IDF format.

The total cooling and heating capacities must be the gross values, i.e., not corrected for the supply fan heating effect. Also the input power has to exclude the supply air fan power, but includes other miscellaneous power inputs (e.g. control panel power). If manufacturers provide the total power, then the supply fan power must be deducted from the former.

The heating performance data is entered in the following input format required by the tool. The supply fan power for selected indoor unit is 150W. Therefore, the heating capacity and power input provided above are reduced by 150W, respectively, for coil gross performance data. Cooling performance curves are generated in the same way, but are not presented in the present report to make the report shorter.

Figure 38. Modeled capacity as a function of indoor and outdoor temperature for cold climate high efficiency unit

Performance Data:	Indoor Air Dry-Bulb Temperature	Outdoor Air Dry-Bulb Temperature	Total Heating Capacity	Compressor Plus Outdoor
	oF	oF	kBtuh	kW
	59	-22	15.278	2.870
	59	-13	19.218	3.080
	59	-4	21.828	3.300
	59	0	23.668	3.450
	59	5	25.288	3.460
	59	17	26.988	3.420
	59	19.4	27.178	3.380
	59	24.8	27.678	3.290
	59	32	31.948	2.860
	59	39.2	35.328	3.100
	59	44.6	32.658	2.400
	59	53.6	30.998	1.750
	54.4	-22	14.838	2.970
	54.4	-13	18.678	3.190
	54.4	-4	21.218	3.420
	54.4	0	23.008	3.570
	54.4	5	24.578	3.580
	54.4	17	26.228	3.530
	54.4	19.4	26.418	3.490
	54.4	24.8	26.898	3.400
	54.4	32	31.048	2.960
	54.4	39.2	34.338	3.210
	54.4	44.6	31.748	2.480
	54.4	53.6	30.128	1.820
	69	-22	14.698	3.070
	69	-13	18.318	3.300
	69	-4	20.808	3.530
	69	0	22.568	3.690
	69	5	24.108	3.690
	69	17	25.728	3.650
	69	19.4	25.908	3.610
	69	24.8	26.388	3.510
	69	32	30.458	3.060
	69	39.2	33.678	3.320
	69	44.6	31.138	2.570
	69	53.6	29.558	1.880
	71.6	-22	13.968	3.160
	71.6	-13	17.588	3.400
	71.6	-4	19.988	3.650
	71.6	0	21.678	3.810
	71.6	5	23.158	3.810
	71.6	17	24.718	3.770
	71.6	19.4	24.898	3.720
	71.6	24.8	25.348	3.630
	71.6	32	29.268	3.160

3. Include performance curves in EnergyPlus input files

The following performance curves replace standard system performance curves to represent a single speed high efficiency heat pump used in cold climates.

Figure 40. Cooling values used for Energy Plus input deck, provided for easier replication by readers.

```
! 0.7719,  R Squared
Curve:Biquadratic,
Cool-Cap-fT_1,  !- Name
-0.1223964072,  !- Coefficient1 Constant
0.1048157538,  !- Coefficient2 x
-0.0021446971,  !- Coefficient3 x**2
0.0045547784,  !- Coefficient4 y
-0.0002350492,  !- Coefficient5 y**2
-0.0000640273,  !- Coefficient6 x*y
15,  !- Minimum Value of x
23,  !- Maximum Value of x
-20,  !- Minimum Value of y
50,  !- Maximum Value of y
0.4624,  !- Minimum Curve Output
1.1426,  !- Maximum Curve Output
Temperature,  !- Input Unit Type for X
Temperature,  !- Input Unit Type for Y
Dimensionless;  !- Output Unit Type

! 0.9769,  R Squared
Curve:Biquadratic,
Cool-EIR-fT_1,  !- Name
1.3403438839,  !- Coefficient1 Constant
-0.0843581664,  !- Coefficient2 x
0.0018971131,  !- Coefficient3 x**2
0.008117669,  !- Coefficient4 y
0.0003036834,  !- Coefficient5 y**2
-0.0002384596,  !- Coefficient6 x*y
15,  !- Minimum Value of x
23,  !- Maximum Value of x
-20,  !- Minimum Value of y
50,  !- Maximum Value of y
0.3961,  !- Minimum Curve Output
1.5156,  !- Maximum Curve Output
Temperature,  !- Input Unit Type for X
Temperature,  !- Input Unit Type for Y
Dimensionless;  !- Output Unit Type
```

Figure 39. Heating values used for Energy Plus input deck, provided for easier replication by readers.

```
! 0.9362,  R Squared
Curve:Biquadratic,
HP_Heat-Cap-fT_1,  !- Name
0.5280497754,  !- Coefficient1 Constant
0.074332633,  !- Coefficient2 x
-0.0023444027,  !- Coefficient3 x**2
0.011296913,  !- Coefficient4 y
-0.0002808102,  !- Coefficient5 y**2
-0.0000953735,  !- Coefficient6 x*y
12.44,  !- Minimum Value of x
22,  !- Maximum Value of x
-30,  !- Minimum Value of y
12,  !- Maximum Value of y
0.5079,  !- Minimum Curve Output
1.2847,  !- Maximum Curve Output
Temperature,  !- Input Unit Type for X
Temperature,  !- Input Unit Type for Y
Dimensionless;  !- Output Unit Type

! 0.9777,  R Squared
Curve:Biquadratic,
HP_Heat-EIR-fT_1,  !- Name
4.299827345,  !- Coefficient1 Constant
-0.3472230727,  !- Coefficient2 x
0.0107280919,  !- Coefficient3 x**2
-0.0414968883,  !- Coefficient4 y
-0.0002263032,  !- Coefficient5 y**2
-0.0006882784,  !- Coefficient6 x*y
12.44,  !- Minimum Value of x
22,  !- Maximum Value of x
-30,  !- Minimum Value of y
12,  !- Maximum Value of y
0.8821,  !- Minimum Curve Output
3.5348,  !- Maximum Curve Output
Temperature,  !- Input Unit Type for X
Temperature,  !- Input Unit Type for Y
Dimensionless;  !- Output Unit Type
```

4. Perform simulations

A group file is created, containing input file names, weather file names and output file names, so that multiple runs can be performed automatically. The feature of Group of Input Files in EP-Launch is used to make multiple simulations. A detailed description of the group file is provided in EnergyPlus documents[13].

System input for oversized comparison

Table A-1 lists input values for a double wide MH located in Chicago with 4 types of HP: standard as baseline, 2 stage with 2 speeds, variable speed and oversize variable speed. The listed inputs are cooling supply flow rate (CFM), cooling capacity (kBtu/h), cooling COP,

[13] DOE EnergyPlus: Running Groups of Input Files in Auxiliary Programs manual

heating supply flow rate (CFM), heating capacity (kBtu/h), heating COP, Fan efficiency, fan pressure rise (psi), and fan flow rate (CFM). All these inputs are provided by BEopt. Standard size cooling COP with variable speed is slightly higher than oversize variable speed HP. These COP values may be from real equipment, so that larger size equipment may have low COP values. That is why cooling energy use with variable speed HP in Chicago is lower than ones with oversize variable speed HP. However, heating COP remains the same with both variable speed and oversize variable speed, as expected.

Table A-1. Inputs used for 2-speed and 4-speed systems in Chicago.

Standard+	CFM	kBtu/h		CFM	kBtu			psi	CFM
	Cool Supp	Cool Capa	Cool COP	Heat Supp	Heat Capa	Heat COP	Fan Eff	Fan Pressu	Fan Flow
	588.3366	30.0281	4.414046	794.9476	30.0281	3.712137	0.117562	0.018064	794.9576
2 stage									
	Cool Supp	Cool Capa	Cool COP	Heat Supp	Heat Capa	Heat COP	Fan Eff	Fan Pressu	Fan Flow
1st speed	474.2451	21.62023	4.982528	683.6549	21.62023	4.595107	0.195937	0.018064	794.9576
2nd speec	551.4478	30.0281	4.397791	794.9476	30.0281	3.921722	0	0	0
Variable Speed									
	Cool Supp	Cool Capa	Cool COP	Heat Supp	Heat Capa	Heat COP	Fan Eff	Fan Pressu	Fan Flow
1st speed	354.1768	14.71377	5.648218	556.4633	14.71377	5.132162	0.195937	0.018064	1001.647
2nd speec	455.3702	20.11882	5.436592	715.4528	20.11882	4.834015	0	0	0
3rd speed	505.9669	30.0281	4.568723	794.9476	30.0281	4.077639	0	0	0
4th speed	637.5183	36.03371	4.126097	1001.634	36.03371	4.111144	0	0	0
Variable Speed Oversize									
	Cool Supp	Cool Capa	Cool COP	Heat Supp	Heat Capa	Heat COP	Fan Eff	Fan Pressu	Fan Flow
1st speed	354.1768	17.65652	5.365807	667.756	17.65652	5.132162	0.195937	0.018064	1201.973
2nd speec	455.3702	24.14259	5.164763	858.5434	24.14259	4.834015	0	0	0
3rd speed	505.9669	36.03371	4.340286	953.9371	36.03371	4.077639	0	0	0
4th speed	637.5183	43.24046	3.919792	1201.961	43.24046	4.111144	0	0	0

Table A-2 lists input values for a double wide MH located in Houston with 4 types of HP: standard as baseline, 2 stage with 2 speeds, variable speed and oversize variable speed. The listed inputs are cooling supply flow rate (CFM), cooling capacity (kBtu/h), cooling COP, heating supply flow rate (CFM), heating capacity (kBtu/h), heating COP, Fan efficiency, fan pressure rise (psi), and fan flow rate (CFM). All these inputs are provided by BEopt.

The cooling supply flow rate and cooling COP are the same in both variable speed and oversized variable speed heat pumps. The differences are cooling capacities. Therefore, annual cooling energy use is reduced with oversized variable speed HP.

Table A-2. Inputs used for 2-speed and 4-speed systems in Houston.

Standard									
	Cool Supp	Cool Capa	Cool COP	Heat Supp	Heat Capa	Heat COP	Fan Eff	Fan Pressu	Fan Flow
	634.9988	24.02248	4.414046	625.161	24.02248	3.712137	0.117562	0	635.0088
2 stage									
	Cool Supp	Cool Capa	Cool COP	Heat Supp	Heat Capa	Heat COP	Fan Eff	Fan Pressu	Fan Flow
1st speed	540.6137	17.29618	4.982528	537.6385	17.29618	4.595107	0.195937	0	628.6306
2nd speec	628.6206	24.02248	4.397791	625.161	24.02248	3.921722	0	0	0
Variable Speed									
	Cool Supp	Cool Capa	Cool COP	Heat Supp	Heat Capa	Heat COP	Fan Eff	Fan Pressu	Fan Flow
1st speed	421.8756	11.77101	5.648218	437.6127	11.77101	5.132162	0.195937	0	787.7029
2nd speec	542.4115	16.09506	5.436592	562.6449	16.09506	4.834015	0	0	0
3rd speed	602.6795	24.02248	4.568723	625.161	24.02248	4.077639	0	0	0
4th speed	759.3762	28.82697	4.126097	787.7029	28.82697	4.111144	0	0	0
Variable Speed Oversize									
	Cool Supp	Cool Capa	Cool COP	Heat Supp	Heat Capa	Heat COP	Fan Eff	Fan Pressu	Fan Flow
1st speed	421.8756	14.71377	5.648218	547.0159	14.71377	5.132162	0.195937	0	984.6412
2nd speec	542.4115	20.11882	5.436592	703.3062	20.11882	4.834015	0	0	0
3rd speed	602.6795	30.0281	4.568723	781.4513	30.0281	4.077639	0	0	0
4th speed	759.3762	36.03371	4.126097	984.6286	36.03371	4.111144	0	0	0

Output for oversized variable speed heat pumps

As discussed, variable speed heat pumps have relatively higher efficiency in low speed and lower efficiency in high speed. When the system is oversized, it is expected for the oversized system to operate more times at low speed than a standard variable speed size system, so that energy use with more operation at lower speed is expected to be lower, compared to the standard variable speed size system.

To know the energy use impact for oversized HP systems, we tested cases with a half-ton increase of both heating and cooling capacities with a double-wide unit in Chicago and Houston (Figure 41. Comparison and cooling energy use of baseline and oversized variable speed systems. Figure 41 shows annual energy use in kBtu. Oversize systems do reduce annual energy use at 5.6 percent in Houston and increase energy use by 0.6 percent in Chicago, respectively. However, the difference is not significant and unlikely to justify a more expensive system.

Figure 41. Comparison and cooling energy use of baseline and oversized variable speed systems

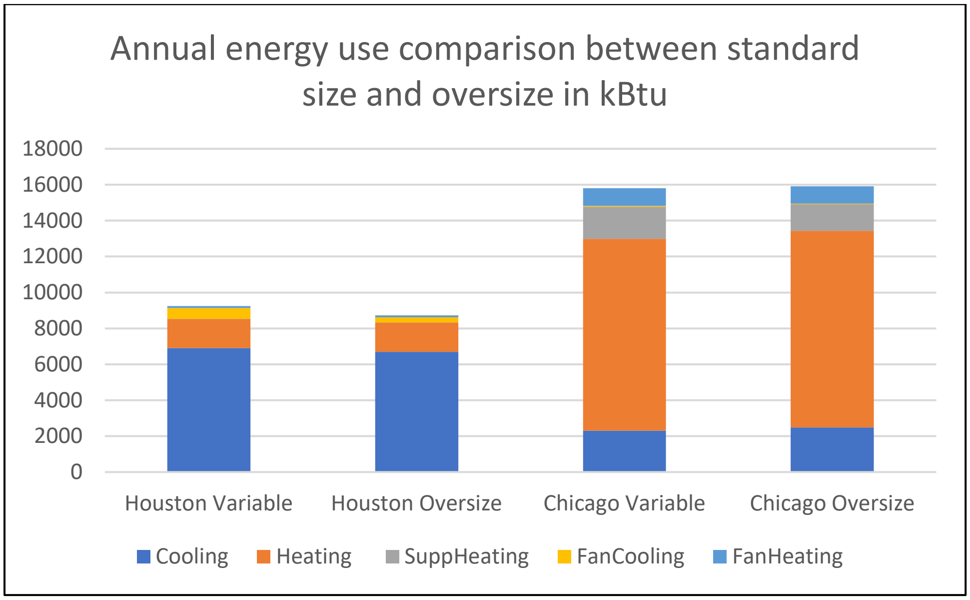


Table A-3 shows annual component energy use, separated by heating, cooling, supplemental heating and fan. The percentage differences are also listed. The positive differences represent less energy use, while negative ones represent more energy use. In Chicago the oversize system was able to greatly reduce the supplemental electric resistance heating, however the model indicated more cooling energy use and significantly more cooling fan energy use for the larger system. The main reason of increase in Chicago is that the cooling COP in oversize HP is slightly lower at low speed. There is a tradeoff of a larger system running for shorter cycles which will reduce efficiency while increasing efficiency by running more time at lower speeds. In heating mode, the additional advantage is that the larger capacity heat pump system will reduce supplemental heating during peak times. Overal,l the heating and cooling for Chicago balanced out. We caution readers to not generalize the actual percentage results as they may be sensitive to the original and oversize capacity and the models used.

Table A-3. Heating and cooling energy use comparisons with variable speed HP systems for Houston and Chicago for baseline and oversized systems.

	Houston Variable	**Houston Oversize**	**Diff (%)**	**Chicago Variable**	**Chicago Oversize**	**Diff (%)**
Cooling	6900	6701	2.9%	2313	2493	-7.8%
Heating	1629	1630	-0.08%	10672	10945	-2.6%
SuppHeating	1.25	0	100.00%	1782	1472	17.4%
FanCooling	599	282	52.90%	59.0	34.5	41.6%
FanHeating	112	107	4.9%	984	961	2.3%
Total	9241	8720	5.6%	15810	15904	-0.60%

APPENDIX B DETAILED SIMULATION OUTPUTS

This appendix presents annual energy use for HVAC systems and associated components. All tables have the same format. The first column provides the case number for each building type and baseline. The second column presents case acronym to show HVAC system type, location, and improvement parameters. The detailed explanation for each acronym is presented in Table B-1. The next 6 columns present annual energy use for cooling coil, heating coil, supplemental heating coil for HP system type, fan energy use during cooling, fan energy use during heating, and total HVAC system energy use, respectively.

Table B-1. Case acronym and corresponding presentation

Acronym	Presentation
EF	AC for cooling and electric resistance furnace for heating
HP	Heat pump with a supplemental electric resistance heater
GF	AC for cooling and gas furnace for heating with AFUE80
Ceil	Attic supply duct
CeilCrawl	Attic and crawl space ducts
Qn06	Duct leakage with Qn = 6%
Qn03	Duct leakage with Qn = 3%
Qn00	Duct leakage with Qn = 0%
R16Duct	Duct insulation with R-16
AFUE90	Gas furnace with AFUE90
2Stage	AC or HP with 2 speeds
VariSpeed	AC or HP with variable speed
CHP	Cold climate HP
CompLock	Compressor lock out with -8C outdoor temperature

Table B-21. Double-wide baseline annual energy use using original-baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
1	EF_Houston	10578	8673	0	3673	289	23212
2	HP_Houston	10417	2806	38	3714	485	17459
3	EF_Phoenix	16966	4284	0	4495	150	25894
4	GF_Phoenix	17108	5791	0	4530	162	27591
5	HP_Phoenix	16786	1336	0	4512	227	22861
6	EF_Atlanta	6929	19269	0	2751	661	29610
7	HP_Atlanta	6730	6256	474	2788	1146	17392
8	EF_Baltimore	5753	31325	0	1512	1028	39619
9	GF_Baltimore	5772	42775	0	1513	1122	51182
10	HP_Baltimore	5222	10324	1543	1523	1908	20520
11	EF_Chicago	4332	49836	0	1059	1652	56879
12	GF_Chicago	4350	67769	0	1062	1801	74982
13	HP_Chicago	4057	16244	4694	893	3259	29145
14	EF_Raleigh	6635	25202	0	2069	841	34747
15	GF_Raleigh	6654	33685	0	2076	900	43315
16	HP_Raleigh	6597	8320	712	2088	1524	19241
17	EF_Denver	5118	35354	0	1024	1412	42908
18	GF_Denver	5109	47419	0	1017	1514	55059
19	HP_Denver	4474	11834	1720	1007	2699	21733
20	EF_Seattle	1630	29506	0	446	957	32539
21	GF_Seattle	1611	39192	0	441	1019	42263
22	HP_Seattle	1479	8905	574	450	1531	12938
23	EF_Houston_Ceil	11677	8966	0	4167	297	25108
24	HP_Houston_Ceil	11412	4136	6	4197	390	20141
25	EF_Atlanta_Ceil	8710	20369	0	3950	694	33723
26	HP_Atlanta_Ceil	7260	8548	418	3548	1087	20861
27	EF_Houston_CeilCrawl	11999	9203	0	4284	303	25790
28	HP_Houston_CeilCrawl	11724	4247	9	4309	401	20691
29	EF_Atlanta_CeilCrawl	7962	20975	0	3602	711	33249
30	HP_Atlanta_CeilCrawl	7450	8786	531	3638	1120	21525

Table B-22. Double-wide annual energy use with duct leakage variations using original-baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
31	EF_Houston_Qn06	10085	8151	0	3499	274	22008
32	HP_Houston_Qn06	9933	2663	19	3541	458	16615
33	EF_Phoenix_Qn06	16350	4057	0	4341	143	24890
34	GF_Phoenix_Qn06	16511	5497	0	4376	154	26539
35	HP_Phoenix_Qn06	16179	1270	0	4353	215	22018
36	EF_Atlanta_Qn06	6635	18331	0	2635	635	28235
37	HP_Atlanta_Qn06	6436	6046	352	2670	1102	16606
38	EF_Baltimore_Qn06	5355	29003	0	1406	964	36728
39	GF_Baltimore_Qn06	5384	39818	0	1413	1061	47675
40	HP_Baltimore_Qn06	4862	9814	1105	1419	1803	19004
41	EF_Chicago_Qn06	4000	45960	0	975	1546	52481
42	GF_Chicago_Qn06	4028	62945	0	978	1695	69646
43	HP_Chicago_Qn06	3782	15559	3814	830	3104	27089
44	EF_Raleigh_Qn06	6256	23610	0	1952	797	32614
45	GF_Raleigh_Qn06	6284	31695	0	1959	856	40794
46	HP_Raleigh_Qn06	6218	7954	472	1971	1451	18065
47	EF_Denver_Qn06	4692	32340	0	938	1309	39278
48	GF_Denver_Qn06	4682	43666	0	935	1416	50699
49	HP_Denver_Qn06	4151	11271	1155	934	2554	20065
50	EF_Seattle_Qn06	1469	26406	0	401	869	29145
51	GF_Seattle_Qn06	1450	35249	0	397	930	38026
52	HP_Seattle_Qn06	1327	8162	293	403	1388	11573
53	EF_Houston_Ceil_Qn06	11080	8511	0	3952	285	23828
54	HP_Houston_Ceil_Qn06	10834	3959	3	3980	370	19146
55	EF_Atlanta_Ceil_Qn06	8237	19364	0	3739	668	32008
56	HP_Atlanta_Ceil_Qn06	6872	8226	304	3359	1038	19800
57	EF_Houston_CeilCrawl_Qn06	11374	8720	0	4060	291	24444
58	HP_Houston_CeilCrawl_Qn06	11118	4061	5	4083	381	19648
59	EF_Atlanta_CeilCrawl_Qn06	7535	19923	0	3411	683	31553
60	HP_Atlanta_CeilCrawl_Qn06	7052	8456	388	3449	1072	20416
61	EF_Houston_Qn03	9857	7905	0	3420	267	21449
62	HP_Houston_Qn03	9715	2593	13	3459	446	16227
63	EF_Phoenix_Qn03	16056	3952	0	4259	139	24406
64	GF_Phoenix_Qn03	16227	5365	0	4304	151	26046
65	HP_Phoenix_Qn03	15876	1242	0	4274	210	21601
66	EF_Atlanta_Qn03	6493	17885	0	2581	623	27581
67	HP_Atlanta_Qn03	6303	5943	303	2609	1078	16236
68	EF_Baltimore_Qn03	5175	27923	0	1358	936	35391
69	GF_Baltimore_Qn03	5204	38434	0	1365	1033	46035

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
70	HP_Baltimore_Qn03	4701	9566	927	1369	1749	18312
71	EF_Chicago_Qn03	3848	44140	0	940	1505	50433
72	GF_Chicago_Qn03	3877	60651	0	943	1654	67124
73	HP_Chicago_Qn03	3649	15231	3441	802	3028	26150
74	EF_Raleigh_Qn03	6085	22871	0	1896	777	31629
75	GF_Raleigh_Qn03	6113	30757	0	1903	836	39609
76	HP_Raleigh_Qn03	6047	7780	381	1914	1412	17535
77	EF_Denver_Qn03	4502	30937	0	902	1269	37609
78	GF_Denver_Qn03	4493	41922	0	895	1370	48680
79	HP_Denver_Qn03	4009	11003	939	902	2482	19335
80	EF_Seattle_Qn03	1393	25013	0	382	831	27619
81	GF_Seattle_Qn03	1374	33467	0	378	892	36112
82	HP_Seattle_Qn03	1261	7817	202	385	1330	10995
83	EF_Houston_Ceil_Qn03	10796	8293	0	3853	279	23222
84	HP_Houston_Ceil_Qn03	10549	3874	2	3884	362	18672
85	EF_Atlanta_Ceil_Qn03	8009	18881	0	3637	656	31183
86	HP_Atlanta_Ceil_Qn03	6692	8075	257	3276	1017	19317
87	EF_Houston_CeilCrawl_Qn03	11080	8502	0	3952	285	23819
88	HP_Houston_CeilCrawl_Qn03	10824	3968	3	3979	371	19146
89	EF_Atlanta_CeilCrawl_Qn03	7336	19421	0	3320	670	30747
90	HP_Atlanta_CeilCrawl_Qn03	6862	8294	331	3358	1049	19895
91	EF_Houston_Qn00	9639	7677	0	3342	260	20918
92	HP_Houston_Qn00	9497	2530	10	3386	434	15857
93	EF_Phoenix_Qn00	15762	3848	0	4186	136	23932
94	GF_Phoenix_Qn00	15952	5232	0	4231	148	25563
95	HP_Phoenix_Qn00	15582	1213	0	4194	204	21193
96	EF_Atlanta_Qn00	6360	17449	0	2526	611	26946
97	HP_Atlanta_Qn00	6170	5835	260	2562	1059	15885
98	EF_Baltimore_Qn00	5004	26880	0	1315	912	34112
99	GF_Baltimore_Qn00	5033	37098	0	1323	1009	44462
100	HP_Baltimore_Qn00	4540	9334	769	1325	1698	17667
101	EF_Chicago_Qn00	3706	42386	0	905	1465	48462
102	GF_Chicago_Qn00	3734	58433	0	911	1619	64698
103	HP_Chicago_Qn00	3526	14914	3113	776	2949	25278
104	EF_Raleigh_Qn00	5914	22150	0	1847	760	30671
105	GF_Raleigh_Qn00	5952	29847	0	1854	818	38472
106	HP_Raleigh_Qn00	5876	7610	304	1864	1377	17032
107	EF_Denver_Qn00	4332	29610	0	866	1229	36036
108	GF_Denver_Qn00	4322	40244	0	862	1337	46765
109	HP_Denver_Qn00	3867	10738	759	871	2408	18644
110	EF_Seattle_Qn00	1327	23714	0	365	801	26207
111	GF_Seattle_Qn00	1317	31799	0	359	855	34330

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
112	HP_Seattle_Qn00	1204	7499	131	366	1264	10464
113	EF_Houston_Ceil_Qn00	10521	8085	0	3755	274	22634
114	HP_Houston_Ceil_Qn00	10284	3790	1	3780	352	18208
115	EF_Atlanta_Ceil_Qn00	7791	18426	0	3536	644	30396
116	HP_Atlanta_Ceil_Qn00	6512	7927	215	3186	994	18833
117	EF_Houston_CeilCrawl_Qn00	10796	8284	0	3853	279	23212
118	HP_Houston_CeilCrawl_Qn00	10549	3884	2	3884	363	18681
119	EF_Atlanta_CeilCrawl_Qn00	7137	18947	0	3236	659	29979
120	HP_Atlanta_CeilCrawl_Qn00	6682	8145	281	3268	1025	19402

Table B-23. Double-wide annual energy use with duct insulation level variations using original-baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
121	EF_Houston_R16Duct	10549	8635	0	3655	287	23127
122	HP_Houston_R16Duct	10388	2789	36	3706	483	17402
123	EF_Phoenix_R16Duct	16909	4265	0	4486	149	25809
124	GF_Phoenix_R16Duct	17051	5772	0	4521	161	27506
125	HP_Phoenix_R16Duct	16729	1327	0	4495	226	22776
126	EF_Atlanta_R16Duct	6919	19193	0	2745	658	29515
127	HP_Atlanta_R16Duct	6711	6232	460	2775	1139	17317
128	EF_Baltimore_R16Duct	5734	31145	0	1503	1018	39401
129	GF_Baltimore_R16Duct	5753	42519	0	1509	1116	50898
130	HP_Baltimore_R16Duct	5204	10259	1494	1516	1896	20369
131	EF_Chicago_R16Duct	4313	49504	0	1053	1638	56509
132	GF_Chicago_R16Duct	4341	67323	0	1057	1787	74508
133	HP_Chicago_R16Duct	4047	16154	4584	890	3243	28918
134	EF_Raleigh_R16Duct	6616	25079	0	2064	837	34595
135	GF_Raleigh_R16Duct	6635	33524	0	2064	894	43116
136	HP_Raleigh_R16Duct	6578	8279	687	2084	1518	19146
137	EF_Denver_R16Duct	5090	35060	0	1018	1399	42566
138	GF_Denver_R16Duct	5080	47040	0	1012	1500	54632
139	HP_Denver_R16Duct	4455	11757	1645	1003	2684	21544
140	EF_Seattle_R16Duct	1621	29269	0	444	949	32283
141	GF_Seattle_R16Duct	1602	38889	0	439	1011	41941
142	HP_Seattle_R16Duct	1469	8829	545	447	1515	12805
143	EF_Houston_Ceil_R16Duct	11326	8739	0	4052	289	24406
144	HP_Houston_Ceil_R16Duct	11071	4015	4	4076	379	19544
145	EF_Atlanta_Ceil_R16Duct	8417	19828	0	3825	677	32747
146	HP_Atlanta_Ceil_R16Duct	7014	8310	334	3428	1055	20141
147	EF_Houston_CeilCrawl_R16Duct	11506	8862	0	4114	293	24776
148	HP_Houston_CeilCrawl_R16Duct	11241	4080	5	4136	385	19847
149	EF_Atlanta_CeilCrawl_R16Duct	7611	20170	0	3448	685	31913
150	HP_Atlanta_CeilCrawl_R16Duct	7128	8439	385	3483	1076	20511

Table B-24. Double-wide annual energy use with HVAC system efficiency variations using original-baseline parameters

Num	Case Acronym	Cooling	Heating	Supp Heating	Fan Cooling	Fan Heating	Total
151	GF_Baltimore_AFUE90	5753	34804	0	1512	1028	43097
152	GF_Chicago_AFUE90	4332	55381	0	1059	1652	62423
153	GF_Denver_AFUE90	5118	39278	0	1024	1412	46832
154	GF_Phoenix_AFUE90	16966	4758	0	4495	150	26368
155	GF_Raleigh_AFUE90	6635	27999	0	2069	841	37543
156	GF_Seattle_AFUE90	1630	32776	0	446	957	35809
157	HP_Atlanta_2Stage	5886	5526	777	1516	209	13914
158	HP_Atlanta_VariSpeed	4720	5524	267	699	220	11431
159	HP_Baltimore_2Stage	4180	9464	2222	776	740	17383
160	HP_Baltimore_VariSpeed	3317	9433	1012	389	606	14758
161	HP_Chicago_2Stage	3327	14971	5909	358	1926	26491
162	HP_Chicago_VariSpeed	2407	15117	3536	141	1470	22672
163	HP_Denver_2Stage	3602	10153	2311	310	1576	17952
164	HP_Denver_VariSpeed	2862	11028	1019	143	1174	16227
165	HP_Houston_2Stage	8786	2454	76	1912	116	13345
166	HP_Houston_VariSpeed	7431	2329	12	1067	80	10919
167	HP_Phoenix_2Stage	14540	1090	0	2354	72	18056
168	HP_Phoenix_VariSpeed	12805	1062	0	1369	34	15269
169	HP_Raleigh_2Stage	5365	7526	1137	1072	501	15601
170	HP_Raleigh_VariSpeed	4436	7438	363	573	394	13203
171	HP_Seattle_2Stage	1280	7784	898	219	786	10966
172	HP_Seattle_VariSpeed	995	7400	343	119	545	9402
173	EF_Atlanta_2Stage	5677	19923	0	1518	93	27212
174	EF_Atlanta_VariSpeed	4000	20283	0	616	95	24994
175	EF_Baltimore_2Stage	4493	32273	0	778	302	37846
176	EF_Baltimore_VariSpeed	2806	32539	0	325	234	35903
177	GF_Baltimore_2Stage	4512	44064	0	779	330	49685
178	GF_Baltimore_VariSpeed	2824	44405	0	325	253	47808
179	EF_Chicago_2Stage	3422	50784	0	543	812	55561
180	EF_Chicago_VariSpeed	2028	51305	0	213	630	54177
181	GF_Chicago_2Stage	3441	69067	0	547	884	73939
182	GF_Chicago_VariSpeed	2057	69740	0	218	682	72698
183	EF_Denver_2Stage	4057	35941	0	408	815	41221
184	EF_Denver_VariSpeed	2588	36178	0	179	580	39524
185	GF_Denver_2Stage	4047	48234	0	406	873	53561
186	GF_Denver_VariSpeed	2588	48547	0	178	618	51931
187	EF_Houston_2Stage	8928	8995	0	1927	54	19904
188	EF_Houston_VariSpeed	6350	9042	0	964	41	16397
189	EF_Phoenix_2Stage	13999	4474	0	2348	12	20833

Num	Case Acronym	Cooling	Heating	Supp Heating	Fan Cooling	Fan Heating	Total
190	EF_Phoenix_VariSpeed	11952	4455	0	1082	8	17497
191	GF_Phoenix_2Stage	14113	6047	0	2366	13	22539
192	GF_Phoenix_VariSpeed	12094	6019	0	1101	8	19222
193	EF_Raleigh_2Stage	5658	26018	0	1079	210	32965
194	EF_Raleigh_VariSpeed	3763	26198	0	503	161	30624
195	GF_Raleigh_2Stage	5687	34775	0	1083	225	41770
196	GF_Raleigh_VariSpeed	3791	35003	0	510	172	39477
197	EF_Seattle_2Stage	1242	29923	0	240	329	31733
198	EF_Seattle_VariSpeed	787	29913	0	98	338	31136
199	GF_Seattle_2Stage	1232	39770	0	238	350	41590
200	GF_Seattle_VariSpeed	777	39761	0	97	358	40993
201	EF_Atlanta_Ceil_2Stage	6711	23534	0	2543	54	32842
202	EF_Atlanta_Ceil_VariSpeed	4834	24018	0	1158	55	30065
203	HP_Atlanta_Ceil_2Stage	7886	6799	2063	2531	123	19402
204	HP_Atlanta_Ceil_VariSpeed	5611	6966	910	1218	146	14852
205	EF_Houston_Ceil_2Stage	10104	10360	0	3415	26	23904
206	EF_Houston_Ceil_VariSpeed	7365	10407	0	1857	20	19648
207	HP_Houston_Ceil_2Stage	11867	3088	296	3371	60	18681
208	HP_Houston_Ceil_VariSpeed	8644	2992	70	2011	46	13762
209	EF_Atlanta_CeilCrawl_2Stage	6957	25686	0	2624	58	35325
210	EF_Atlanta_CeilCrawl_VariSpeed	5061	26236	0	1210	60	32567
211	HP_Atlanta_CeilCrawl_2Stage	8142	7260	2910	2607	132	21051
212	HP_Atlanta_CeilCrawl_VariSpeed	5981	7589	1396	1342	165	16473
213	EF_Houston_CeilCrawl_2Stage	10492	11175	0	3536	28	25231
214	EF_Houston_CeilCrawl_VariSpeed	7782	11232	0	1998	21	21032
215	HP_Houston_CeilCrawl_2Stage	12303	3317	465	3490	65	19639
216	HP_Houston_CeilCrawl_VariSpeed	8985	3282	121	2062	52	14502
217	HP_Chicago_VariSpeed_Oversize	2588	15346	2672	81	1398	22084
218	HP_Houston_VariSpeed_Oversize	7241	2350	0	801	119	10511

Table B-25. Double-wide annual energy use with cold climate HP and compressor operation using original-baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
219	HP_Baltimore_CHP	3810	11089	266	1579	1605	18350
220	HP_Chicago_CHP	2910	18604	1546	895	2679	26634
221	HP_Denver_CHP	3365	13022	248	1043	2208	19885
222	HP_Seattle_CHP	1090	8365	137	464	1375	11431
223	HP_Houston_CompLock	10417	2806	38	3714	485	17459
224	HP_Phoenix_CompLock	16786	1336	0	4512	227	22861
225	HP_Atlanta_CompLock	6730	6178	656	2788	1146	17497
226	HP_Baltimore_CompLock	5222	9587	3284	1523	1908	21525
227	HP_Chicago_CompLock	4057	13191	11652	892	3269	33060
228	HP_Raleigh_CompLock	6597	8221	954	2088	1524	19383
229	HP_Denver_CompLock	4474	10736	4240	1008	2707	23165
230	HP_Seattle_CompLock	1479	8905	574	450	1531	12938
231	HP_Houston_Ceil_CompLock	11412	4136	6	4197	390	20141
232	HP_Atlanta_Ceil_CompLock	7260	8440	631	3548	1087	20966
233	HP_Houston_CeilCrawl_CompLock	11724	4247	9	4309	401	20691
234	HP_Atlanta_CeilCrawl_CompLock	7450	8667	744	3638	1120	21620

Table B-26. Single-wide annual energy use using original-baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
1	EF_Houston	8,151	5,317	0	2,694	178	16,340
2	HP_Houston	8,000	1,740	23	2,779	301	12,843
3	EF_Phoenix	12,625	2,550	0	3,531	89	18,795
4	GF_Phoenix	12,682	3,384	0	3,545	95	19,705
5	HP_Phoenix	12,473	796	0	3,542	136	16,947
6	EF_Atlanta	5,431	12,198	0	2,026	419	20,075
7	HP_Atlanta	5,327	4,035	239	2,046	741	12,388
8	EF_Baltimore	4,550	19,108	0	1,061	627	25,345
9	GF_Baltimore	4,559	25,676	0	1,061	674	31,970
10	HP_Baltimore	4,114	6,480	714	1,070	1,205	13,582
11	EF_Chicago	3,384	30,245	0	746	1,007	35,382
12	GF_Chicago	3,403	40,538	0	748	1,081	45,770
13	HP_Chicago	3,185	10,398	2,104	601	2,110	18,397
14	EF_Raleigh	5,222	15,980	0	1,551	534	23,288
15	GF_Raleigh	5,232	21,023	0	1,552	562	28,368
16	HP_Raleigh	5,147	5,371	354	1,595	983	13,450
17	EF_Denver	3,924	20,947	0	723	841	26,435
18	GF_Denver	3,914	27,752	0	719	892	33,278
19	HP_Denver	3,478	7,410	685	725	1,692	13,990
20	EF_Seattle	1,422	16,265	0	285	530	18,501
21	GF_Seattle	1,412	21,402	0	283	560	23,658
22	HP_Seattle	1,261	5,131	35	284	882	7,592
23	EF_Houston_Ceil	8,815	5,535	0	3,190	184	17,724
24	HP_Houston_Ceil	8,151	2,436	10	3,097	268	13,961
25	EF_Atlanta_Ceil	5,962	12,890	0	2,280	440	21,572
26	HP_Atlanta_Ceil	5,801	5,712	165	2,296	671	14,644
27	EF_Houston_CeilCrawl	9,127	5,706	0	3,299	189	18,321
28	HP_Houston_CeilCrawl	8,436	2,517	14	3,201	277	14,445
29	EF_Atlanta_CeilCrawl	6,161	13,374	0	2,353	453	22,340
30	HP_Atlanta_CeilCrawl	6,000	5,924	218	2,372	699	15,212

Table B-27. Single-wide annual energy use with duct leakage variations using original-baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
31	EF_Houston_Qn06	7,819	5,042	0	2,588	170	15,620
32	HP_Houston_Qn06	7,687	1,664	14	2,670	287	12,322
33	EF_Phoenix_Qn06	12,189	2,436	0	3,412	86	18,122
34	GF_Phoenix_Qn06	12,265	3,232	0	3,425	91	19,013
35	HP_Phoenix_Qn06	12,047	768	0	3,424	130	16,369
36	EF_Atlanta_Qn06	5,222	11,668	0	1,946	404	19,241
37	HP_Atlanta_Qn06	5,128	3,900	185	1,968	714	11,895
38	EF_Baltimore_Qn06	4,265	17,791	0	992	591	23,639
39	GF_Baltimore_Qn06	4,275	23,999	0	993	637	29,904
40	HP_Baltimore_Qn06	3,848	6,159	495	1,003	1,139	12,644
41	EF_Chicago_Qn06	3,185	28,349	0	701	957	33,193
42	GF_Chicago_Qn06	3,204	38,169	0	703	1,032	43,107
43	HP_Chicago_Qn06	3,024	10,004	1,805	570	2,018	17,421
44	EF_Raleigh_Qn06	4,957	15,099	0	1,479	511	22,046
45	GF_Raleigh_Qn06	4,976	19,914	0	1,480	539	26,909
46	HP_Raleigh_Qn06	4,900	5,148	255	1,523	942	12,767
47	EF_Denver_Qn06	3,696	19,601	0	680	799	24,776
48	GF_Denver_Qn06	3,687	26,074	0	677	849	31,287
49	HP_Denver_Qn06	3,279	7,071	483	682	1,602	13,118
50	EF_Seattle_Qn06	1,317	14,966	0	264	494	17,042
51	GF_Seattle_Qn06	1,308	19,753	0	263	524	21,847
52	HP_Seattle_Qn06	1,175	4,790	16	264	817	7,061
53	EF_Houston_Ceil_Qn06	8,426	5,289	0	3,054	178	16,947
54	HP_Houston_Ceil_Qn06	7,801	2,344	6	2,967	256	13,374
55	EF_Atlanta_Ceil_Qn06	5,706	12,331	0	2,181	426	20,643
56	HP_Atlanta_Ceil_Qn06	5,554	5,525	124	2,199	644	14,047
57	EF_Houston_CeilCrawl_Qn06	8,729	5,450	0	3,155	182	17,516
58	HP_Houston_CeilCrawl_Qn06	8,066	2,417	9	3,071	266	13,829
59	EF_Atlanta_CeilCrawl_Qn06	5,886	12,786	0	2,253	438	21,364
60	HP_Atlanta_CeilCrawl_Qn06	5,734	5,720	166	2,268	670	14,558
61	EF_Houston_Qn03	7,658	4,919	0	2,535	166	15,279
62	HP_Houston_Qn03	7,526	1,629	11	2,611	280	12,056
63	EF_Phoenix_Qn03	11,980	2,379	0	3,356	84	17,800
64	GF_Phoenix_Qn03	12,066	3,166	0	3,370	89	18,691
65	HP_Phoenix_Qn03	11,838	749	0	3,361	127	16,075
66	EF_Atlanta_Qn03	5,128	11,412	0	1,907	397	18,843
67	HP_Atlanta_Qn03	5,023	3,838	161	1,933	702	11,658
68	EF_Baltimore_Qn03	4,132	17,165	0	961	575	22,833
69	GF_Baltimore_Qn03	4,142	23,203	0	967	625	28,937

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
70	HP_Baltimore_Qn03	3,734	6,001	406	970	1,105	12,217
71	EF_Chicago_Qn03	3,099	27,439	0	682	938	32,159
72	GF_Chicago_Qn03	3,109	37,031	0	684	1,013	41,837
73	HP_Chicago_Qn03	2,948	9,808	1,670	556	1,975	16,956
74	EF_Raleigh_Qn03	4,834	14,682	0	1,443	500	21,459
75	GF_Raleigh_Qn03	4,853	19,392	0	1,444	528	26,217
76	HP_Raleigh_Qn03	4,777	5,046	214	1,487	920	12,445
77	EF_Denver_Qn03	3,583	18,966	0	661	780	23,989
78	GF_Denver_Qn03	3,583	25,269	0	657	831	30,340
79	HP_Denver_Qn03	3,185	6,918	399	664	1,563	12,729
80	EF_Seattle_Qn03	1,270	14,369	0	253	477	16,369
81	GF_Seattle_Qn03	1,261	18,985	0	252	506	21,004
82	HP_Seattle_Qn03	1,128	4,624	11	255	788	6,805
83	EF_Houston_Ceil_Qn03	8,246	5,175	0	2,982	174	16,577
84	HP_Houston_Ceil_Qn03	7,630	2,298	5	2,906	251	13,089
85	EF_Atlanta_Ceil_Qn03	5,573	12,066	0	2,139	420	20,198
86	HP_Atlanta_Ceil_Qn03	5,431	5,428	107	2,147	630	13,743
87	EF_Houston_CeilCrawl_Qn03	8,530	5,327	0	3,091	179	17,127
88	HP_Houston_CeilCrawl_Qn03	7,895	2,372	7	3,001	259	13,535
89	EF_Atlanta_CeilCrawl_Qn03	5,753	12,502	0	2,204	431	20,890
90	HP_Atlanta_CeilCrawl_Qn03	5,602	5,628	144	2,215	656	14,246
91	EF_Houston_Qn00	7,497	4,796	0	2,482	163	14,938
92	HP_Houston_Qn00	7,383	1,594	8	2,560	274	11,819
93	EF_Phoenix_Qn00	11,772	2,332	0	3,292	82	17,478
94	GF_Phoenix_Qn00	11,857	3,099	0	3,315	88	18,359
95	HP_Phoenix_Qn00	11,630	739	0	3,307	124	15,800
96	EF_Atlanta_Qn00	5,023	11,165	0	1,874	391	18,454
97	HP_Atlanta_Qn00	4,929	3,783	141	1,891	687	11,431
98	EF_Baltimore_Qn00	4,000	16,568	0	935	563	22,065
99	GF_Baltimore_Qn00	4,019	22,444	0	936	609	28,008
100	HP_Baltimore_Qn00	3,621	5,861	329	939	1,071	11,819
101	EF_Chicago_Qn00	3,014	26,567	0	664	919	31,164
102	GF_Chicago_Qn00	3,024	35,922	0	665	994	40,604
103	HP_Chicago_Qn00	2,872	9,620	1,545	541	1,924	16,501
104	EF_Raleigh_Qn00	4,720	14,274	0	1,407	489	20,890
105	GF_Raleigh_Qn00	4,739	18,881	0	1,408	517	25,544
106	HP_Raleigh_Qn00	4,673	4,950	178	1,452	899	12,151
107	EF_Denver_Qn00	3,478	18,359	0	641	762	23,240
108	GF_Denver_Qn00	3,478	24,501	0	638	812	29,430
109	HP_Denver_Qn00	3,090	6,762	327	644	1,517	12,341
110	EF_Seattle_Qn00	1,223	13,800	0	246	465	15,734
111	GF_Seattle_Qn00	1,213	18,255	0	242	488	20,198

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
112	HP_Seattle_Qn00	1,090	4,466	7	246	758	6,568
113	EF_Houston_Ceil_Qn00	8,066	5,061	0	2,919	171	16,217
114	HP_Houston_Ceil_Qn00	7,469	2,252	4	2,845	245	12,814
115	EF_Atlanta_Ceil_Qn00	5,459	11,810	0	2,089	413	19,771
116	HP_Atlanta_Ceil_Qn00	5,317	5,338	93	2,102	618	13,468
117	EF_Houston_CeilCrawl_Qn00	8,341	5,213	0	3,019	176	16,748
118	HP_Houston_CeilCrawl_Qn00	7,725	2,326	6	2,940	254	13,250
119	EF_Atlanta_CeilCrawl_Qn00	5,630	12,236	0	2,154	424	20,444
120	HP_Atlanta_CeilCrawl_Qn00	5,478	5,533	125	2,171	644	13,952

Table B-28. Single-wide annual energy use with duct insulation level variations using original-baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
121	EF_Houston_R16Duct	8,151	5,317	0	2,694	178	16,340
122	HP_Houston_R16Duct	8,000	1,740	23	2,779	301	12,843
123	EF_Phoenix_R16Duct	12,615	2,550	0	3,531	89	18,786
124	GF_Phoenix_R16Duct	12,682	3,384	0	3,545	95	19,705
125	HP_Phoenix_R16Duct	12,473	796	0	3,542	136	16,947
126	EF_Atlanta_R16Duct	5,431	12,189	0	2,026	419	20,065
127	HP_Atlanta_R16Duct	5,327	4,036	239	2,046	741	12,388
128	EF_Baltimore_R16Duct	4,550	19,099	0	1,061	627	25,335
129	GF_Baltimore_R16Duct	4,559	25,667	0	1,061	674	31,960
130	HP_Baltimore_R16Duct	4,114	6,472	712	1,070	1,205	13,573
131	EF_Chicago_R16Duct	3,384	30,226	0	746	1,007	35,363
132	GF_Chicago_R16Duct	3,393	40,519	0	748	1,081	45,742
133	HP_Chicago_R16Duct	3,185	10,401	2,101	601	2,110	18,397
134	EF_Raleigh_R16Duct	5,222	15,971	0	1,551	534	23,278
135	GF_Raleigh_R16Duct	5,232	21,013	0	1,552	562	28,359
136	HP_Raleigh_R16Duct	5,147	5,362	353	1,595	983	13,440
137	EF_Denver_R16Duct	3,924	20,937	0	723	841	26,425
138	GF_Denver_R16Duct	3,914	27,743	0	719	892	33,268
139	HP_Denver_R16Duct	3,478	7,402	683	725	1,692	13,980
140	EF_Seattle_R16Duct	1,422	16,265	0	285	530	18,501
141	GF_Seattle_R16Duct	1,412	21,392	0	283	560	23,648
142	HP_Seattle_R16Duct	1,261	5,131	35	284	882	7,592
143	EF_Houston_Ceil_R16Duct	8,597	5,412	0	3,109	179	17,298
144	HP_Houston_Ceil_R16Duct	7,943	2,371	8	3,019	260	13,601
145	EF_Atlanta_Ceil_R16Duct	5,810	12,596	0	2,224	430	21,060
146	HP_Atlanta_Ceil_R16Duct	5,658	5,569	137	2,238	653	14,255
147	EF_Houston_CeilCrawl_R16Duct	8,767	5,507	0	3,173	182	17,629
148	HP_Houston_CeilCrawl_R16Duct	8,113	2,417	9	3,080	266	13,886
149	EF_Atlanta_CeilCrawl_R16Duct	5,924	12,862	0	2,264	437	21,487
150	HP_Atlanta_CeilCrawl_R16Duct	5,763	5,686	162	2,279	668	14,558

Table B-29. Single-wide annual energy use with HVAC system efficiency variations using original-baseline parameters

Num	Case Acronym	Cooling	Heating	Supp Heating	Fan Cooling	Fan Heating	Total
151	GF_Baltimore_AFUE90	4,550	21,231	0	1,061	627	27,468
152	GF_Chicago_AFUE90	3,384	33,600	0	746	1,007	38,737
153	GF_Denver_AFUE90	3,924	23,278	0	723	841	28,766
154	GF_Phoenix_AFUE90	12,625	2,824	0	3,531	89	19,070
155	GF_Raleigh_AFUE90	5,222	17,753	0	1,551	534	25,060
156	GF_Seattle_AFUE90	1,422	18,075	0	285	530	20,312
157	HP_Atlanta_2Stage	4,474	3,560	364	1,105	155	9,658
158	HP_Atlanta_VariSpeed	3,668	3,520	139	517	156	8,000
159	HP_Baltimore_2Stage	3,308	5,939	1,018	542	596	11,402
160	HP_Baltimore_VariSpeed	2,550	5,866	504	267	472	9,658
161	HP_Chicago_2Stage	2,682	9,760	2,628	169	1,262	16,501
162	HP_Chicago_VariSpeed	1,867	9,680	1,845	64	884	14,340
163	HP_Denver_2Stage	2,815	6,393	943	184	991	11,326
164	HP_Denver_VariSpeed	2,161	6,851	447	81	686	10,227
165	HP_Houston_2Stage	6,673	1,516	39	1,399	80	9,706
166	HP_Houston_VariSpeed	5,640	1,442	8	781	53	7,924
167	HP_Phoenix_2Stage	10,331	654	0	1,857	39	12,881
168	HP_Phoenix_VariSpeed	9,213	635	0	1,138	18	11,004
169	HP_Raleigh_2Stage	4,180	4,855	538	799	358	10,729
170	HP_Raleigh_VariSpeed	3,422	4,738	210	430	271	9,071
171	HP_Seattle_2Stage	1,005	4,341	57	127	489	6,019
172	HP_Seattle_VariSpeed	720	4,063	13	33	280	5,109
173	EF_Atlanta_2Stage	4,445	12,483	0	1,102	83	18,113
174	EF_Atlanta_VariSpeed	3,109	12,691	0	445	86	16,331
175	EF_Baltimore_2Stage	3,602	19,459	0	544	290	23,894
176	EF_Baltimore_VariSpeed	2,152	19,639	0	215	221	22,226
177	GF_Baltimore_2Stage	3,611	26,150	0	543	310	30,614
178	GF_Baltimore_VariSpeed	2,161	26,378	0	217	238	28,994
179	EF_Chicago_2Stage	2,682	30,652	0	276	587	34,197
180	EF_Chicago_VariSpeed	1,507	30,823	0	92	420	32,842
181	GF_Chicago_2Stage	2,692	41,097	0	278	632	44,699
182	GF_Chicago_VariSpeed	1,517	41,325	0	93	447	43,382
183	EF_Denver_2Stage	3,118	21,297	0	191	482	25,089
184	EF_Denver_VariSpeed	1,877	21,440	0	75	342	23,733
185	GF_Denver_2Stage	3,109	28,226	0	190	511	32,036
186	GF_Denver_VariSpeed	1,877	28,416	0	75	361	30,728
187	EF_Houston_2Stage	6,881	5,459	0	1,405	45	13,791
188	EF_Houston_VariSpeed	4,805	5,488	0	686	34	11,014
189	EF_Phoenix_2Stage	10,379	2,625	0	1,858	9	14,871

Num	Case Acronym	Cooling	Heating	Supp Heating	Fan Cooling	Fan Heating	Total
190	EF_Phoenix_VariSpeed	8,066	2,616	0	942	6	11,630
191	GF_Phoenix_2Stage	10,435	3,488	0	1,867	10	15,800
192	GF_Phoenix_VariSpeed	8,142	3,469	0	951	6	12,568
193	EF_Raleigh_2Stage	4,455	16,340	0	805	181	21,781
194	EF_Raleigh_VariSpeed	2,900	16,454	0	365	137	19,857
195	GF_Raleigh_2Stage	4,464	21,506	0	805	190	26,965
196	GF_Raleigh_VariSpeed	2,919	21,648	0	375	146	25,089
197	EF_Seattle_2Stage	1,128	16,483	0	136	309	18,056
198	EF_Seattle_VariSpeed	597	16,577	0	27	219	17,421
199	GF_Seattle_2Stage	1,118	21,696	0	133	322	23,269
200	GF_Seattle_VariSpeed	588	21,809	0	27	229	22,653
201	EF_Atlanta_Ceil_2Stage	5,061	14,189	0	1,732	50	21,032
202	EF_Atlanta_Ceil_VariSpeed	3,583	14,435	0	754	51	18,824
203	HP_Atlanta_Ceil_2Stage	5,962	4,325	936	1,722	98	13,042
204	HP_Atlanta_Ceil_VariSpeed	4,180	4,370	360	817	111	9,838
205	EF_Houston_Ceil_2Stage	7,497	6,094	0	2,289	23	15,904
206	EF_Houston_Ceil_VariSpeed	5,393	6,123	0	1,186	18	12,720
207	HP_Houston_Ceil_2Stage	8,881	1,876	123	2,277	45	13,203
208	HP_Houston_Ceil_VariSpeed	6,331	1,791	29	1,303	33	9,488
209	EF_Atlanta_CeilCrawl_2Stage	5,308	15,440	0	1,803	54	22,605
210	EF_Atlanta_CeilCrawl_VariSpeed	3,858	15,724	0	835	56	20,473
211	HP_Atlanta_CeilCrawl_2Stage	6,227	4,684	1,448	1,798	108	14,265
212	HP_Atlanta_CeilCrawl_VariSpeed	4,474	4,852	608	875	129	10,938
213	EF_Houston_CeilCrawl_2Stage	7,886	6,549	0	2,401	25	16,862
214	EF_Houston_CeilCrawl_VariSpeed	5,744	6,587	0	1,279	19	13,630
215	HP_Houston_CeilCrawl_2Stage	9,317	2,046	200	2,386	50	13,999
216	HP_Houston_CeilCrawl_VariSpeed	6,720	1,996	52	1,364	38	10,170

Table B-30. Single-wide annual energy use with cold climate HP and compressor operation using original-baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
217	HP_Baltimore_CHP	2,967	6,907	116	1,093	993	12,075
218	HP_Chicago_CHP	2,275	11,663	753	590	1,675	16,956
219	HP_Denver_CHP	2,606	8,011	92	741	1,354	12,805
220	HP_Seattle_CHP	919	4,765	2	285	776	6,748
221	HP_Houston_CompLock	8,000	1,740	23	2,779	301	12,843
222	HP_Phoenix_CompLock	12,473	796	0	3,542	136	16,947
223	HP_Atlanta_CompLock	5,327	3,976	374	2,046	741	12,464
224	HP_Baltimore_CompLock	4,114	5,934	1,999	1,069	1,206	14,322
225	HP_Chicago_CompLock	3,185	8,133	7,174	601	2,157	21,250
226	HP_Raleigh_CompLock	5,147	5,288	532	1,595	983	13,544
227	HP_Denver_CompLock	3,478	6,609	2,490	725	1,701	15,004
228	HP_Seattle_CompLock	1,261	5,131	35	284	882	7,592
229	HP_Houston_Ceil_CompLock	8,151	2,436	10	3,097	268	13,961
230	HP_Atlanta_Ceil_CompLock	5,801	5,622	331	2,296	671	14,720
231	HP_Houston_CeilCrawl_CompLock	8,436	2,517	14	3,201	277	14,445
232	HP_Atlanta_CeilCrawl_CompLock	6,000	5,833	385	2,372	699	15,288

Table B-31. Double-wide baseline annual energy use using efficient baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
1	EF_Houston	10,644	6,151	0	2,405	202	19,402
2	HP_Houston	10,483	1,993	7	2,426	351	15,260
3	EF_Phoenix	14,378	2,815	0	3,107	96	20,397
4	GF_Phoenix	14,378	2,967	0	3,107	96	20,549
5	HP_Phoenix	14,170	872	0	3,119	151	18,312
6	EF_Atlanta	7,128	14,739	0	1,624	499	23,989
7	HP_Atlanta	6,985	4,820	147	1,626	895	14,473
8	EF_Baltimore	6,199	23,932	0	1,176	767	32,074
9	GF_Baltimore	6,199	25,193	0	1,176	767	33,335
10	HP_Baltimore	5,422	7,863	458	1,162	1,482	16,388
11	EF_Chicago	4,208	35,704	0	839	1,142	41,894
12	GF_Chicago	4,208	37,581	0	839	1,142	43,770
13	HP_Chicago	3,820	11,749	2,070	711	2,454	20,805
14	EF_Raleigh	7,213	18,710	0	1,678	606	28,207
15	GF_Raleigh	7,213	19,696	0	1,678	606	29,193
16	HP_Raleigh	7,099	6,214	193	1,690	1,163	16,359
17	EF_Denver	4,739	24,397	0	749	938	30,823
18	GF_Denver	4,739	25,676	0	749	938	32,103
19	HP_Denver	4,085	8,335	337	740	1,952	15,449
20	EF_Seattle	1,630	19,174	0	335	603	21,743
21	GF_Seattle	1,630	20,179	0	335	603	22,748
22	HP_Seattle	1,441	5,790	87	336	1,020	8,673
23	EF_Houston_Ceil	10,511	6,445	0	3,694	211	20,861
24	HP_Houston_Ceil	10,341	2,155	16	3,743	380	16,634
25	EF_Atlanta_Ceil	6,910	15,516	0	2,613	525	25,563
26	HP_Atlanta_Ceil	6,758	5,241	284	2,646	975	15,904
27	EF_Houston_CeilCrawl	10,957	6,701	0	3,857	218	21,733
28	HP_Houston_CeilCrawl	10,777	2,259	26	3,904	399	17,364
29	EF_Atlanta_CeilCrawl	7,175	16,236	0	2,716	544	26,672
30	HP_Atlanta_CeilCrawl	7,023	5,499	416	2,746	1,027	16,710

Table B-32. Double-wide annual energy use with duct leakage variations using efficient baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
31	EF_Houston_Qn03	10,047	5,782	0	2,266	189	18,283
32	HP_Houston_Qn03	9,895	1,892	3	2,285	331	14,407
33	EF_Phoenix_Qn03	13,933	2,701	0	3,016	93	19,743
34	GF_Phoenix_Qn03	13,933	2,843	0	3,016	93	19,885
35	HP_Phoenix_Qn03	13,734	844	0	3,021	145	17,743
36	EF_Atlanta_Qn03	6,701	13,942	0	1,527	473	22,643
37	HP_Atlanta_Qn03	6,587	4,622	107	1,531	858	13,705
38	EF_Baltimore_Qn03	5,763	22,482	0	1,097	723	30,065
39	GF_Baltimore_Qn03	5,763	23,658	0	1,097	723	31,240
40	HP_Baltimore_Qn03	5,090	7,574	350	1,093	1,429	15,535
41	EF_Chicago_Qn03	3,952	34,046	0	787	1,090	39,875
42	GF_Chicago_Qn03	3,952	35,837	0	787	1,090	41,666
43	HP_Chicago_Qn03	3,630	11,500	1,949	677	2,404	20,160
44	EF_Raleigh_Qn03	6,786	17,667	0	1,578	573	26,605
45	GF_Raleigh_Qn03	6,786	18,606	0	1,578	573	27,544
46	HP_Raleigh_Qn03	6,682	5,944	131	1,589	1,112	15,459
47	EF_Denver_Qn03	4,455	23,184	0	702	890	29,231
48	GF_Denver_Qn03	4,455	24,406	0	702	890	30,453
49	HP_Denver_Qn03	3,877	8,091	269	702	1,895	14,833
50	EF_Seattle_Qn03	1,469	17,563	0	306	557	19,895
51	GF_Seattle_Qn03	1,469	18,492	0	306	557	20,824
52	HP_Seattle_Qn03	1,308	5,387	44	305	946	7,990
53	EF_Houston_Ceil_Qn03	10,066	6,151	0	3,542	202	19,961
54	HP_Houston_Ceil_Qn03	9,905	2,074	11	3,587	365	15,942
55	EF_Atlanta_Ceil_Qn03	6,616	14,900	0	2,500	504	24,520
56	HP_Atlanta_Ceil_Qn03	6,474	5,089	238	2,533	945	15,279
57	EF_Houston_CeilCrawl_Qn03	10,483	6,398	0	3,687	208	20,776
58	HP_Houston_CeilCrawl_Qn03	10,312	2,172	17	3,730	383	16,615
59	EF_Atlanta_CeilCrawl_Qn03	6,872	15,563	0	2,596	522	25,553
60	HP_Atlanta_CeilCrawl_Qn03	6,720	5,327	351	2,626	994	16,018
61	EF_Houston_Qn00	9,554	5,459	0	2,153	179	17,345
62	HP_Houston_Qn00	9,412	1,799	2	2,176	317	13,705
63	EF_Phoenix_Qn00	13,554	2,597	0	2,934	89	19,174
64	GF_Phoenix_Qn00	13,554	2,730	0	2,934	89	19,307
65	HP_Phoenix_Qn00	13,355	815	0	2,940	140	17,250
66	EF_Atlanta_Qn00	6,341	13,269	0	1,445	451	21,506
67	HP_Atlanta_Qn00	6,246	4,484	85	1,453	831	13,099
68	EF_Baltimore_Qn00	5,393	21,288	0	1,023	683	28,387
69	GF_Baltimore_Qn00	5,393	22,406	0	1,023	683	29,506

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
70	HP_Baltimore_Qn00	4,805	7,363	304	1,030	1,387	14,890
71	EF_Chicago_Qn00	3,734	32,700	0	747	1,054	38,235
72	GF_Chicago_Qn00	3,734	34,425	0	747	1,054	39,960
73	HP_Chicago_Qn00	3,469	11,352	1,946	644	2,370	19,781
74	EF_Raleigh_Qn00	6,417	16,795	0	1,493	545	25,250
75	GF_Raleigh_Qn00	6,417	17,677	0	1,493	545	26,131
76	HP_Raleigh_Qn00	6,322	5,743	95	1,504	1,074	14,739
77	EF_Denver_Qn00	4,208	22,169	0	664	853	27,894
78	GF_Denver_Qn00	4,208	23,335	0	664	853	29,060
79	HP_Denver_Qn00	3,687	7,913	238	668	1,853	14,359
80	EF_Seattle_Qn00	1,346	16,255	0	280	517	18,397
81	GF_Seattle_Qn00	1,346	17,108	0	280	517	19,250
82	HP_Seattle_Qn00	1,204	5,057	23	279	887	7,450
83	EF_Houston_Ceil_Qn00	9,677	5,895	0	3,399	194	19,165
84	HP_Houston_Ceil_Qn00	9,516	2,002	8	3,439	352	15,317
85	EF_Atlanta_Ceil_Qn00	6,350	14,340	0	2,396	485	23,572
86	HP_Atlanta_Ceil_Qn00	6,218	4,949	207	2,435	921	14,729
87	EF_Houston_CeilCrawl_Qn00	10,066	6,123	0	3,535	200	19,923
88	HP_Houston_CeilCrawl_Qn00	9,905	2,092	12	3,583	370	15,961
89	EF_Atlanta_CeilCrawl_Qn00	6,597	14,966	0	2,492	503	24,558
90	HP_Atlanta_CeilCrawl_Qn00	6,455	5,187	311	2,520	968	15,440

Table B-33. Double-wide annual energy use with duct insulation level variations using efficient baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
91	EF_Houston_R16Duct	10,597	6,113	0	2,396	201	19,307
92	HP_Houston_R16Duct	10,426	1,975	6	2,411	348	15,165
93	EF_Phoenix_R16Duct	14,312	2,806	0	3,098	96	20,312
94	GF_Phoenix_R16Duct	14,312	2,948	0	3,098	96	20,454
95	HP_Phoenix_R16Duct	14,104	872	0	3,110	151	18,236
96	EF_Atlanta_R16Duct	7,090	14,625	0	1,610	494	23,819
97	HP_Atlanta_R16Duct	6,947	4,781	138	1,615	887	14,369
98	EF_Baltimore_R16Duct	6,161	23,724	0	1,172	762	31,818
99	GF_Baltimore_R16Duct	6,161	24,975	0	1,172	762	33,069
100	HP_Baltimore_R16Duct	5,393	7,796	431	1,156	1,469	16,246
101	EF_Chicago_R16Duct	4,189	35,420	0	836	1,135	41,581
102	GF_Chicago_R16Duct	4,189	37,287	0	836	1,135	43,448
103	HP_Chicago_R16Duct	3,801	11,669	2,017	709	2,438	20,634
104	EF_Raleigh_R16Duct	7,175	18,568	0	1,672	603	28,017
105	GF_Raleigh_R16Duct	7,175	19,553	0	1,672	603	29,003
106	HP_Raleigh_R16Duct	7,061	6,160	181	1,680	1,154	16,236
107	EF_Denver_R16Duct	4,711	24,179	0	746	932	30,567
108	GF_Denver_R16Duct	4,711	25,458	0	746	932	31,847
109	HP_Denver_R16Duct	4,066	8,261	316	737	1,936	15,317
110	EF_Seattle_R16Duct	1,621	18,975	0	333	596	21,525
111	GF_Seattle_R16Duct	1,621	19,971	0	333	596	22,520
112	HP_Seattle_R16Duct	1,431	5,722	78	332	1,004	8,568
113	EF_Houston_Ceil_R16Duct	10,066	6,189	0	3,541	202	19,999
114	HP_Houston_Ceil_R16Duct	9,895	2,048	9	3,583	360	15,895
115	EF_Atlanta_Ceil_R16Duct	6,597	14,900	0	2,492	503	24,492
116	HP_Atlanta_Ceil_R16Duct	6,455	5,000	194	2,530	929	15,108
117	EF_Houston_CeilCrawl_R16Duct	10,312	6,331	0	3,632	207	20,482
118	HP_Houston_CeilCrawl_R16Duct	10,142	2,102	12	3,676	371	16,302
119	EF_Atlanta_CeilCrawl_R16Duct	6,748	15,288	0	2,548	513	25,098
120	HP_Atlanta_CeilCrawl_R16Duct	6,606	5,144	249	2,586	959	15,544

Table B-34. Double-wide annual energy use with HVAC system efficiency variations using efficient baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
121	HP_Atlanta_2Stage	5,725	4,202	224	761	509	11,421
122	HP_Atlanta_VariSpeed	4,426	4,068	55	330	315	9,194
123	HP_Baltimore_2Stage	4,464	7,104	715	458	859	13,601
124	HP_Baltimore_VariSpeed	3,327	6,868	307	189	560	11,251
125	HP_Chicago_2Stage	3,298	10,875	2,584	167	1,454	18,378
126	HP_Chicago_VariSpeed	2,313	10,673	1,782	59	984	15,810
127	HP_Denver_2Stage	3,431	7,086	525	140	1,130	12,312
128	HP_Denver_VariSpeed	2,531	7,511	176	59	737	11,014
129	HP_Houston_2Stage	8,720	1,713	12	1,238	194	11,876
130	HP_Houston_VariSpeed	6,900	1,629	1	599	112	9,241
131	HP_Phoenix_2Stage	12,407	711	0	1,626	71	14,814
132	HP_Phoenix_VariSpeed	10,360	701	0	857	34	11,952
133	HP_Raleigh_2Stage	5,829	5,503	298	841	666	13,137
134	HP_Raleigh_VariSpeed	4,597	5,282	92	377	419	10,767
135	HP_Seattle_2Stage	1,232	4,827	130	97	557	6,843
136	HP_Seattle_VariSpeed	872	4,472	30	45	335	5,753
137	EF_Atlanta_2Stage	6,246	15,042	0	831	240	22,359
138	EF_Atlanta_VariSpeed	3,867	15,165	0	348	183	19,563
139	EF_Baltimore_2Stage	5,004	24,283	0	604	448	30,340
140	EF_Baltimore_VariSpeed	2,919	24,435	0	217	323	27,894
141	GF_Baltimore_2Stage	5,004	25,563	0	604	448	31,619
142	GF_Baltimore_VariSpeed	6,199	25,193	0	1,176	767	33,335
143	EF_Chicago_2Stage	3,412	36,140	0	311	694	40,557
144	EF_Chicago_VariSpeed	1,905	36,339	0	89	490	38,823
145	GF_Chicago_2Stage	3,412	38,036	0	311	694	42,453
146	GF_Chicago_VariSpeed	1,905	38,244	0	89	490	40,728
147	EF_Denver_2Stage	3,858	24,776	0	181	558	29,373
148	EF_Denver_VariSpeed	2,218	24,937	0	65	399	27,619
149	GF_Denver_2Stage	3,858	26,074	0	181	558	30,671
150	GF_Denver_VariSpeed	2,218	26,245	0	65	399	28,927
151	EF_Houston_2Stage	9,355	6,294	0	1,238	89	16,975
152	EF_Houston_VariSpeed	6,009	6,350	0	558	68	12,985
153	EF_Phoenix_2Stage	12,236	2,929	0	1,628	11	16,805
154	EF_Phoenix_VariSpeed	9,563	2,929	0	599	7	13,099
155	GF_Phoenix_2Stage	12,236	3,090	0	1,628	11	16,966
156	GF_Phoenix_VariSpeed	9,563	3,080	0	599	7	13,250
157	EF_Raleigh_2Stage	6,322	19,099	0	865	282	26,567
158	EF_Raleigh_VariSpeed	4,019	19,250	0	390	216	23,876
159	GF_Raleigh_2Stage	6,322	20,103	0	865	282	27,572

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
160	GF_Raleigh_VariSpeed	4,019	20,264	0	390	216	24,890
161	EF_Seattle_2Stage	1,289	19,411	0	170	361	21,231
162	EF_Seattle_VariSpeed	758	19,516	0	43	261	20,577
163	GF_Seattle_2Stage	1,289	20,435	0	170	361	22,255
164	GF_Seattle_VariSpeed	758	20,549	0	43	261	21,610
165	EF_Atlanta_Ceil_2Stage	5,858	17,364	0	1,397	100	24,719
166	EF_Atlanta_Ceil_VariSpeed	4,114	17,449	0	644	76	22,283
167	HP_Atlanta_Ceil_2Stage	5,820	5,141	763	1,384	246	13,355
168	HP_Atlanta_Ceil_VariSpeed	4,805	5,241	208	744	194	11,194
169	EF_Houston_Ceil_2Stage	9,004	7,175	0	1,967	42	18,189
170	EF_Houston_Ceil_VariSpeed	6,464	7,184	0	1,013	29	14,691
171	HP_Houston_Ceil_2Stage	8,881	2,123	67	1,957	100	13,127
172	HP_Houston_Ceil_VariSpeed	7,383	2,086	8	1,153	60	10,691
173	EF_Atlanta_CeilCrawl_2Stage	6,161	18,956	0	1,464	109	26,691
174	EF_Atlanta_CeilCrawl_VariSpeed	4,455	19,061	0	722	83	24,321
175	HP_Atlanta_CeilCrawl_2Stage	6,132	5,576	1,258	1,454	271	14,691
176	HP_Atlanta_CeilCrawl_VariSpeed	5,166	5,826	373	806	227	12,397
177	EF_Houston_CeilCrawl_2Stage	9,507	7,734	0	2,078	45	19,364
178	EF_Houston_CeilCrawl_VariSpeed	6,966	7,753	0	1,115	32	15,866
179	HP_Houston_CeilCrawl_2Stage	9,383	2,313	123	2,070	110	13,999
180	HP_Houston_CeilCrawl_VariSpeed	7,933	2,316	16	1,248	69	11,582

Table B-35. Double-wide annual energy use with cold climate HP and compressor operation using efficient baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
181	HP_Baltimore_CHP	3,933	8,331	48	1,171	1,208	14,691
182	HP_Chicago_CHP	2,739	13,015	776	699	1,917	19,146
183	HP_Denver_CHP	3,042	8,904	15	741	1,533	14,236
184	HP_Seattle_CHP	1,071	5,328	8	340	892	7,639
185	HP_Houston_CompLock	10,483	1,993	7	2,426	351	15,260
186	HP_Phoenix_CompLock	14,170	872	0	3,119	151	18,312
187	HP_Atlanta_CompLock	6,985	4,743	327	1,626	895	14,577
188	HP_Baltimore_CompLock	5,422	7,151	2,156	1,165	1,489	17,383
189	HP_Chicago_CompLock	3,820	9,045	8,167	711	2,530	24,274
190	HP_Raleigh_CompLock	7,099	6,112	428	1,689	1,164	16,492
191	HP_Denver_CompLock	4,085	7,345	2,598	740	1,980	16,748
192	HP_Seattle_CompLock	1,441	5,790	87	336	1,020	8,673
193	HP_Houston_Ceil_CompLock	10,341	2,155	16	3,743	380	16,634
194	HP_Atlanta_Ceil_CompLock	6,758	5,163	467	2,646	975	16,009
195	HP_Houston_CeilCrawl_CompLock	10,777	2,259	26	3,904	399	17,364
196	HP_Atlanta_CeilCrawl_CompLock	7,023	5,420	598	2,746	1,027	16,814
197	HP_Chicago_VariSpeed_Oversize	2,493	10,945	1,472	34	961	15,904
198	HP_Houston_VariSpeed_Oversize	6,701	1,630	0	282	107	8,720

Table B-36. Single-wide baseline annual energy use using efficient baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
1	EF_Houston	8,284	3,687	0	1,841	121	13,933
2	HP_Houston	8,132	1,208	5	1,853	213	11,412
3	EF_Phoenix	10,938	1,640	0	2,588	56	15,222
4	GF_Phoenix	10,938	1,725	0	2,588	56	15,307
5	HP_Phoenix	10,815	512	0	2,594	89	14,009
6	EF_Atlanta	5,602	9,109	0	1,274	309	16,293
7	HP_Atlanta	5,497	3,025	93	1,275	563	10,454
8	EF_Baltimore	4,805	14,198	0	862	455	20,321
9	GF_Baltimore	4,824	15,440	0	884	471	21,620
10	HP_Baltimore	4,246	4,826	217	867	915	11,071
11	EF_Chicago	3,374	21,866	0	634	702	26,577
12	GF_Chicago	3,374	23,013	0	634	702	27,724
13	HP_Chicago	3,109	7,465	1,132	516	1,579	13,800
14	EF_Raleigh	5,706	11,838	0	1,293	385	19,222
15	GF_Raleigh	5,706	12,464	0	1,293	385	19,847
16	HP_Raleigh	5,592	3,969	126	1,294	744	11,724
17	EF_Denver	3,801	14,634	0	577	560	19,572
18	GF_Denver	3,801	15,412	0	577	560	20,350
19	HP_Denver	3,308	5,141	167	582	1,209	10,407
20	EF_Seattle	1,431	10,104	0	232	318	12,085
21	GF_Seattle	1,431	10,635	0	232	318	12,615
22	HP_Seattle	1,251	3,152	4	231	555	5,194
23	EF_Houston_Ceil	8,170	3,886	0	2,716	127	14,900
24	HP_Houston_Ceil	8,075	1,305	12	2,745	231	12,369
25	EF_Atlanta_Ceil	5,497	9,696	0	1,919	327	17,440
26	HP_Atlanta_Ceil	5,431	3,316	162	1,941	619	11,469
27	EF_Houston_CeilCrawl	8,587	4,066	0	2,853	132	15,639
28	HP_Houston_CeilCrawl	8,483	1,382	20	2,883	245	13,014
29	EF_Atlanta_CeilCrawl	5,772	10,236	0	2,018	342	18,369
30	HP_Atlanta_CeilCrawl	5,696	3,519	244	2,039	663	12,160

Table B-37. Single-wide annual energy use with duct leakage variations using efficient baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
31	EF_Houston_Qn03	7,905	3,507	0	1,752	115	13,279
32	HP_Houston_Qn03	7,772	1,153	3	1,768	204	10,900
33	EF_Phoenix_Qn03	10,653	1,583	0	2,523	55	14,814
34	GF_Phoenix_Qn03	10,653	1,668	0	2,523	55	14,900
35	HP_Phoenix_Qn03	10,530	493	0	2,530	86	13,639
36	EF_Atlanta_Qn03	5,346	8,720	0	1,212	295	15,573
37	HP_Atlanta_Qn03	5,251	2,924	71	1,218	545	10,009
38	EF_Baltimore_Qn03	4,559	13,582	0	823	438	19,402
39	GF_Baltimore_Qn03	4,587	14,767	0	839	450	20,643
40	HP_Baltimore_Qn03	4,047	4,683	170	822	884	10,606
41	EF_Chicago_Qn03	3,232	21,165	0	608	681	25,686
42	GF_Chicago_Qn03	3,232	22,283	0	608	681	26,804
43	HP_Chicago_Qn03	2,995	7,350	1,086	498	1,558	13,487
44	EF_Raleigh_Qn03	5,431	11,307	0	1,226	366	18,331
45	GF_Raleigh_Qn03	5,431	11,895	0	1,226	366	18,918
46	HP_Raleigh_Qn03	5,327	3,830	94	1,234	719	11,203
47	EF_Denver_Qn03	3,640	14,122	0	556	544	18,862
48	GF_Denver_Qn03	3,640	14,862	0	556	544	19,601
49	HP_Denver_Qn03	3,175	5,009	137	558	1,177	10,056
50	EF_Seattle_Qn03	1,355	9,620	0	219	302	11,497
51	GF_Seattle_Qn03	1,355	10,123	0	219	302	11,999
52	HP_Seattle_Qn03	1,185	3,021	2	221	537	4,967
53	EF_Houston_Ceil_Qn03	7,886	3,744	0	2,626	123	14,378
54	HP_Houston_Ceil_Qn03	7,801	1,271	9	2,648	224	11,952
55	EF_Atlanta_Ceil_Qn03	5,308	9,374	0	1,853	317	16,852
56	HP_Atlanta_Ceil_Qn03	5,241	3,234	140	1,879	605	11,099
57	EF_Houston_CeilCrawl_Qn03	8,284	3,914	0	2,754	128	15,080
58	HP_Houston_CeilCrawl_Qn03	8,189	1,340	15	2,786	238	12,568
59	EF_Atlanta_CeilCrawl_Qn03	5,564	9,886	0	1,944	331	17,724
60	HP_Atlanta_CeilCrawl_Qn03	5,497	3,428	212	1,962	644	11,743
61	EF_Houston_Qn00	7,573	3,346	0	1,681	110	12,710
62	HP_Houston_Qn00	7,450	1,107	2	1,699	197	10,454
63	EF_Phoenix_Qn00	10,407	1,535	0	2,459	53	14,454
64	GF_Phoenix_Qn00	10,407	1,611	0	2,459	53	14,530
65	HP_Phoenix_Qn00	10,274	483	0	2,466	83	13,307
66	EF_Atlanta_Qn00	5,118	8,379	0	1,157	283	14,938
67	HP_Atlanta_Qn00	5,033	2,845	55	1,166	531	9,630
68	EF_Baltimore_Qn00	4,350	13,051	0	783	420	18,606
69	GF_Baltimore_Qn00	4,379	14,189	0	799	433	19,800

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
70	HP_Baltimore_Qn00	3,858	4,567	144	785	864	10,217
71	EF_Chicago_Qn00	3,109	20,568	0	582	660	24,918
72	GF_Chicago_Qn00	3,109	21,648	0	582	660	25,999
73	HP_Chicago_Qn00	2,891	7,270	1,080	480	1,539	13,260
74	EF_Raleigh_Qn00	5,194	10,834	0	1,174	352	17,554
75	GF_Raleigh_Qn00	5,194	11,412	0	1,174	352	18,132
76	HP_Raleigh_Qn00	5,099	3,720	71	1,180	697	10,767
77	EF_Denver_Qn00	3,497	13,658	0	534	528	18,217
78	GF_Denver_Qn00	3,497	14,378	0	534	528	18,937
79	HP_Denver_Qn00	3,052	4,923	119	535	1,152	9,781
80	EF_Seattle_Qn00	1,289	9,184	0	210	292	10,976
81	GF_Seattle_Qn00	1,289	9,668	0	210	292	11,459
82	HP_Seattle_Qn00	1,128	2,909	1	208	512	4,758
83	EF_Houston_Ceil_Qn00	7,630	3,621	0	2,535	119	13,904
84	HP_Houston_Ceil_Qn00	7,554	1,235	7	2,568	218	11,582
85	EF_Atlanta_Ceil_Qn00	5,128	9,080	0	1,796	308	16,312
86	HP_Atlanta_Ceil_Qn00	5,071	3,165	124	1,816	591	10,767
87	EF_Houston_CeilCrawl_Qn00	8,009	3,772	0	2,663	123	14,568
88	HP_Houston_CeilCrawl_Qn00	7,924	1,297	11	2,689	230	12,151
89	EF_Atlanta_CeilCrawl_Qn00	5,374	9,563	0	1,878	321	17,137
90	HP_Atlanta_CeilCrawl_Qn00	5,308	3,356	189	1,899	631	11,383

Table B-38. Single-wide annual energy use with duct insulation level variations using efficient baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
91	EF_Houston_R16Duct	8,274	3,687	0	1,841	121	13,923
92	HP_Houston_R16Duct	8,132	1,208	5	1,853	213	11,412
93	EF_Phoenix_R16Duct	10,938	1,640	0	2,588	56	15,222
94	GF_Phoenix_R16Duct	10,938	1,725	0	2,588	56	15,307
95	HP_Phoenix_R16Duct	10,805	512	0	2,594	89	13,999
96	EF_Atlanta_R16Duct	5,602	9,099	0	1,267	307	16,274
97	HP_Atlanta_R16Duct	5,497	3,016	93	1,275	563	10,445
98	EF_Baltimore_R16Duct	4,796	14,189	0	862	455	20,302
99	GF_Baltimore_R16Duct	4,824	15,430	0	884	471	21,610
100	HP_Baltimore_R16Duct	4,246	4,817	216	867	915	11,061
101	EF_Chicago_R16Duct	3,374	21,857	0	634	702	26,567
102	GF_Chicago_R16Duct	3,374	23,004	0	634	702	27,714
103	HP_Chicago_R16Duct	3,109	7,466	1,130	516	1,579	13,800
104	EF_Raleigh_R16Duct	5,706	11,838	0	1,293	385	19,222
105	GF_Raleigh_R16Duct	5,706	12,464	0	1,293	385	19,847
106	HP_Raleigh_R16Duct	5,583	3,969	126	1,294	744	11,715
107	EF_Denver_R16Duct	3,791	14,634	0	577	560	19,563
108	GF_Denver_R16Duct	3,791	15,402	0	577	560	20,331
109	HP_Denver_R16Duct	3,308	5,132	166	582	1,209	10,398
110	EF_Seattle_R16Duct	1,431	10,104	0	232	318	12,085
111	GF_Seattle_R16Duct	1,431	10,635	0	232	318	12,615
112	HP_Seattle_R16Duct	1,251	3,152	4	231	555	5,194
113	EF_Houston_Ceil_R16Duct	7,895	3,753	0	2,626	123	14,397
114	HP_Houston_Ceil_R16Duct	7,810	1,253	8	2,659	222	11,952
115	EF_Atlanta_Ceil_R16Duct	5,308	9,374	0	1,854	316	16,852
116	HP_Atlanta_Ceil_R16Duct	5,241	3,183	125	1,879	594	11,023
117	EF_Houston_CeilCrawl_R16Duct	8,132	3,858	0	2,708	126	14,824
118	HP_Houston_CeilCrawl_R16Duct	8,037	1,297	11	2,737	229	12,312
119	EF_Atlanta_CeilCrawl_R16Duct	5,459	9,668	0	1,912	325	17,364
120	HP_Atlanta_CeilCrawl_R16Duct	5,393	3,291	159	1,931	618	11,393

Table B-39. Single-wide annual energy use with HVAC system efficiency variations using efficient baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
121	HP_Atlanta_2Stage	4,483	2,643	134	582	319	8,161
122	HP_Atlanta_VariSpeed	3,460	2,567	40	250	195	6,512
123	HP_Baltimore_2Stage	3,516	4,390	340	296	528	9,071
124	HP_Baltimore_VariSpeed	2,569	4,273	134	121	333	7,431
125	HP_Chicago_2Stage	2,730	7,014	1,374	92	941	12,151
126	HP_Chicago_VariSpeed	1,858	6,924	1,057	33	621	10,492
127	HP_Denver_2Stage	2,777	4,395	259	99	698	8,227
128	HP_Denver_VariSpeed	2,009	4,701	94	41	442	7,289
129	HP_Houston_2Stage	6,748	1,043	9	914	119	8,834
130	HP_Houston_VariSpeed	5,298	992	3	435	68	6,796
131	HP_Phoenix_2Stage	8,891	417	0	1,349	35	10,691
132	HP_Phoenix_VariSpeed	7,564	408	0	742	17	8,729
133	HP_Raleigh_2Stage	4,587	3,523	183	598	426	9,317
134	HP_Raleigh_VariSpeed	3,592	3,382	77	268	263	7,583
135	HP_Seattle_2Stage	1,024	2,646	8	65	304	4,047
136	HP_Seattle_VariSpeed	711	2,499	3	16	173	3,403
137	EF_Atlanta_2Stage	4,891	9,241	0	619	177	14,928
138	EF_Atlanta_VariSpeed	2,986	9,289	0	236	124	12,634
139	EF_Baltimore_2Stage	3,877	14,388	0	318	270	18,852
140	EF_Baltimore_VariSpeed	2,189	14,464	0	105	189	16,947
141	GF_Baltimore_2Stage	3,886	15,648	0	337	279	20,151
142	GF_Baltimore_VariSpeed	2,218	15,724	0	115	197	18,255
143	EF_Chicago_2Stage	2,730	22,122	0	155	433	25,439
144	EF_Chicago_VariSpeed	1,479	22,236	0	44	307	24,065
145	GF_Chicago_2Stage	2,730	23,278	0	155	433	26,596
146	GF_Chicago_VariSpeed	1,479	23,411	0	44	307	25,240
147	EF_Denver_2Stage	3,080	14,862	0	102	334	18,378
148	EF_Denver_VariSpeed	1,706	14,957	0	35	240	16,937
149	GF_Denver_2Stage	3,080	15,648	0	102	334	19,165
150	GF_Denver_VariSpeed	1,706	15,743	0	35	240	17,724
151	EF_Houston_2Stage	7,270	3,744	0	946	68	12,028
152	EF_Houston_VariSpeed	4,597	3,772	0	405	50	8,824
153	EF_Phoenix_2Stage	9,165	1,687	0	1,347	8	12,208
154	EF_Phoenix_VariSpeed	6,568	1,687	0	564	5	8,824
155	GF_Phoenix_2Stage	9,165	1,772	0	1,347	8	12,293
156	GF_Phoenix_VariSpeed	6,568	1,772	0	564	5	8,909
157	EF_Raleigh_2Stage	4,995	11,999	0	636	227	17,857
158	EF_Raleigh_VariSpeed	3,118	12,066	0	265	162	15,611
159	GF_Raleigh_2Stage	4,995	12,634	0	636	227	18,492

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
160	GF_Raleigh_VariSpeed	3,118	12,701	0	265	162	16,246
161	EF_Seattle_2Stage	1,156	10,236	0	71	194	11,658
162	EF_Seattle_VariSpeed	569	10,284	0	13	139	11,004
163	GF_Seattle_2Stage	1,156	10,767	0	71	194	12,189
164	GF_Seattle_VariSpeed	569	10,824	0	13	139	11,544
165	EF_Atlanta_Ceil_2Stage	4,654	10,388	0	1,012	87	16,141
166	EF_Atlanta_Ceil_VariSpeed	3,223	10,435	0	473	67	14,198
167	HP_Atlanta_Ceil_2Stage	4,512	3,197	338	1,012	183	9,241
168	HP_Atlanta_Ceil_VariSpeed	3,763	3,227	109	545	137	7,782
169	EF_Houston_Ceil_2Stage	6,976	4,161	0	1,435	34	12,606
170	EF_Houston_Ceil_VariSpeed	4,957	4,170	0	705	25	9,857
171	HP_Houston_Ceil_2Stage	6,767	1,256	33	1,421	67	9,545
172	HP_Houston_Ceil_VariSpeed	5,677	1,236	5	821	42	7,782
173	EF_Atlanta_CeilCrawl_2Stage	4,957	11,307	0	1,071	95	17,430
174	EF_Atlanta_CeilCrawl_VariSpeed	3,554	11,364	0	543	73	15,535
175	HP_Atlanta_CeilCrawl_2Stage	4,805	3,527	605	1,067	203	10,208
176	HP_Atlanta_CeilCrawl_VariSpeed	4,114	3,647	192	603	165	8,720
177	EF_Houston_CeilCrawl_2Stage	7,450	4,464	0	1,527	37	13,478
178	EF_Houston_CeilCrawl_VariSpeed	5,459	4,483	0	807	27	10,777
179	HP_Houston_CeilCrawl_2Stage	7,232	1,380	60	1,518	75	10,265
180	HP_Houston_CeilCrawl_VariSpeed	6,237	1,382	11	918	49	8,597

Table B-40. Single-wide Annual energy use with cold climate HP and compressor operation using efficient baseline parameters

Num	Case Acronym	Cooling	Heating	SuppHeat	FanCool	FanHeat	Total
181	HP_Baltimore_CHP	3,080	5,114	32	867	735	9,829
182	HP_Chicago_CHP	2,237	8,238	491	501	1,214	12,682
183	HP_Denver_CHP	2,455	5,488	9	577	939	9,469
184	HP_Seattle_CHP	919	2,919	0	228	482	4,550
185	HP_Houston_CompLock	8,132	1,208	5	1,853	213	11,412
186	HP_Phoenix_CompLock	10,815	512	0	2,594	89	14,009
187	HP_Atlanta_CompLock	5,497	2,961	223	1,275	564	10,521
188	HP_Baltimore_CompLock	4,246	4,323	1,383	867	925	11,743
189	HP_Chicago_CompLock	3,109	5,601	5,176	516	1,702	16,103
190	HP_Raleigh_CompLock	5,592	3,898	292	1,293	745	11,819
191	HP_Denver_CompLock	3,308	4,470	1,643	582	1,248	11,251
192	HP_Seattle_CompLock	1,251	3,152	4	231	555	5,194
193	HP_Houston_Ceil_CompLock	8,075	1,305	12	2,745	231	12,369
194	HP_Atlanta_Ceil_CompLock	5,431	3,257	297	1,940	619	11,544
195	HP_Houston_CeilCrawl_CompLock	8,483	1,382	20	2,883	245	13,014
196	HP_Atlanta_CeilCrawl_CompLock	5,696	3,459	379	2,039	663	12,236

APPENDIX C WEIGHTING FACTORS

This appendix provides a complete listing of the weighting factors used to estimate regional- and national-average energy-costs, innovation cost-savings and break-even incremental costs. Weights are scaled to sum to 100,000 annual shipments of new manufactured homes, with 57,000 being single-wide homes and 43,000 being double-wide homes.

Region	City	Home type[a]	HVAC type[b]	Heating fuel	Duct location	System type[c]	Weight
1	Atlanta	DW	Furnace	Electricity	Ceiling	Split	809
1	Atlanta	DW	Furnace	Electricity	Floor	Split	3,488
1	Atlanta	DW	Heat Pump	Electricity	Ceiling	Split	346
1	Atlanta	DW	Heat Pump	Electricity	Floor	Split	1,498
1	Atlanta	SW	Furnace	Electricity	Ceiling	Split	734
1	Atlanta	SW	Furnace	Electricity	Floor	Split	3,190
1	Atlanta	SW	Heat Pump	Electricity	Ceiling	Split	313
1	Atlanta	SW	Heat Pump	Electricity	Floor	Split	1,369
1	Houston	DW	Furnace	Electricity	Ceiling	Package	1,247
1	Houston	DW	Furnace	Electricity	Ceiling	Split	4,867
1	Houston	DW	Furnace	Electricity	Floor	Split	6,608
1	Houston	DW	Heat Pump	Electricity	Ceiling	Package	530
1	Houston	DW	Heat Pump	Electricity	Ceiling	Split	2,084
1	Houston	DW	Heat Pump	Electricity	Floor	Split	2,928
1	Houston	SW	Furnace	Electricity	Ceiling	Package	1,213
1	Houston	SW	Furnace	Electricity	Ceiling	Split	4,735
1	Houston	SW	Furnace	Electricity	Floor	Split	6,547
1	Houston	SW	Heat Pump	Electricity	Ceiling	Package	517
1	Houston	SW	Heat Pump	Electricity	Ceiling	Split	2,028
1	Houston	SW	Heat Pump	Electricity	Floor	Split	2,887
2	Raleigh	DW	Furnace	Electricity	Floor	Split	5,515
2	Raleigh	DW	Furnace	Nat Gas	Floor	Split	475
2	Raleigh	DW	Furnace	Propane	Floor	Split	600
2	Raleigh	DW	Heat Pump	Electricity	Floor	Split	2,324
2	Raleigh	SW	Furnace	Electricity	Floor	Split	4,805
2	Raleigh	SW	Furnace	Nat Gas	Floor	Split	563
2	Raleigh	SW	Furnace	Propane	Floor	Split	618
2	Raleigh	SW	Heat Pump	Electricity	Floor	Split	2,016
3	Phoenix	DW	Furnace	Electricity	Floor	Split	1,707
3	Phoenix	DW	Furnace	Nat Gas	Floor	Split	2,787
3	Phoenix	DW	Furnace	Propane	Floor	Split	947
3	Phoenix	DW	Heat Pump	Electricity	Floor	Split	293
3	Phoenix	SW	Furnace	Electricity	Floor	Split	604
3	Phoenix	SW	Furnace	Nat Gas	Floor	Split	790

Region	City	Home type[a]	HVAC type[b]	Heating fuel	Duct location	System type[c]	Weight
3	Phoenix	SW	Furnace	Propane	Floor	Split	318
3	Phoenix	SW	Heat Pump	Electricity	Floor	Split	95
4	Baltimore	DW	Furnace	Electricity	Floor	Split	811
4	Baltimore	DW	Furnace	Fuel Oil	Floor	Split	105
4	Baltimore	DW	Furnace	Nat Gas	Floor	Split	279
4	Baltimore	DW	Furnace	Propane	Floor	Split	298
4	Baltimore	DW	Heat Pump	Electricity	Floor	Split	347
4	Baltimore	SW	Furnace	Electricity	Floor	Split	644
4	Baltimore	SW	Furnace	Fuel Oil	Floor	Split	105
4	Baltimore	SW	Furnace	Nat Gas	Floor	Split	320
4	Baltimore	SW	Furnace	Propane	Floor	Split	333
4	Baltimore	SW	Heat Pump	Electricity	Floor	Split	276
4	Chicago	DW	Furnace	Electricity	Floor	Split	475
4	Chicago	DW	Furnace	Fuel Oil	Floor	Split	892
4	Chicago	DW	Furnace	Nat Gas	Floor	Split	574
4	Chicago	DW	Furnace	Propane	Floor	Split	941
4	Chicago	DW	Heat Pump	Electricity	Floor	Split	23
4	Chicago	SW	Furnace	Electricity	Floor	Split	345
4	Chicago	SW	Furnace	Fuel Oil	Floor	Split	756
4	Chicago	SW	Furnace	Nat Gas	Floor	Split	475
4	Chicago	SW	Furnace	Propane	Floor	Split	789
4	Chicago	SW	Heat Pump	Electricity	Floor	Split	16
5	Baltimore	DW	Furnace	Electricity	Floor	Split	156
5	Baltimore	DW	Furnace	Nat Gas	Floor	Split	204
5	Baltimore	DW	Furnace	Propane	Floor	Split	62
5	Baltimore	DW	Heat Pump	Electricity	Floor	Split	67
5	Baltimore	SW	Furnace	Electricity	Floor	Split	360
5	Baltimore	SW	Furnace	Nat Gas	Floor	Split	454
5	Baltimore	SW	Furnace	Propane	Floor	Split	136
5	Baltimore	SW	Heat Pump	Electricity	Floor	Split	153
5	Chicago	DW	Furnace	Electricity	Floor	Split	870
5	Chicago	DW	Furnace	Nat Gas	Floor	Split	2,657
5	Chicago	DW	Furnace	Propane	Floor	Split	917
5	Chicago	DW	Heat Pump	Electricity	Floor	Split	47
5	Chicago	SW	Furnace	Electricity	Floor	Split	1,660
5	Chicago	SW	Furnace	Nat Gas	Floor	Split	3,782
5	Chicago	SW	Furnace	Propane	Floor	Split	1,290
5	Chicago	SW	Heat Pump	Electricity	Floor	Split	89
6	Denver	DW	Furnace	Electricity	Floor	Split	1,258
6	Denver	DW	Furnace	Nat Gas	Floor	Split	804
6	Denver	DW	Furnace	Propane	Floor	Split	269

Region	City	Home type[a]	HVAC type[b]	Heating fuel	Duct location	System type[c]	Weight
6	Denver	DW	Heat Pump	Electricity	Floor	Split	75
6	Denver	SW	Furnace	Electricity	Floor	Split	415
6	Denver	SW	Furnace	Nat Gas	Floor	Split	742
6	Denver	SW	Furnace	Propane	Floor	Split	203
6	Denver	SW	Heat Pump	Electricity	Floor	Split	24
6	Seattle	DW	Furnace	Electricity	Floor	Split	1,210
6	Seattle	DW	Furnace	Nat Gas	Floor	Split	88
6	Seattle	DW	Furnace	Propane	Floor	Split	115
6	Seattle	DW	Heat Pump	Electricity	Floor	Split	403
6	Seattle	SW	Furnace	Electricity	Floor	Split	194
6	Seattle	SW	Furnace	Nat Gas	Floor	Split	15
6	Seattle	SW	Furnace	Propane	Floor	Split	17
6	Seattle	SW	Heat Pump	Electricity	Floor	Split	65

Notes:

a) SW = single-wide; DW = double-wide

b) “Furnace” HVAC type also implies central air conditioning

c) “Split” means central split-system air-condioner or heat pump; “Package” means outdoor package unit.