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Modeling and Economics of Select HVAC and Envelope Improvements in Manufactured Housing

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EXECUTIVE SUMMARY

This modeling effort explores energy savings, peak demand savings, and CO_2e emission savings from improved HVAC equipment and quality installation improvements for new manufactured homes across the United States. The modeling also examines how those improvements impact homes built with DOE Zero Energy Ready Manufactured Home (ZERH) envelope requirements. We examine the savings cost effectiveness by looking at the first cost that could be added to a baseline home for achieving the savings using prevalent purchase financing rates and shipment-weighted regional average utility costs. The economic value of the peak electrical savings and CO_2e emission savings are discussed separately but would tend to add societal value to the break-even first costs presented.

We ran simulations for eight cities within six industry shipment regions representing most Building America climate zones (color variation in Figure EX-1). Figure EX- 2 shows a break-even cost for each of the regions for a single-speed cold climate heat pump (HP) and a variable-speed heat pump (VSHP). At any incremental cost below the break-even level, it is financially advantageous for a consumer to upgrade their HVAC equipment. In the Southern regions, which have less heating, the savings are lowest; however, those locations are likely to have central air conditioning, and thus the increased cost for a heat pump unit tends to be small. A heat pump is recommended instead of electric resistance heat in all regions represented in the 48-state map, except where there are little to no heating needs in the most southern parts of Florida and Texas (Climate zone 1 in IECC building codes).

Figure EX-1 Map depicting manufactured home shipment regions (Region #), Building America climate zones from hot-humid (orange color) to cold/very cold (dark blue color) and the eight cities modeled for simulations.

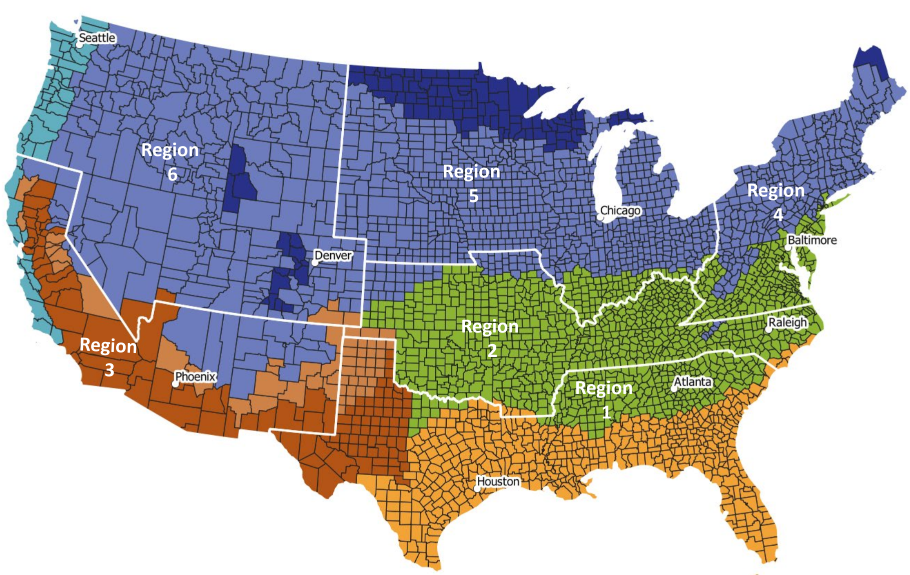
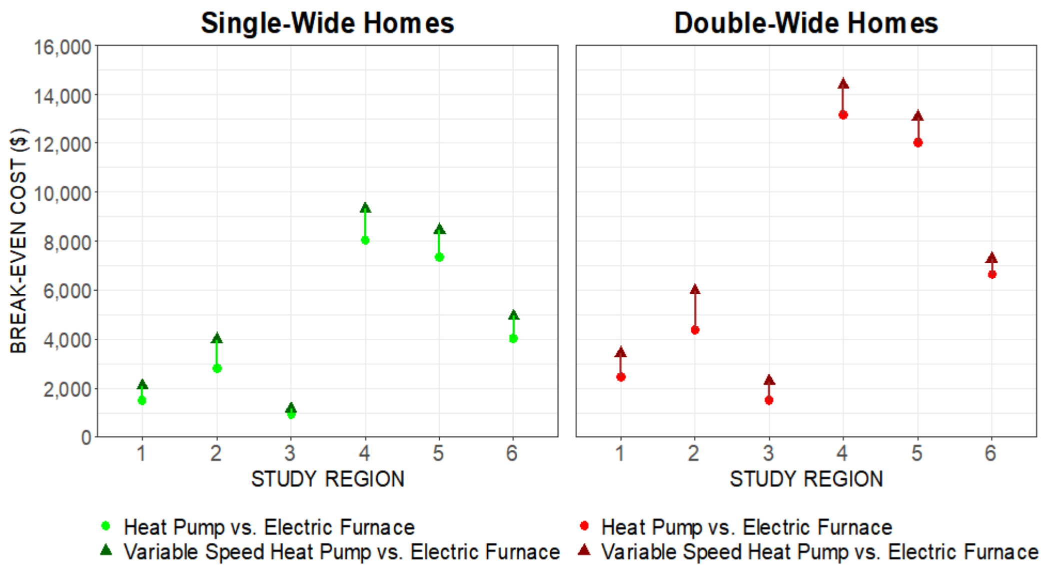


Figure EX-2. Incremental first cost at which a single-speed heat pump or a variable-speed heat pump is a good choice relative to an electric furnace from a consumer cost savings perspective by MHU shipment region.

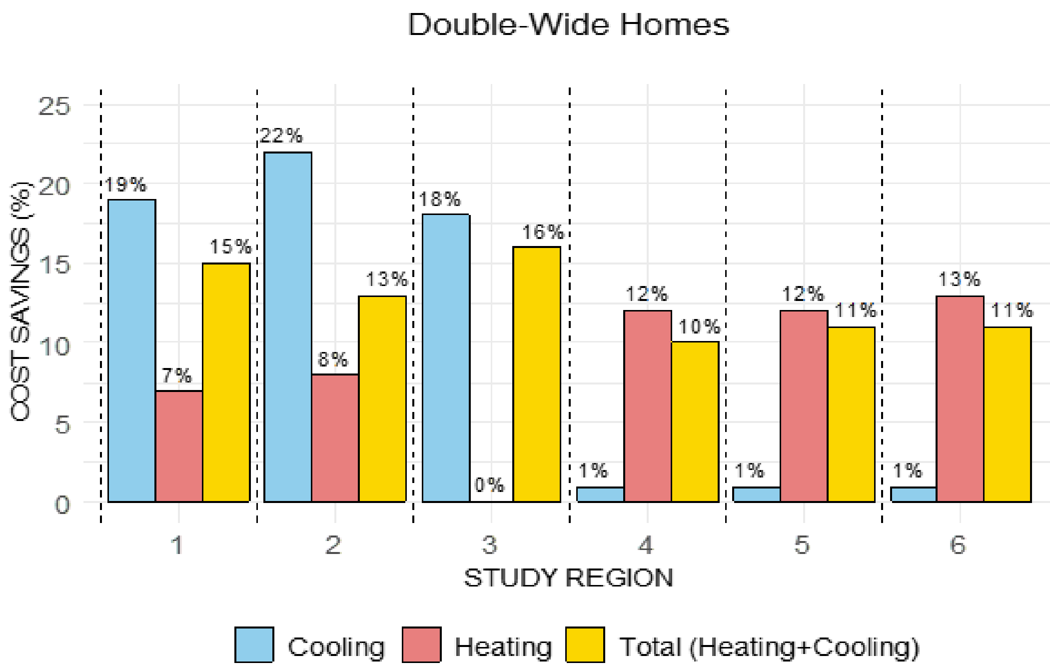


Findings from the study show envelope specifications that are part of the ZERH manufactured Home Program Version 1[1] provide savings for cooling and heating with variations by location, ranging by study region from 10% to 16% as shown in Figure EX-3.

Note that ZERH home specifications require improvements beyond envelope requirements, and total whole house energy use savings would be greater than what is shown in Figure EX-3.

[1] See https://www.energy.gov/eere/buildings/zerh-manufactured-homes for details

Figure EX-3. The percentage of annual cost savings for the Zero Energy Ready Home envelope improvements. All homes in this example were modeled with heat pumps.



Quality duct installations and particularly crossover ducts can provide meaningful and cost-effective savings as well as significant IAQ benefits. A novel belly-zone model was developed to separately represent belly conditions for the typical location of manufactured home ductwork. We also modeled ducts in attics as some southern homes ship with attic ducts. This study showed that ducts located in the belly saved about 5000 kBtu or 20% of total heating and cooling energy use relative to attic ducts for a baseline house with fairly leaky ducts in the southeastern U.S.

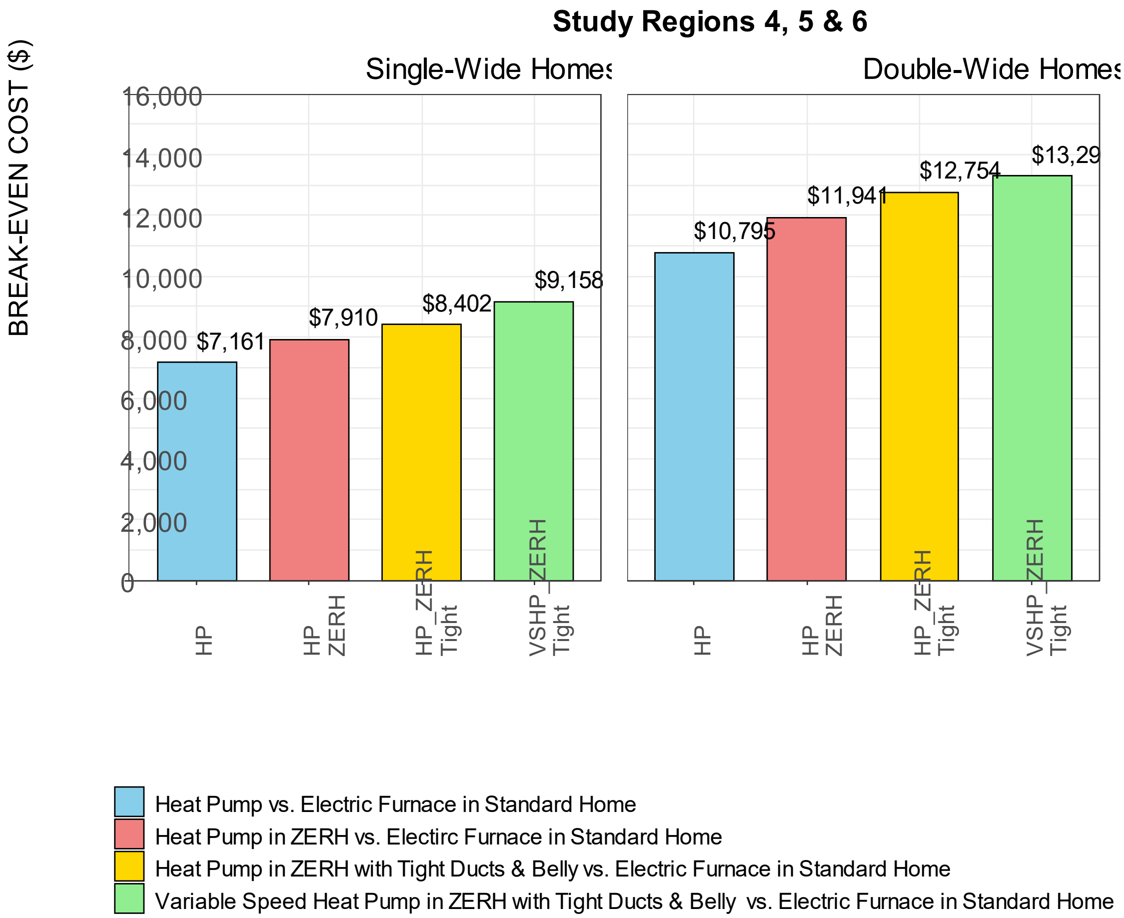
The condition of the belly zone tightness was modeled but only for homes with ducts in the belly. Further research to discover real world leakage rates from the belly to the crawlspace is warranted, and the modeling results in this study should not be interpreted to mean that there is little potential energy savings to be gained from sealing leaks from the belly to the crawlspace. To explore potential impacts, the air leakage for the belly was set to 60 ACH50, 30 ACH50, 15 ACH50 and 3 ACH50 for a Baltimore heat pump home with ductwork in the belly. If real world leakage was found to be 60 ACH50 then tightening the belly to 15 ACH50 or 3 ACH50 could result in savings of 4.2% and 6.2% respectively in double-wide homes with typical ducts. In homes with tighter ductwork, tightening the belly in the simulation indicated savings of 3.1% and 4.7% for tightening the belly leakage to 15 ACH50 and 3 ACH50 respectively. Savings were smaller for single-wide homes.

Some of the lost HVAC energy from duct air leakage into the belly is recovered due to the low thermal conductivity of the floor between the belly and living space. Reduction in duct leakage from 0.08 cfm25/ft2 to 0.04 cfm25/ft2 yielded 2% to 4% savings in total heating and cooling energy use across climates.

A summary of the average results for the heat pump, ZERH envelope, duct and belly tightening measures and variable-speed heat pumps are presented in Figure EX-4 for the hotter climates and EX-5 for the colder climates relative to electric furnace baseline. The break-even first cost for these measures is greater for the colder climates represented in EX-5 than in the warmer climates of EX-4. These figures also show that the smaller single-wide homes save less in absolute terms because they are smaller.

EX-4 Incremental first cost for various measure packages showing consumer cost savings. Weighted average of regions 1, 2 and 3 (warm climates).

EX-5 Incremental first cost for various measure packages showing consumer cost savings. Weighted average of regions 4, 5 and 6 (cold climates).



Winter peak demand savings –the hour of the year the heating was greatest - for switching from an electric furnace to a heat pump was as high as 2.3 kW (in study regions 1 and 2) for double-wide homes and as high as 1.5 kW (in study region 1) for single-wide homes. For utilities experiencing winter peaks as sometimes occurs in regions 1 and 2 this can be beneficial. In the coldest climates peak savings will depend on the ability of the heat pump to produce useful heat at very cold temperatures. In Chicago, the coldest climate we simulated, the backup electric coil ran full out for the peak as it was too cold for the heat pump even though the cold-climate heat pump modeled ran down to -22°F. In the other cities modeled there were peak winter savings as the heatpump was able to operate at the coldest temperatures.

Peak demand savings increases by as much as about 600 Watts (for double-wide homes in study regions 5 and 6) when the home's envelope is improved to a ZERH level for homes with heat pump. Tightening very leaky ducts located in the belly saved as much as about 440 Watts, depending on home type and region, though the impact was much more muted among the single-wide homes in the warmer climates. A study referenced in this report indicates the value of peak savings from $500/kW to over $2000/kW, depending on location.

CO_2e annual emissions were computed consistent with RESNET methodology[2] from hourly simulation outputs. CO_2e equates greenhouse pollutant emissions to CO_2 such that 1 ton of methane is calculated as 28 tons of CO_2e as it produces 28 times the detriment as CO_2. The electricity emissions are based on estimated regional electric grid emissions averaged from 2025 to 2050 and vary by grid region. Fossil fuel emissions are based on household combustion fuels. RESNET uses the combined pre-combustion plus combustion CO_2e emission rates from ASHRAE Standard 189.1, Appendix J for the 100-year GWP time horizon. Figure EX-6 shows the tons of emissions for four different HVAC systems as modeled in the six regions. In the colder regions the difference between electric furnaces and heat pumps are two to three tons of emissions per double-wide home per year. For single-wide homes, which represent about half the manufactured home market, the CO_2e emission rates are about 9% to 26% less than that of double-wide homes.

Figure EX-6. Annual CO_2e emissions of different HVAC systems by region for double-wide homes. Note that the projected electric grid emission rate is different for each region so there is not a one-to-one correlation to energy savings between gas and electric.

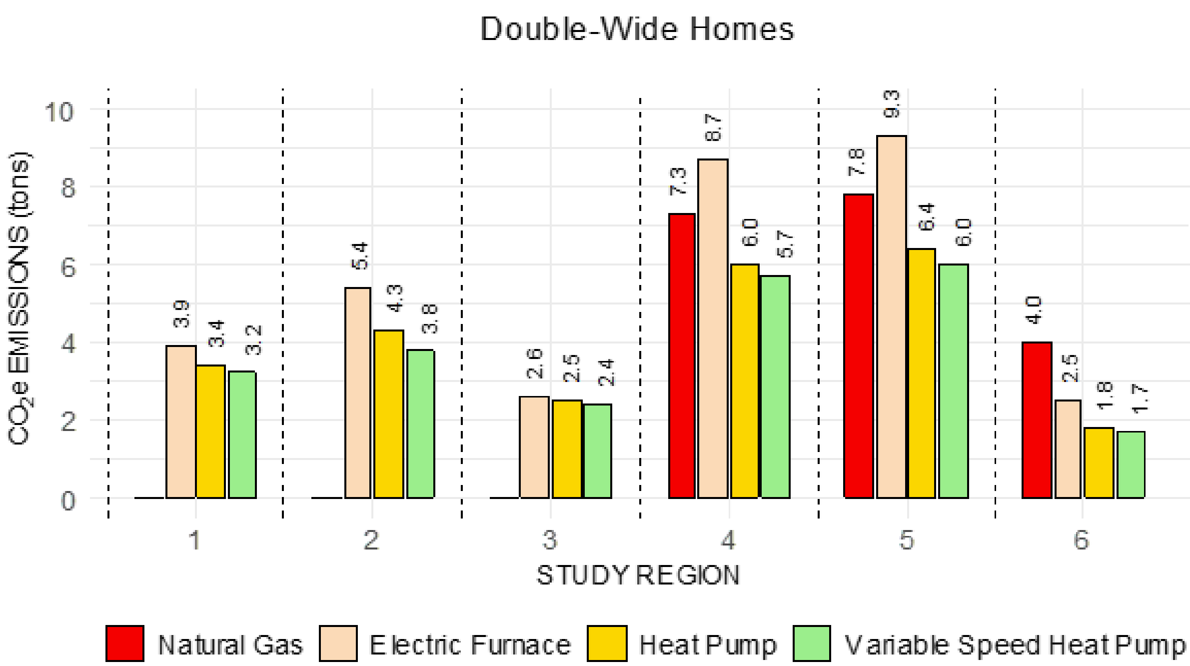
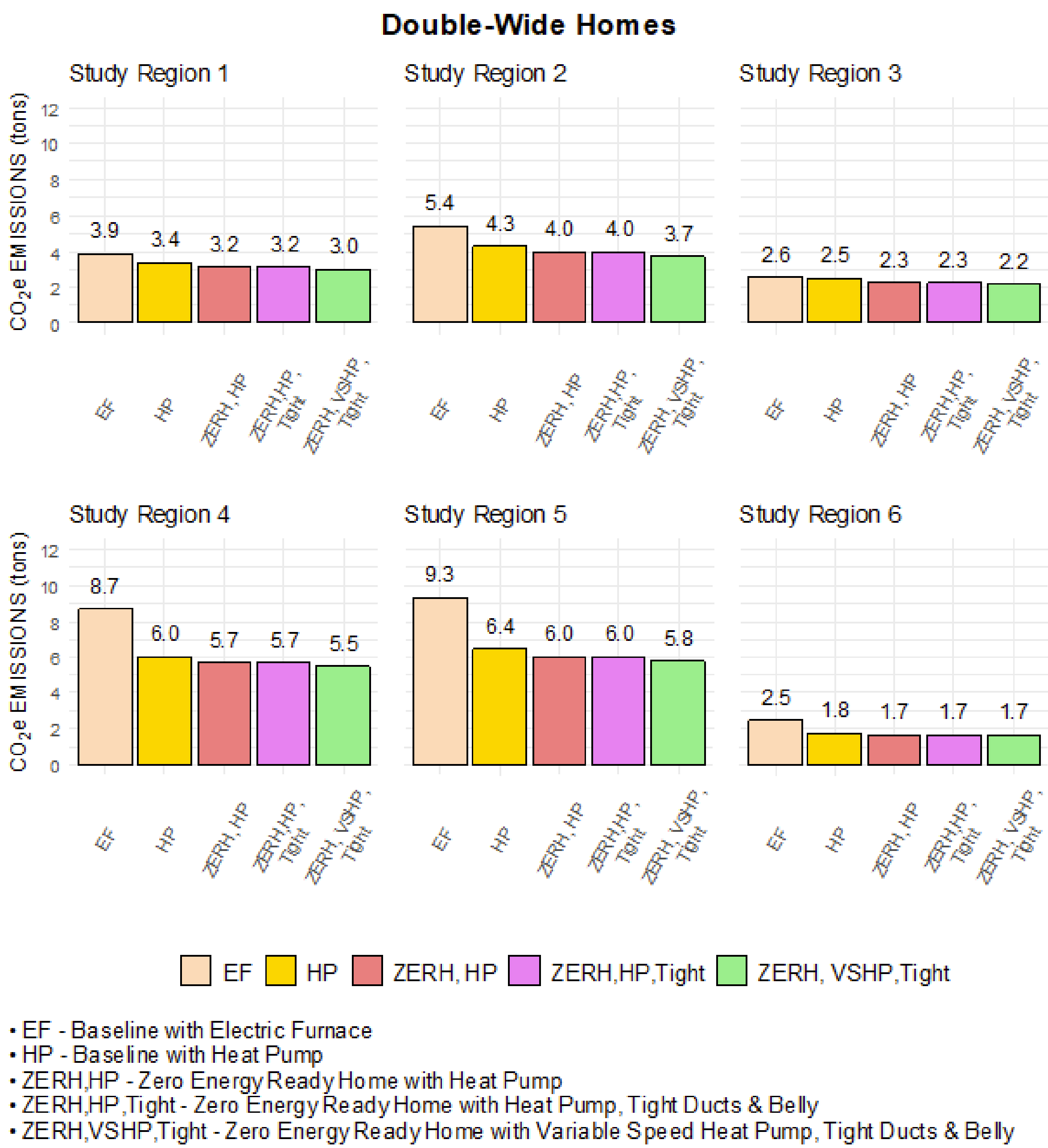


Figure EX-7 shows the estimated CO_2e emission savings for double-wide homes in all six study regions for cumulative measures of heat pumps, ZERH envelope, quality duct and belly tightening and variable-speed heat pumps. In study region 5, where the baseline CO2e

[2] See Appendix for CO_2e methodology

emissions are the highest, the combination of all measures is estimated to save 3.5 tons of CO_2e per double-wide house.

Figure EX-7 Simulated annual CO_2e emissions from combinations of HVAC and other improvements for double-wide homes by study region.



The economics look good for heat pumps in manufactured homes as a replacement for electric resistance units. The ZERH envelope saves a significant amount of energy. Although heat-pump cost and carbon savings appear much more impactful than do envelope-related savings, the combination of envelope improvements and heat-pumps addresses IAQ and comfort more comprehensively, and envelope improvements can reduce heat-pump required capacity, reducing the first cost. However, if we model the homes with a heat pump, from a consumer standpoint the ZERH envelope improvements may have to be accomplished at a cost (approximately) as low as $700 for single-wide homes in warm climates to $1,150 for double-wide homes in cold climates. There are also peak savings and significant emissions reductions from these measures that are not factored into these break-even points. If state policies determine a way the consumer can benefit economically from reducing CO_2e and reducing peak demand then the benefit may increase. Duct sealing and testing to reduce leakage may prove economical if manufacturers can keep costs low. Empirical research is needed to determine home belly leakage rates after installation to determine if a belly-tightening program on site is worthwhile.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

MODELING AND ECONOMICS OF SELECT HVAC IMPROVEMENTS IN MANUFACTURED HOUSING

OVERVIEW

A series of HVAC improvements modeled during the project's first phase examined their potential impact on the HUD-code manufactured housing industry. Modeling was performed with EnergyPlus, a detailed whole-building energy modeling tool, using two manufactured-home prototypes (single-wide and double-wide). These baseline models 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. A similar but slightly revised set of baseline models were modeled for this study, as well as recent ENERGY STAR and DOE Zero Energy Ready (ZERH) Manufactured Homes programs. Further revisions to the earlier models include the addition of a belly space zone with associated impacts of duct leakage, a more detailed cold climate heat pump model as well as additional outputs to account for carbon and electric demand profiles. The objective of the simulations is to inform industry and policy decision makers about returns on investments (financial, environmental) in HVAC and quality assurance measures.

Why Conduct Modeling?

The purpose of modeling is to determine a range of energy savings from proposed HVAC and quality installation improvements where sufficient empirical data does not exist. These improvements directly relate to the work on innovations in this project:

- Partial Factory-Install of Ducted Heat Pumps to increase heat pump penetration and installation quality in this market
- Simplified Field-Testing Protocol to improve home and duct tightness after site installation in order to save energy and reduce callbacks
- Factory-floor testing using a duct-leakage tester to test duct leakage on every home before leaving the factory to save energy and reduce callbacks
- Improved cross-over duct designs to improve durability and duct tightness and thermal resistance

Once simulated, the economics of the measures can be quantified based on consumer benefit to determine break-even costs for the measures. Then manufacturers can weigh marketability and potential company profit on improved homes for each measure to determine which to include or exclude. The simulations may also guide federal, state, local and utility decision makers interested in reaching efficiency, renewable energy, greenhouse gas and affordable housing goals to determine the incentives that may accelerate industry adoption.

BACKGROUND

The first phase of this project identified 13 innovations. Four of those innovations involved improving ductwork either through different design, such as crossover ductwork or interior ductwork, or via improved practices such as new testing protocols or sealing product. The other innovations related to heat pump installations and their control. Through discussions with industry, the project is moving forward with the four innovations identified above with the intent of fostering greater industry adoption.

Some important changes have occurred since the phase one modeling effort. There was new legislation passed, the Inflation Reduction Act (IRA), that offers increased incentives for new efficient manufactured homes that comply with the ENERGY STAR or DOE Zero Energy Ready Manufactured Home programs. These incentives provide some leverage, particularly as the programs can be updated over time. But, we need to understand what is happening currently in the industry and what changes might make a difference beyond those already incorporated in these programs.

House Air Leakage

Unfortunately, research into some key energy aspects of manufactured homes is limited. House air leakage rates at the factory and in the field could be impacted by quality inspections and testing that comes with advanced programs, but the data on manufactured home air leakage is largely limited to some studies done years ago. A nine-home study conducted by Davis, et. al, during 1994 and 1995 in new homes in a program in the Pacific Northwest program had field assessed air leakage of 4.5 ACH50. A study (Baylon, et. al.) conducted in 2006 by the Northwest Energy Efficient Manufactured Homes (NEEM) showed even tighter new homes with an average of 3.9 ACH50 and a maximum of 6.7. A 2015/2016 study that included 17 homes that were less than 15 years old in Minnesota had an average ACH50 level of 5.7 with a maximum ACH50 of 10.9.[3] However that study (Pigg, et. al, 2016) also examined older homes and found overall ACH50 levels averaged 12.9 and low income households had average ACH50 levels of 15.5.

Nabinger and Persily (2011) measured air leakage of the living space to the belly and the belly to the crawl space and crawl space to outside in one home and found the ELA at 4 Pascals of living space to belly was 510 cm^2, belly to crawl space was 258 cm^2 and crawl space to outside was 787 cm^2. The ACH50 of the home was 10.1 with the forced air system sealed and 11.8 unsealed. Air sealing retrofits reduced the overall airflow to 9 ACH50, cutting the total ELA from 728 cm^2 with unsealed air system to 555 cm^2. The researchers only measured post-retrofit leakage from living space to crawl space (at 362 cm^2) and not to the belly. They assume post retrofit had equally distributed leakage of 181 cm^2 ELA between living and belly, and belly and crawl space. This represents a reduction of 65% of ELA between living and belly. A field study measuring leakage between the belly and crawl space and living and belly in many homes is needed, ideally when homes are new and repeated after 5 or 10 years.

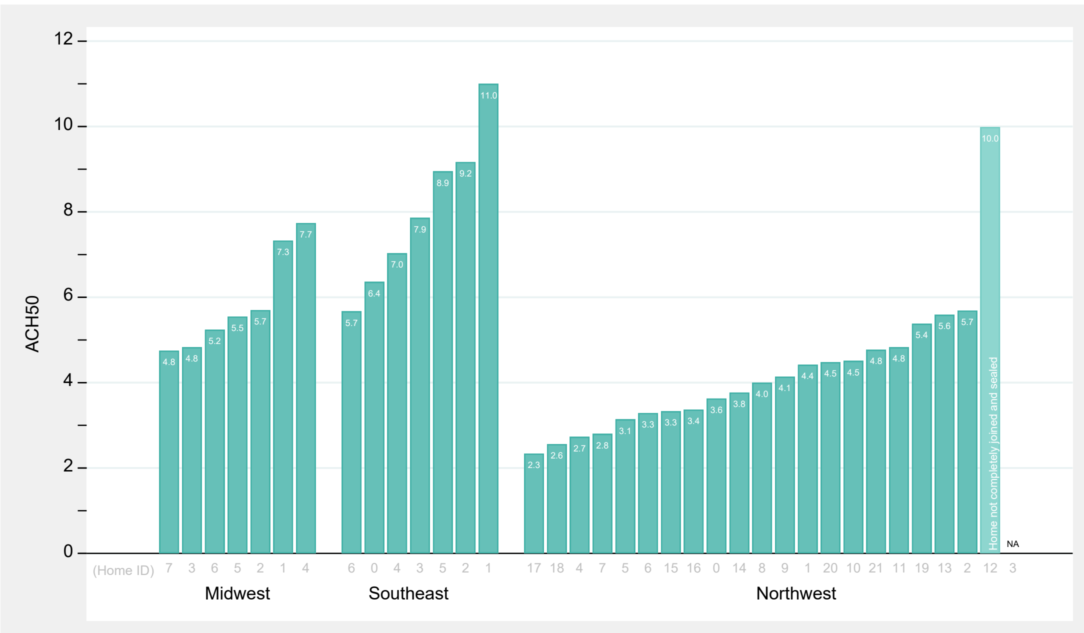
The belly condition was observed in the Minnesota study that researched largely older homes. Twenty- nine of the 89 homes had "damp" belly areas and five others had standing water in the

[3] Private correspondence from Slipstream with details from the Pigg, et. al., 2016 report.

crawl space. Twenty-two percent of the homes had either floor or belly insulation in need of repair. The researchers labeled 50% of the homes in the study as having a "Good" belly condition, 29% "Fair", 11% "Poor" and 10% "Very Poor." Problem areas observed that could be readily air sealed included electrical and plumbing connections and marriage joints.

As part of this current DOE ABC project's effort to develop new test protocols, a limited number of homes were tested in 2022.[4] Figure 1 shows the results. The homes built in the Northwest U.S. are much tighter than the homes in the other regions, albeit, sample sizes are small. Short of more extensive field studies, it would appear the long term work and continued inspections done in the Northwest U.S. have resulted in improved air leakage.

Figure 1. Air leakage test results from 2022 in three different regions.

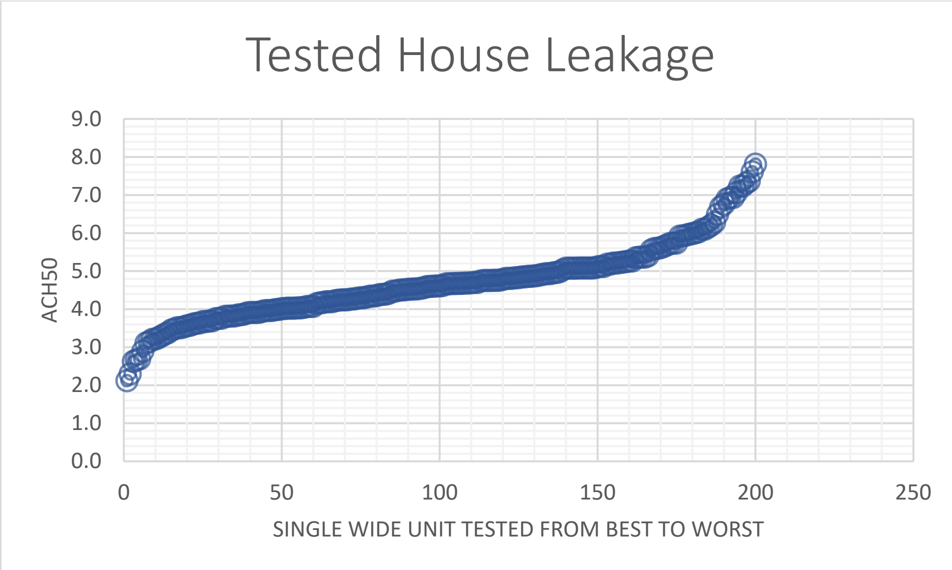


Recent (2022) building tightness results from 200 factory-tested, mostly single-wide manufactured homes from multiple plants in the Southeast found an average air leakage of 4.7 ach50.5 However, as Figure 2 shows, these ranged from 2 to more than 7 ach50, and leakage rates are expected to be somewhat higher after setup.

[4] Data not yet published

[5] Private communication from Bobby Parks, unpublished.

Figure 2. Factory tested building tightness results from 200 mostly single-wide HUD home's, from multiple plants in the southeast



Duct Air Leakage

The quality of ducts has been a focus of working with manufactured home builders for some time. McIlvaine, et. al, (2004) reported on duct tightness tests conducted on floors where the goal was to meet Total Qn of under 6% or Qn to outside of 3%, where Qn is defined as leakage at 25 Pa per square foot of floor area. As shown in Figure 3, systems sealed with mastic achieved those results while systems sealed with tape did not.

Pigg, et. al., found in their Minnesota field study that homes less than fifteen years old averaged 5.9 CFM25/100ft2 leakage to outside. The NEEM 2006 report indicated average CFM25/100ft2 to outside duct leakage of 3.9 with the majority of homes double-wide units and an average conditioned floor area of 1739 square feet. They looked at leakage through the ducts at 50 Pascals comparing homes with cross-over connections "secured" and not secured, where "secured" means securely fastened to the trunk duct collar and much less likely to experience mechanical failure over time. The results are shown in Table 1. Houses with secured cross-over connections were significantly tighter.

Figure 3. Duct leakage as tested on factory floors show mastic sealed ducts out performed taped sealed ducts (McIlvaine, et. al, 2004).

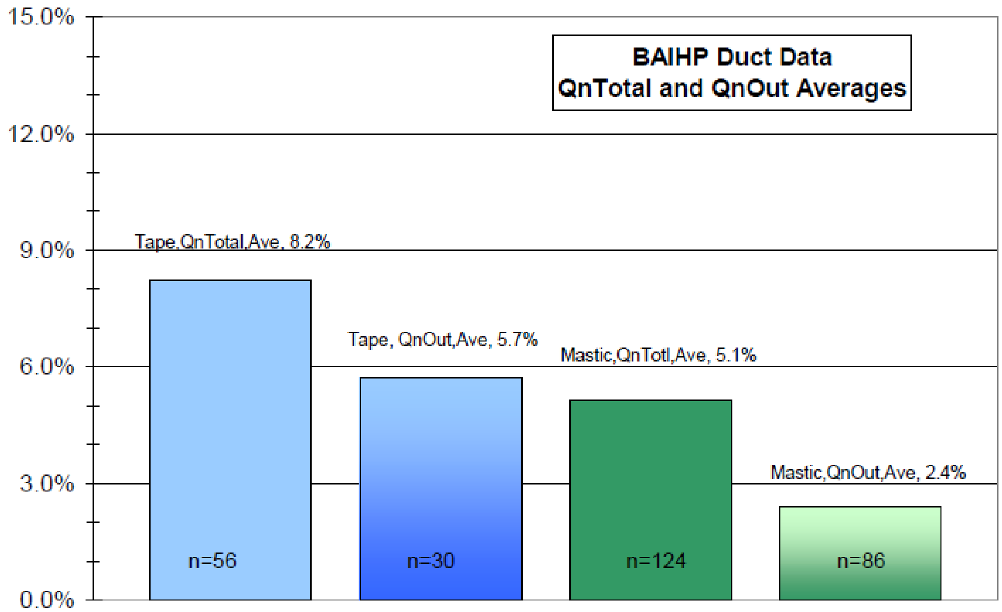


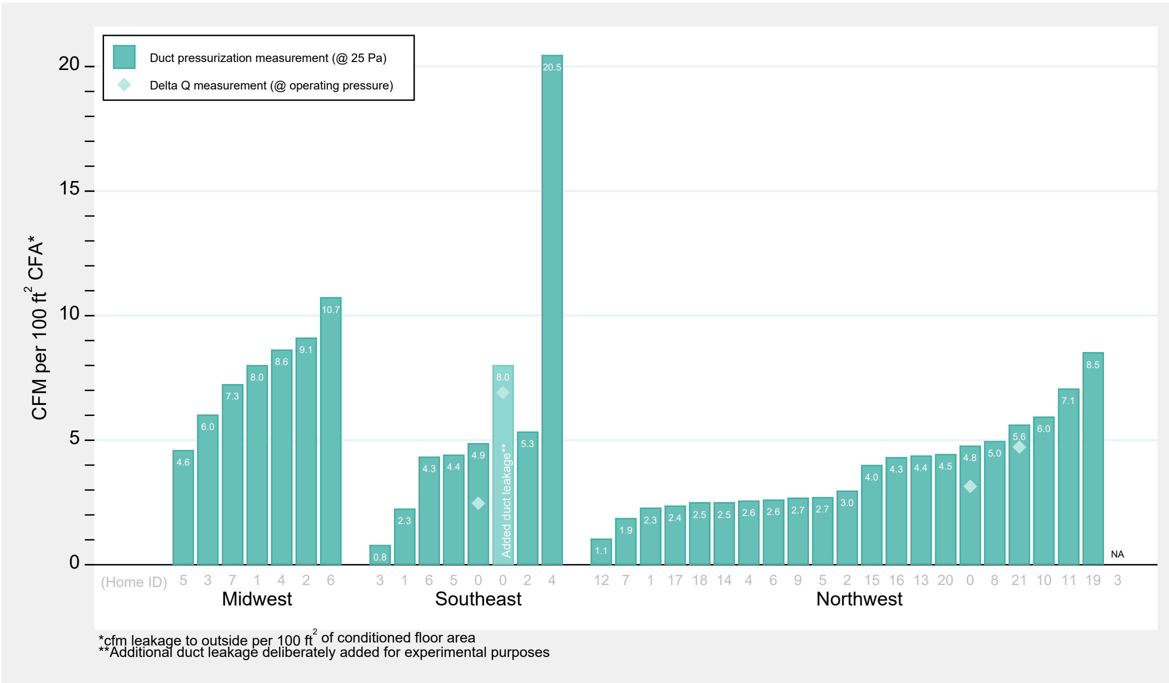
Table 1. Cross-over status vs. duct air leakage (Baylon, et. al. 2006)

Cross-Over Status	Sample Size	CFM Leakage @ 50 Pa	
		Mean	Std. Deviation
Not Secured	17	135.2	139.5
Secured	32	83.8	51.7
Total	49	101.6	94

The NEEM program stopped producing reports on follow-up visits in the field after 2006.

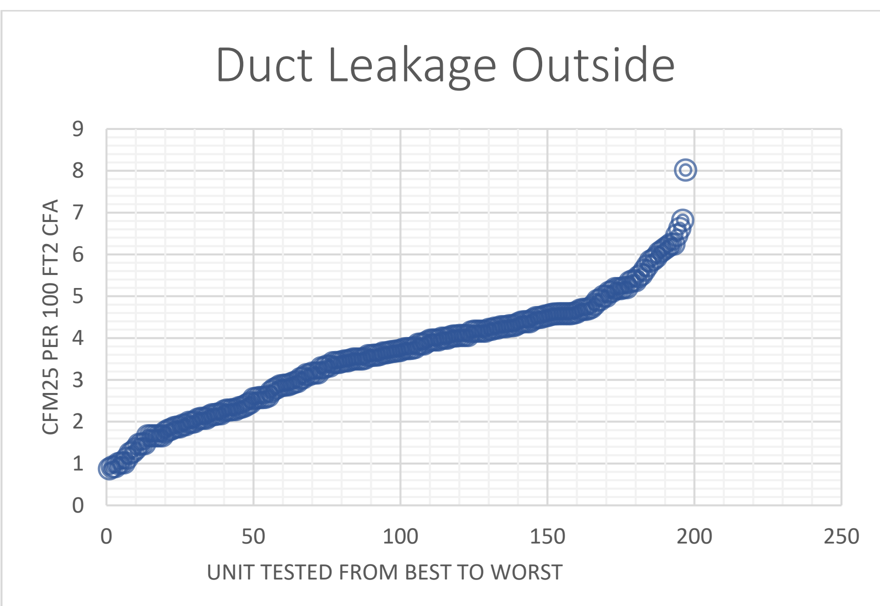
Duct leakage data were collected in 2022 for a limited number of homes as part of the new testing protocol for this project. Similar to the envelope-tightness results, the Northwest U.S. homes tested performed better than the other regions as shown in Figure 4.

Figure 4. 2022 Duct leakage results from homes in three regions.



The aforementioned 2022 sample of 200 factory-tested homes in the southeast showed an average of 3.6 CFM25/100 ft2 to outside. Twenty-nine of the 200 units (14%) had leakage to outside > 5 CFM25/100 ft2 and ten (5%) were > 6 CFM25/100 ft2 as depicted in Figure 5. [6]

Figure 5. Tested duct leakage results from 200 HUD home's, from multiple plants in the southeast.



[6] Private communication from Bobby Parks, unpublished.

The lack of knowledge about belly air tightness and lack of field measurements of leakage in other parts of the country leave some uncertainty. Should every home be tested for air leakage and duct leakage in the factory? Should the belly be tested? What should be required in the field after utility and HVAC hook-ups are complete to qualify a home for the advanced programs like Zero Energy Ready Manufactured Home?

Simulations can help assess the magnitude of potential savings by providing parametric analysis of duct leakage and belly leakage.

MODELING PARAMETERS

Simulation Weather Profiles

The revised models were run with the same eight weather profiles of cities used for the original baseline models in the earlier report. TMY3 weather files were used. Although these are what is typically used in EnergyPlus analysis there is concern that the weather files should be updated due to the impact of climate change (Robert and Kummert, 2012; de Wilde, 2012, Crawley and Lawrie, 2020). Most North American cities are becoming warmer. Such an impact would show more cooling energy use and less heating energy use. It may not impact peak winter conditions as cold peaks still occur (for example the cold winter extremes central Texas experienced this decade).

These cities were chosen to represent the shipment-weighted climate midpoint by region and HUD thermal zone for the continental US:

Zone 1: Houston, TX and Atlanta, GA

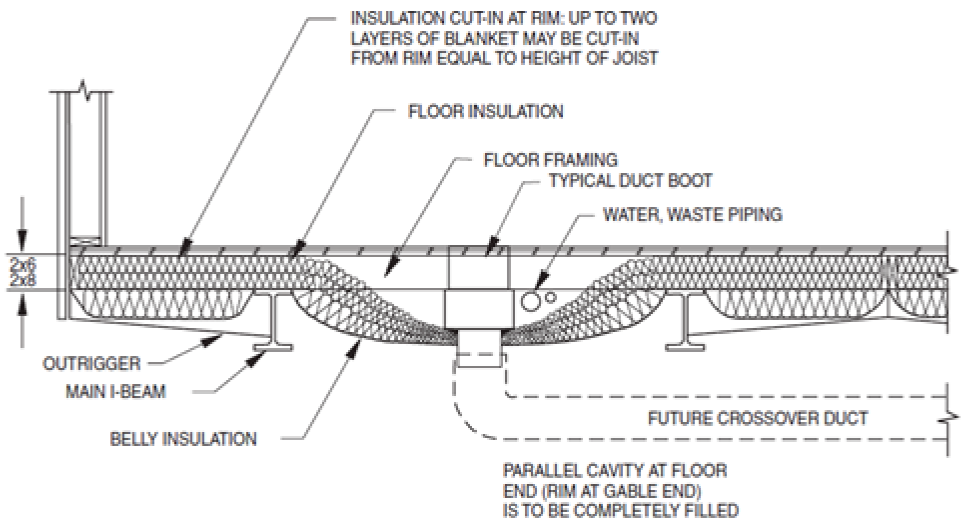
Zone 2: Raleigh, NC and Phoenix, AZ

Zone 3: Baltimore, MD; Chicago, IL; Denver, CO; and Seattle, WA

Enhanced Modeling of Belly Space

The original building models consisted of three zones: Living, Attic and Crawlspace. The addition of a fourth zone (Belly) is here intended to better represent this housing stock and assess the relative importance of having a tightly sealed belly structure. The "belly" area of a manufactured home is the area below the floor but above the ground. The belly is the typical location of the manufactured home ductwork (floor ducts) for the HVAC system, with the ducts located above a road barrier and layer of insulation (Figure 6). 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.

Figure 6. Belly cross-section showing insulation and routing of HVAC ducts, water, and waste pipes.



The original model used simplifying assumptions to avoid the need for a separate belly zone including:

- The main duct system was assumed to be "inside" and not subject to conductive losses.
- Belly insulation was modeled at nominal R-values without adjustment for compression or compromise.
- Due to issues related to the highly unbalanced nature of duct leaks in manufactured homes, the modeling for duct leakage used a less-refined, mass-conservation approach for duct leakage instead of EnergyPlus's more-refined airflow-network model.

Modeling a separate belly zone may provide a better representation of heat and mass transfer between the living area and crawlspace. The belly zone modeled consists of components as seen in Figure 6 including:

- 8-ft by 7-in cross-sectional airspace by length of trunk duct
- 2x6 floor joists
- 4in I-beams
- ¾" OSB decking, 50% carpet, 50% hard flooring
- floor insulation levels from R13 to R30 (per new rulemaking)

The model used a rectangular shaped zone in order to keep the effort reasonable. Models for single-wide and double-wide are represented in Figures 7 and 8.

Figure 7. Single-wide Belly Model Cross-section showing free air zone where trunk duct resides.

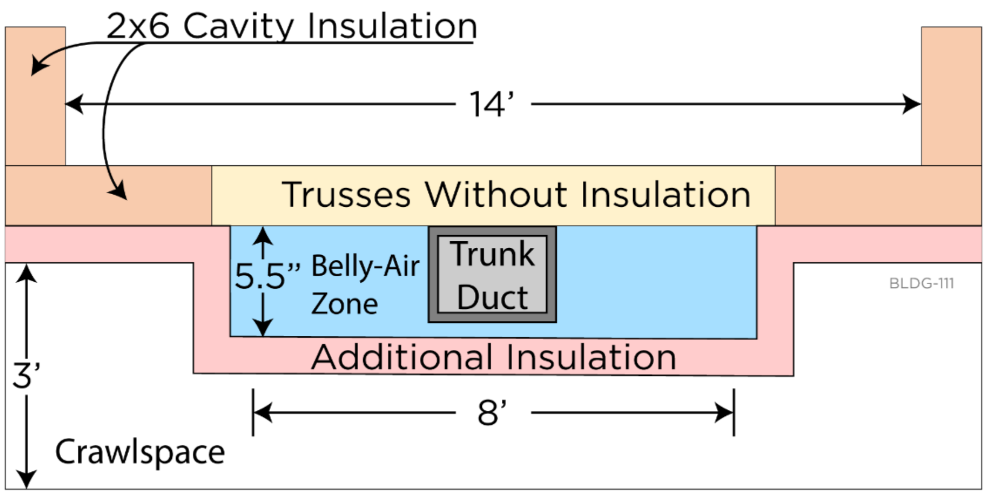
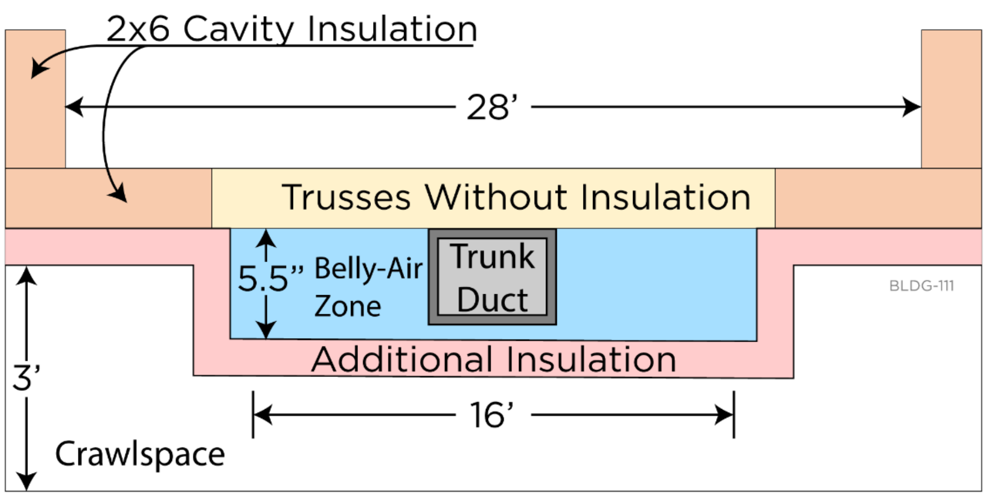


Figure 8. Belly Model single cross-section modified for a double-wide showing free air zone where trunk duct resides.



Figures 7 and 8 illustrate a 2-D cross-section of the belly. The modeled belly air zone length is 8′ wide for the single-wide and 16′ wide for the double-wide and runs the entire length of the trunk duct. While the double-wide model represents two belly-air zones together (one for each floor) and has slightly less surface area than two separate floors with 7″ high sides, this is seen as insignificant. The R-value of the insulation blanket below the ducts varies by region, as discussed later. The area directly above this zone is modeled without insulation between the trusses, resulting in only the ¾″ OSB decking, 50% carpet, 50% hard flooring restricting heat flow between the conditioned space and the belly zone. The belly zone is modeled at varying levels of air leakage to the crawlspace, going as high as ACH50 of 60 to represent some of the damage that occurs to the belly-barrier through delivery and in early life on the site. Duct heat transfer and leakage is discussed in the Ducts section below.

Equipment Configurations

There is electric resistance and an 80 AFUE gas furnace modeled as baseline systems in each location except for Atlanta and Houston where the gas-furnace model is omitted because gas is less prevalent in those regions.

For heat pumps, in one city, Chicago, we ran a parametric analysis to explore the difference between a dual-fuel configuration with a heat pump and a natural gas furnace instead of an electric coil as the backup system for the heat pump. In other cases the backup to heat pumps was just electric resistance coil. In simulations with heat pumps, the electric heat pump is the primary heating source, and the supplemental heater is the secondary source. The supplemental heater provides additional heat to meet the heating load when the heat pump is unable to meet the heating load. Additionally, when the heat pump is unable to turn on under very low outdoor temperature, the supplemental heater will be the only heating source to meet the heating load. This included some hours where the heat pump did not run at all in the coldest city (Chicago). For the simulation supplemental electric and gas furnaces were both controlled in this manner.

Single speed: Cold Climate Heat Pump Characteristics (based on Carrier 40MBAAQ indoor unit, 38MARBQ outdoor unit):

- Lowest outdoor temperature to still provide heat: -22 F (-30 C)
- This equipment was tested at the FSEC Manufactured Housing Laboratory and in a Oregon manufactured home and will be reported on in another document
- Although the equipment has two speeds, performance data provided by Carrier is single speed only, so that we used that performance data to simulate it as single speed.

Variable-speed cold climate heat pump characteristics (based on Carrier 25VNA Infinity Variable-speed Heat Pump with Greenspeed Intelligence[7])

- Lowest outdoor temperature to still provide heat with COP =1.75: -3 F (-19.4 C)
- This unit was installed in Minnesota homes (Schoenbauer et. al. 2017)
- Depending on capacity the units have a SEER of 16.8 -- 20 , an EER of 1.4 -- 16 and an HSPF of 10.3 -- 13.0
- Variable-speed compressor with capacity range from 40--100%

Ducts

Duct tightness levels were modeled with Qn of 0.12 for the baseline as done in the previous modeling effort. Reduced duct leakage scenarios were modeled with Qn of 0.04 and 0.08. Houston and Atlanta are the only locations where attic ducts are prevalent: these were modeled with both attic and belly ducts for comparison. All other cities were modeled with floor ducts only. Duct leakage was modeled with supply-side leakage only in all cases. Return-side leakage

[7] https://www.shareddocs.com/hvac/docs/1009/Public/01/25VNA-05PD.pdf

is typically not present with interior air handlers and un-ducted central return in manufactured housing.

Envelope Specifications

The new baseline models incorporate the envelope specifications shown in Table 2.

ENERGY STAR Version 3 was recently published as detailed in Table 2. DOE ZERH Manufactured Homes Version 1 was also recently released with the same insulation, window, and duct insulation requirements as ENERGY STAR V3 plus a list of mandatory factory and field installed technical requirements. Please note that envelope and duct airtightness requirements are not specifically identified in these programs (other than 0.04 cfm25/ft2 for ZERH). Baseline envelope and duct leakage levels for this study were kept consistent with previous HUD code home modeling studies at 8 ACH50 for envelope leakage and 0.12 cfm25/ft2 for duct leakage.

Table 2. Summary of envelope specifications for the baseline, ENERGY STAR Version 3 and ZERH Manufactured Homes Version 1.

Component, HUD Climate Zone 1/2/3	Baseline	ENERGY STAR 3.0	ZERH MH 1.0
wall (zones 1/2/3)	R-11/11/19	R-13/21/21	
Floor	R-11/11/22	R-22/22/33	
Ceiling	R-30/30/30	R-33/33/38	
window U-value	0.48/0.48/0.34	0.30/0.30/0.30	
window SHGC	0.62/0.62/0.32	0.25/0.25/NA	
ACH50	8	8	
Ducts		Enclosed or buried in insulation, R-8 ducts in unconditioned spaces	
Electric Heat Pump (multi-section homes only)		7.5HSPF2 / 14.3 SEER2	

MODEL SIMULATIONS AND OUTPUTS

The results of each simulation include modeled hourly energy use by fuel in order to facilitate estimating carbon emissions. The results also include peak kW demand. Annual energy use is tallied by heating, backup heating, cooling, fan energy, lights, and hot water. CO_2e emissions were calculated based on the hourly outputs (See Appendix A for methodology). The electric grid selected was the one serving the city modeled.

Table 3 shows the modeling-run matrix. For each city there is a baseline and improved building envelope. The improved envelope runs include two different levels of heat pumps. There are three different levels of duct tightness simulated and two different levels of belly tightness simulated. This information can shed light as to the value of quality inspections and sealing of these areas.

Table 3. Simulation matrix of runs for each floor plan (single/double-wide)

Equipment			Envelope	Duct Location	Leakage	# of Simulations
14.3 SEER2 AC +Electric Furnace (EF)	**14.3 SEER2 AC +Gas Furnace (GF)**	**Improved option: 7.5 HSPF2 Heat Pump plus Backup Electric Furnace**	**Baseline /Improved Envelope**	**Attic or Belly**	**Leakage Scenarios and Improvements**	
Chicago, Baltimore*, Denver, Seattle						
Elec. Heat COP = 1	Gas Furnace AFUE = 0.8	**Single Speed** – Chicago also with Backup Gas Furnace	Baseline/ ZERH	Belly	1. Duct Leakage Qn =0.12 base, 0.08, 0.04 improved 2. Belly Leakage 15 ACH50 Base, 3 ACH50 Improv.	48 Simulation Runs for each home type
		Variable-speed - Chicago also with Backup Gas Furnace				
Simulations per city for both single-wide and double-wide homes (Baltimore, Denver, Seattle)						**96**
Simulations for Chicago (gas supplement included) for both single-wide and double-wide homes						**144**
Number of simulations for 4 cities (Chicago, Baltimore, Denver, Seattle)						**432**
Raleigh, Phoenix						
Elec. Heat COP = 1	Not applicable	**Single Speed** – with Backup Elec. Heating (EF)	Baseline/ ZERH	Belly	1. Duct Leakage Qn =0.12 base, 0.08, 0.04 improved 2. Belly Leakage 15 ACH50 Base, 3 ACH50 Improv.	36 Simulation Runs for each home type
		Variable-speed - with Backup Elec. Heating (EF)				
Simulations per city for both single-wide and double-wide homes						**72**
Simulations for 2 cities (Raleigh, Phoenix)						**144**
Atlanta, Houston						
Elec. Heat COP = 1	Not applicable	**Single Speed** – with Backup Elec. Heating (EF)	Baseline/ ZERH	Belly and Attic	1. Duct Leakage Qn =0.12 base, 0.08, 0.04 improved 2. Belly Leakage 15 ACH50 Base, 3 ACH50 Improv.	54 Simulation Runs for each home type
		Variable-speed - with Backup Elec. Heating (EF)				
Simulations per city for both single-wide and double-wide homes						**108**
Simulations for 2 cities (Atlanta, Houston)						**216**
Total all simulations, all cities						**792**

*There were added runs for Baltimore with belly leakage of 30 ACH50 and 60 ACH50 with duct leakage at Qn of 0.04 and 0.08 since, 15 ACH50 represents only a very small hole. This resulted in another 8 simulations for a total of 800.

SIMULATION RESULT ANALYSIS

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 in the region. Due to the low percentage of fuel-fired manufactured homes in Study Regions 1 and 2, fuel-fired heating was not modeled for Atlanta, Houston, Raleigh, or Phoenix.

All units consisted of centrally-ducted air conditioning with one of three types of heating: 1) electric resistance, 2) gas furnace, 3) electric heat pump with supplemental electric-resistance heat. The vast majority of manufactured homes use split-cooling systems with separate indoor and outdoor components, but a significant number of packaged systems (evaporator and condenser combined in a single outdoor unit) are prevalent in the hot, humid climates along the Gulf Coast. Packaged systems therefore require a portion of the supply and return ductwork to be in the crawlspace to deliver air from the outdoor unit to the indoor ductwork. Table 4 shows which mechanical systems were modeled by HUD climate zone and which were excluded from the analysis due to low incidence of use in those regions. A total of 372 simulations were required for each home type (single/double-wide).

Table 4. 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 (EF)	All cities	All cities	All cities
Split-system AC + Gas Furnace (GF)	Not modeled	Not modeled	All cities
Split-system Heat Pump (HP)	All cities	All cities	All cities
Floor supply air (ducts in belly)	All cities	All cities	All cities
Ceiling supply air (ducts in attic)	All cities	Not modeled	Not modeled

Modeled baseline annual heating, cooling and air-handler fan energy for the baseline condition (as defined in Table 2) are presented in Figure 9 for Houston and Atlanta where two different duct locations were modeled. Energy in this figure, as well as all others in this report, is site energy (as opposed to source energy). The modeling indicates higher HVAC use for attic ducts compared to belly ducts, due to energy losses in the unconditioned attic space. Figure 10 shows results for the other locations where only belly ducts were modeled. Except for Phoenix, space heating dominates overall space-conditioning use for these regions.

Figure 9. Baseline energy use with belly and attic ducts in Houston and Atlanta, for double-wide (DW) and single-wide (SW) prototype homes, by HVAC type.

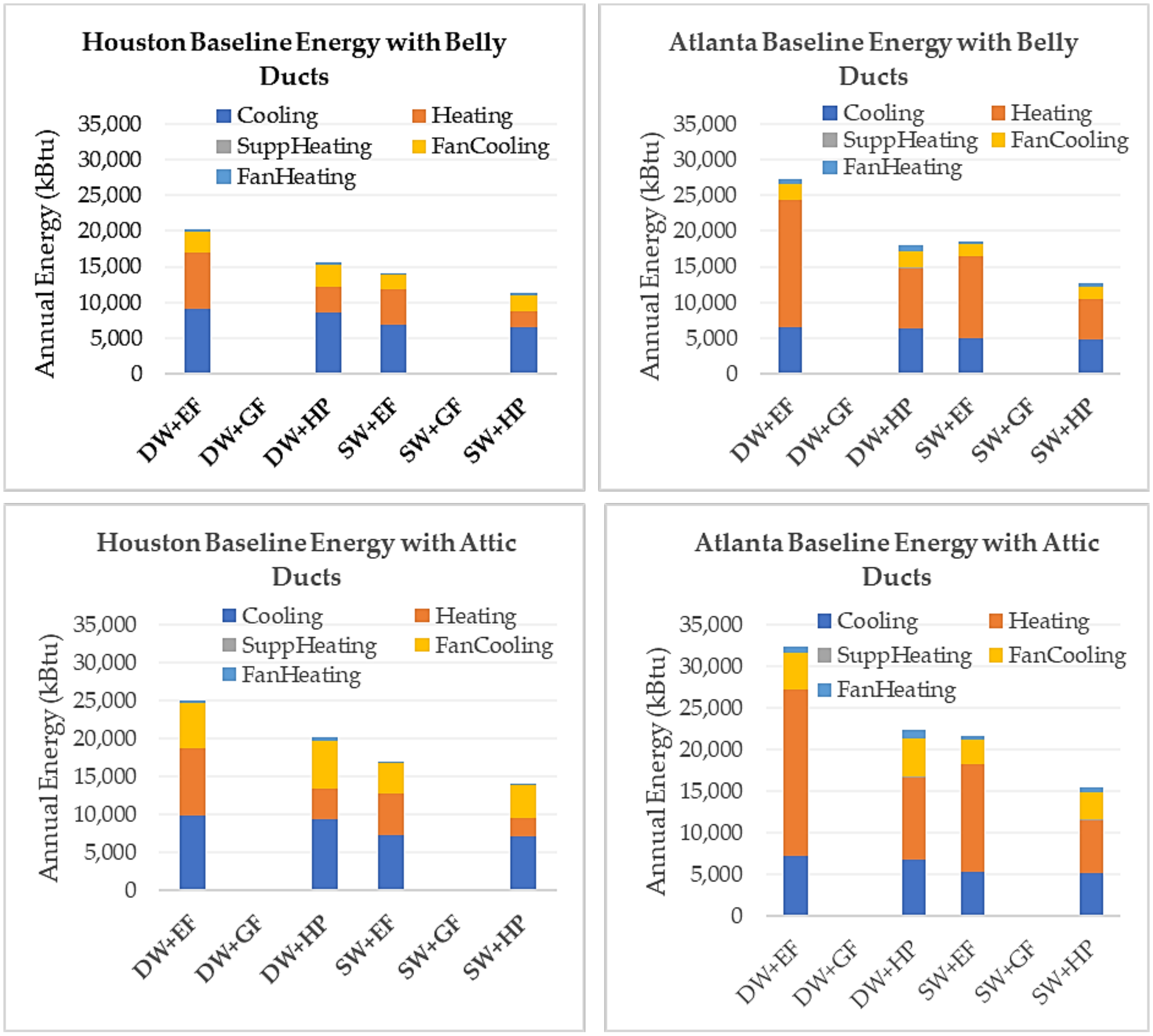
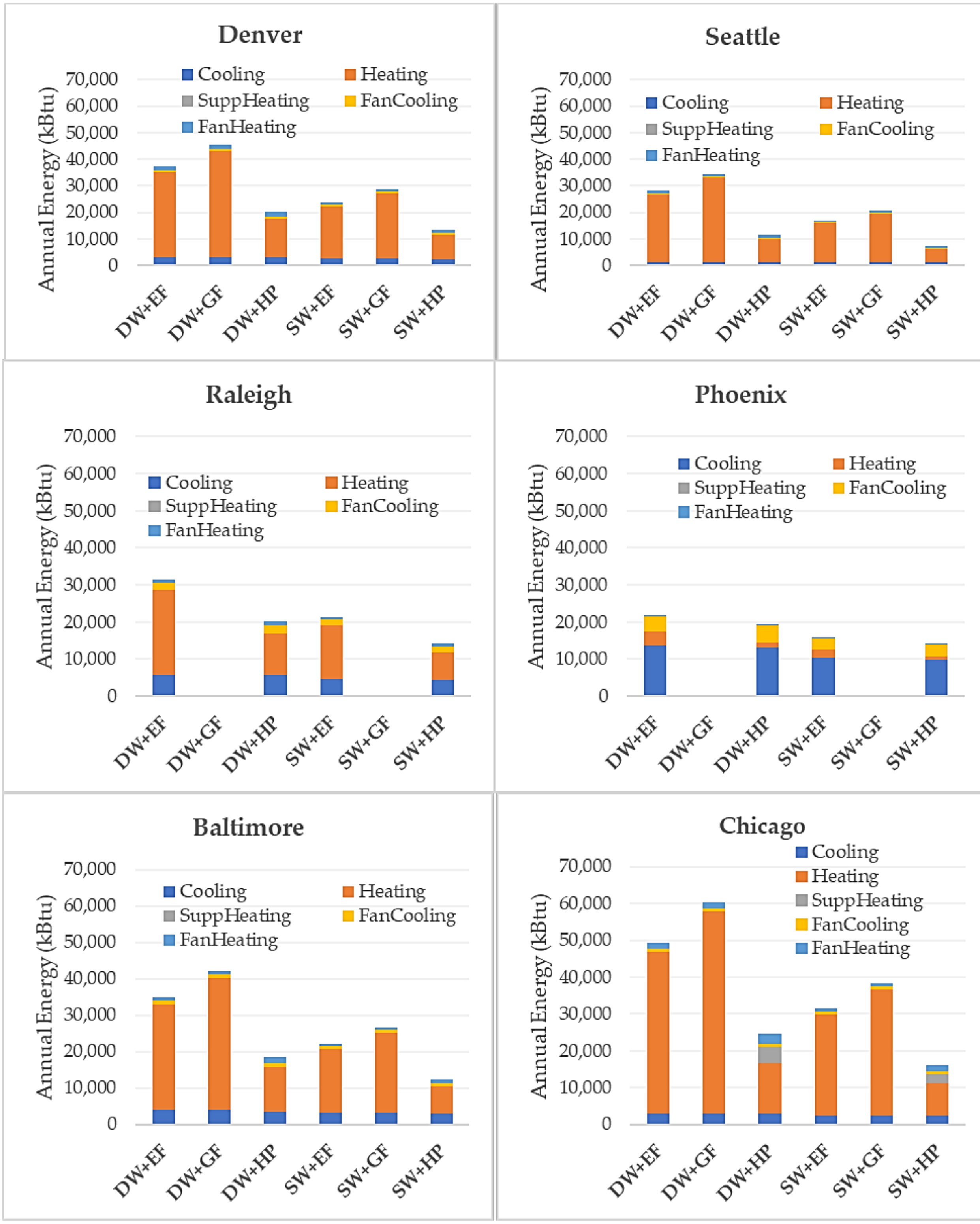


Figure 10. Modeled HVAC energy use with belly ducts for single-wide (SW) and double-wide (DW) homes by location and mechanical system type (EF=electric furnace, GF = gas furnace, HP = heat pump).



SAVINGS FOR HEAT PUMPS

Heat pumps offer a great opportunity for energy savings for manufactured home residents. There are several possible approaches to what is often a cost-effective option. One simple thing manufacturers can do is make the system heat pump ready by installing a heat pump-equipped air handler (including indoor coil) in the factory instead of an electric resistance-only furnace. Since matched systems are sized, this may mean specifying the outdoor system to be installed. Other options include factory installation of heat pump systems, including multi-split options with 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. The sizing of heat pumps can also affect the amount of supplemental heat required, although larger systems can consume more fan power and cycle on and off more frequently. Variable-speed systems overcome some of these problems. In this section, we look at savings from single-speed HPs and variable-speed high-efficiency units.

Single-speed heat pump savings relative to electric resistance

Tables 5 and 6 show electric energy savings for a single-speed HP (HSPF 10.3) 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 kBtu savings there are small. Homes with attic ducts show somewhat reduced savings in this comparison.

Table 5. HVAC energy savings for a single-speed heat pump over an electric-resistance furnace with standard central air conditioning in a double-wide home.

Electric Savings (Sigle-speed Heat Pump vs Electric Furnace) Double-wide				
City	Belly kBtu	Attic kBtu	Belly %	Attic %
Atlanta	9146	9933	33.6%	30.7%
Baltimore	16530		47.3%	
Chicago	24492		49.8%	
Denver	17146		46.1%	
Houston	4502	4749	22.3%	19.0%
Phoenix	2388		11.0%	
Raleigh	11137		35.5%	
Seattle	16568		59.0%	

Table 6. HVAC energy savings for a single-speed heat pump over an electric-resistance furnace with standard central air conditioning in a single-wide home.

Electric Savings (Single-speed Heat Pump vs Electric Furnace) Single Wide				
City	Belly kBtu	Attic kBtu	Belly %	Attic %
Atlanta	5791	6180	31.2%	28.5%
Baltimore	9952		44.8%	
Chicago	15307		48.6%	
Denver	10417		44.0%	

Houston	2824	2834	20.0%	16.7%
Phoenix	1517		9.7%	
Raleigh	7128		33.5%	
Seattle	9478		56.6%	

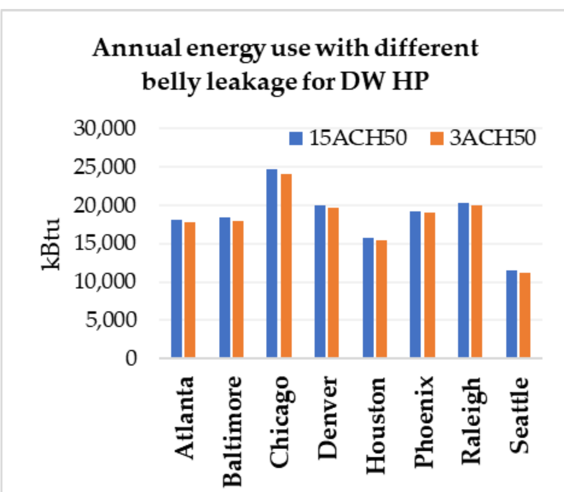
BELLY LEAKAGE IMPACTS

The previous modeling study assumed that the living space and the belly space were modeled as a single zone. In this study, the belly zone is modeled as a separate zone. This section examines how belly leakage affects the energy use of the HVAC system in both SW and DW homes. The baseline belly leakage to the crawlspace is 15 ACH50. Simulations were also run with a tight belly leakage to the crawl space of 3 ACH50 in all eight cities. In addition a single, mixed-climate city was chosen to illustrate higher levels of damage to the belly barrier with leakage levels of 30 and 60 ACH50 but only in the Baltimore climate.

Figure 11 on the left shows the annual HVAC system energy use with different levels of belly leakage for the eight modeled locations for a double-wide home using a single-speed HP system. Annual energy use varies by location from a low of 11,000 kBtu in Seattle to a high of 24,000 kBtu in Chicago.

Figure 11 on the right shows the absolute and percentage savings in annual energy consumption with different levels of belly leakage for the eight locations. The other conditions are the same as in the figure above. The columns represent absolute savings, while the markers represent percentage savings. The absolute differences in annual energy use vary from a low of 190 kBtu in Houston to a high of 600 kBtu in Chicago. The percentage differences in annual energy use range from a low of 1.0% in Phoenix to a high of 2.7% in Seattle.

Figure 11. Impact of a tighter belly on annual energy use for double-wide unit. Note: The legend 'Abs' in the right figure denotes 'Absolute'



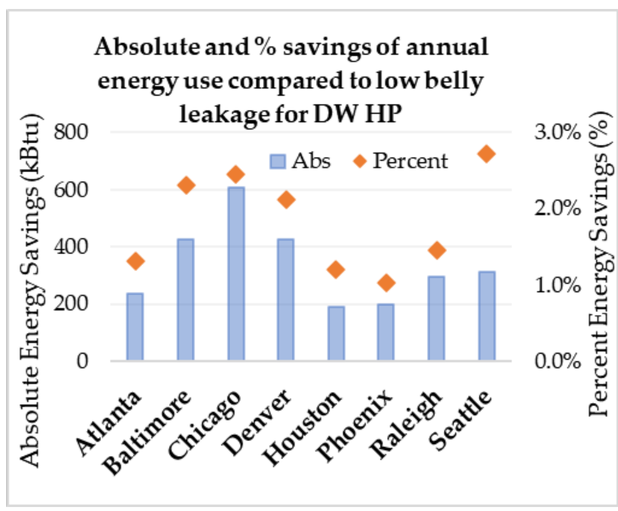
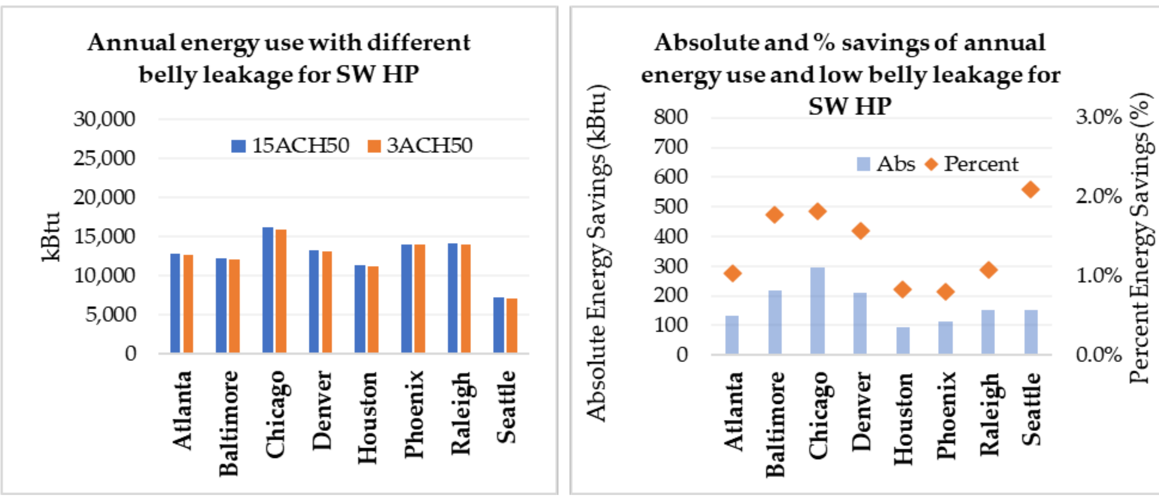


Figure 12 shows the annual HVAC system energy use with different levels of belly leakage in 8 locations for a single wide home using a single-speed HP system. Annual energy use varies by location from a low of 7,200 kBtu in Seattle to a high of 16,000 kBtu in Chicago.

Figure 12 on the right shows the absolute and percentage savings in annual energy consumption with different levels of belly leakage at 8 sites. The other conditions are the same as in the figure above. The columns represent absolute savings, while the markers represent percentage savings. The absolute differences in annual energy use vary from a low of 95 kBtu in Houston to a high of 290 kBtu in Chicago. The percentage differences in annual energy use range from a low of 0.8% in Houston to a high of 2.1% in Seattle. In general, variations in belly leakage have a small impact on energy consumption. The highest percentage differences are 2.5% for double-wide and 1.8% for single wide.

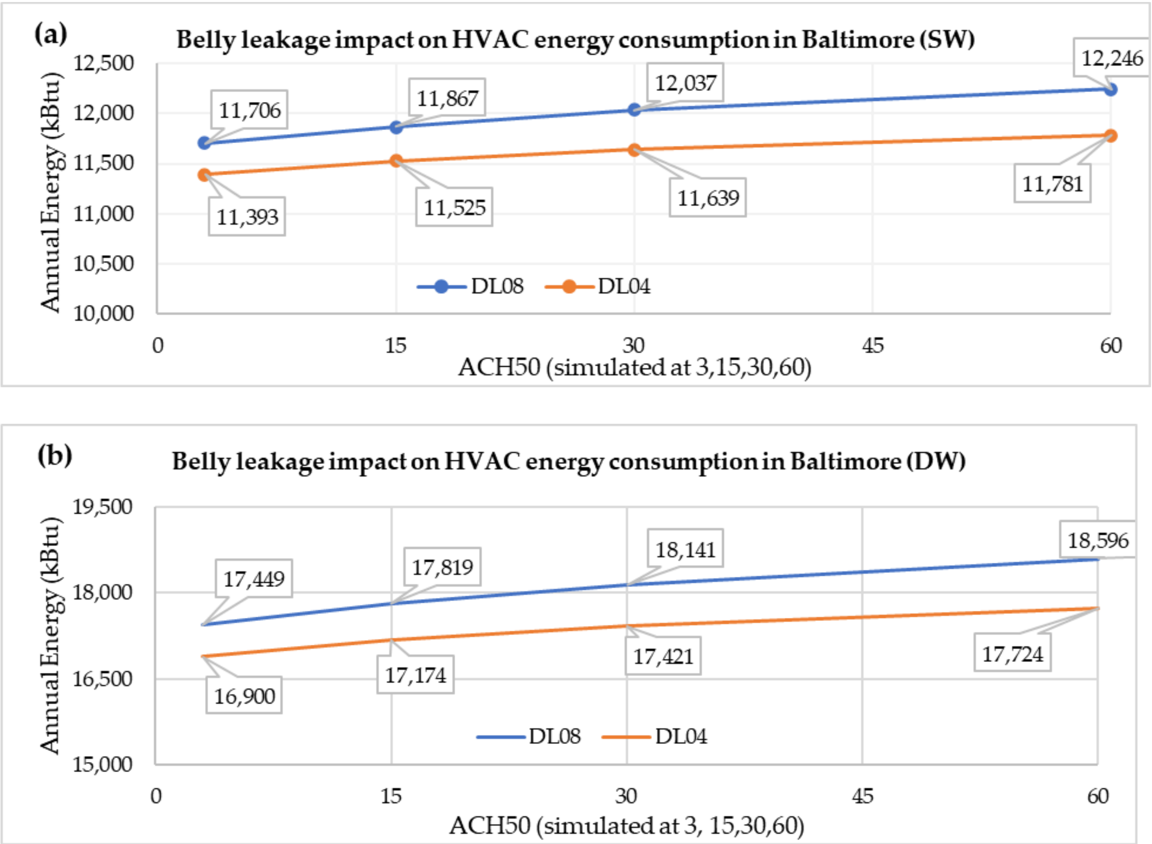
Figure 12. Impact of tightening belly on annual energy use in single-wide homes. Note: The legend 'Abs' in the right figure denotes 'Absolute'



Additional modeling was performed to show the impact of belly leakage of 30 and 60 ACH50 as may be the case with higher levels of damage to the belly barrier. The Baltimore climate was chosen to show one example of the impact of unrepaired damage that may occur during transport and/or setup in a mixed-climate location with a fair amount of heating and cooling. Figure 13 shows annual energy use in kBtus for single wide (SW) and double-wide (DW) homes in Baltimore at two levels of duct leakage with belly leakage rates of 3, 15, 30 and 60 ACH50. Results show a nearly linear relationship between annual energy use and simulated belly leakage with energy savings of 6.2% when tightening from ACH50 of 60 to 3 in double-wides and 4.4% for the same comparison in single wides.

Converting belly ACH50 leakage rates to effective leakage area (ELA) provides a physical reference of estimated opening sizes at each leakage rate where ELA represents the sum of all holes in the belly. For example, cumulative breaches in a double-wide belly would amount to 2.5, 12.5, 25 and 50 square inches at ACH50s of 3, 15, 30 and 60 respectively. Equivalent opening areas for a single wide belly at the same ACH50s would be 1.5, 7.4, 14.7 and 29 square inches respectively.

Figure 13. Impact of increased belly leakage on (a) single wide and (b) double-wide energy use in the Baltimore climate.



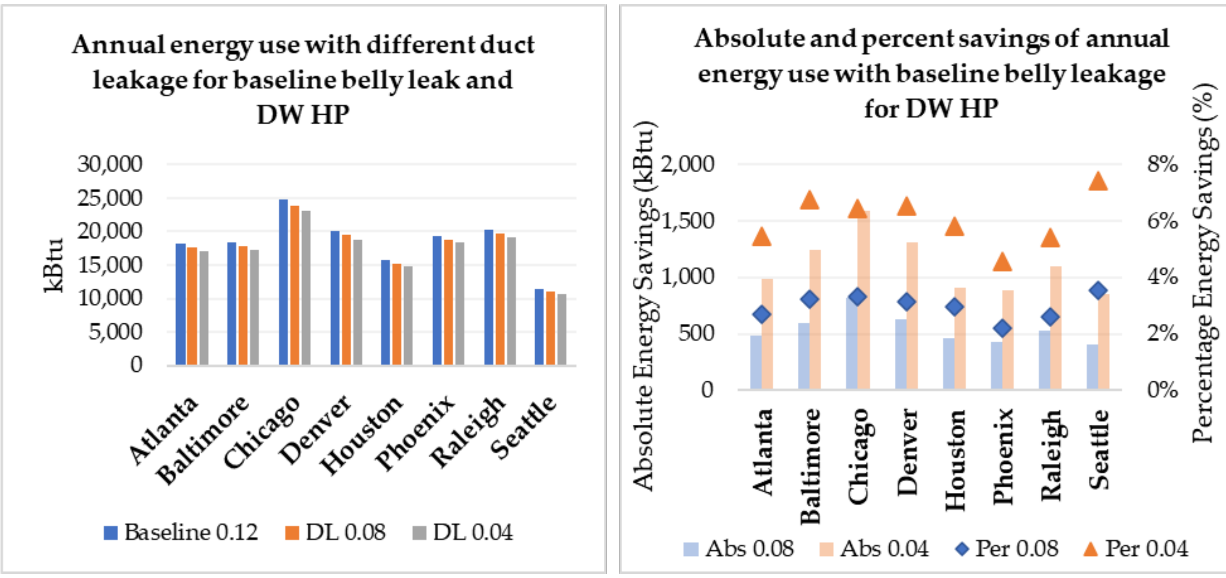
Duct Leakage and Combined Duct and Belly Leakage Impacts

The previous section evaluates the impact of belly leakage on annual HVAC system energy use in both single and double-wide homes at 8 sites. The preliminary conclusion is that belly leakage has little impact on HVAC energy use. This section examines the impact of duct leakage on annual energy use with 2 different levels of belly leakage. The baseline duct leakage is 0.12 cfm25/ft2, while the other duct leakage cases are 0.08 and 0.04 cfm25/ft2, respectively. As shown in the background section where duct testing is prevalent, the 0.04 value is regulary achieved whereas some individual homes and those in places where duct testing is not prevalent may exceed the 0.08 level; however, most will fall at or below 0.08 cfm25/ft2. For reference, the duct testing requirement for ZERH manufactured homes calls for 0.04 cfm25/ft2.

Figure 14 on the left presents annual HVAC system energy use with different levels of duct leakages in 8 locations for a double-wide home using a single-speed HP system at the baseline belly leakage. The annual energy use varies with location from the lowest of 11,000 kBtu in Seattle to the highest of 24,000 kBtu in Chicago.

Figure 14 on the right shows the absolute and percentage savings in annual energy use by comparing the baseline duct leakage in 8 locations at the baseline belly leakage. The columns represent absolute savings at two different duct leakage levels, while the markers represent percentage savings at the same two duct leakage levels. Based on the observation of HVAC system energy consumption, the annual energy consumption at different duct leakage levels appears proportional to the duct leakage levels.

Figure 14. Impact of duct leakage for belly ducts at 0.12, 0.08 and 0.04 cfm25/ft^2 leakage for double-wide homes. Homes are for cases where belly is baseline leakage of 15 ACH50. Note: The legend 'Abs' and 'Per' in the right figure denotes 'Absolute' and 'Percentage', respectively.

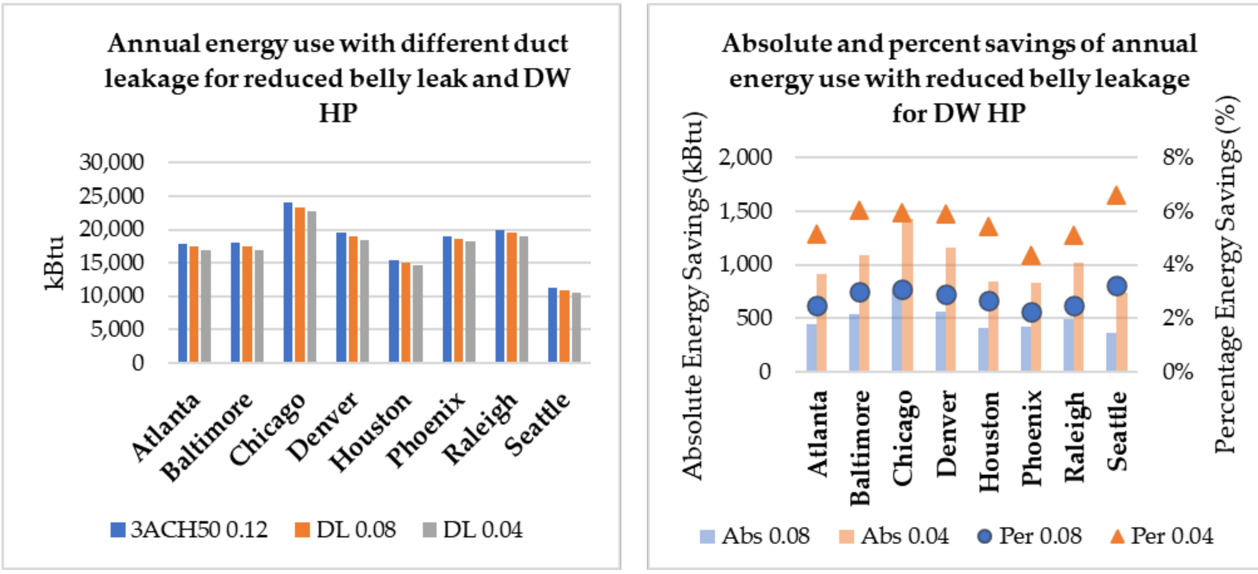


The average percentage of annual energy reduction across all locations is 3.0% with 0.08 duct leakage and 6.0% with 0.04 duct leakage, respectively.

Figure 15 on the left shows the annual HVAC system energy use at different levels of duct leakage in 8 locations for a double-wide home using a single-speed HP system at the reduced belly leakage. Annual energy use varies by location from a low of 11,000 kBtu in Seattle to a high of 24,000 kBtu in Chicago.

Figure 15 on the right shows the absolute and percentage savings in annual energy use by comparing the baseline duct leakage in 8 locations to models run with reduced belly leakage (3 ACH50 vs. 15 ACH50). The columns represent absolute savings at two different duct leakage levels, while the markers represent percentage savings at the same duct leakage levels. Based on the earlier observation of HVAC system energy consumption, the annual energy use at different duct leakage levels appears proportional to the duct leakage levels. The average percentage annual energy reduction across all locations is 2.8% at 0.08 duct leakage and 5.6% at 0.04 duct leakage.

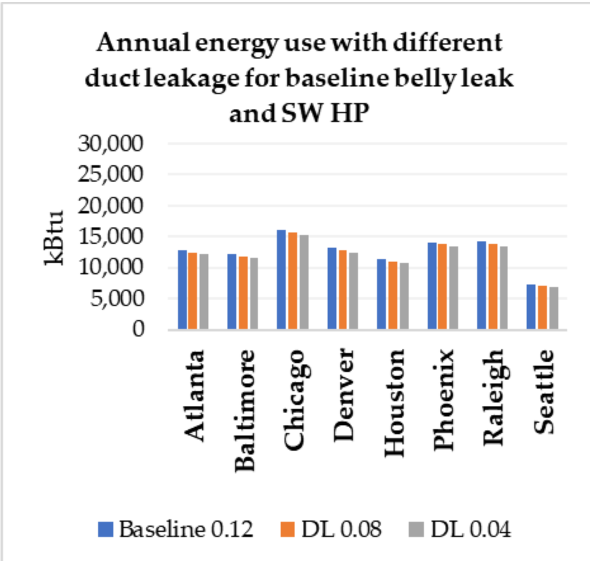
Figure 15. Impact of duct leakage for double-wide homes with heat pump at 0.12, 0.08 and 0.04 cfm25/ft^2 leakage. Homes are for cases where belly is modeled as “tight” with 3 ACH50. Note: The legend ‘Abs’ and ‘Per’ in the right figure denotes ‘Absolute’ and ‘Percentage’, respectively.



Single-wide home annual HVAC system energy use is shown in Figure 16. On the left is the annual HVAC system energy use at different levels of duct leakage in 8 locations for a single-wide home using a single-speed HP system at the base leakage level. Annual energy use varies by location from a low of 7,000 kBtu in Seattle to a high of 16,000 kBtu in Chicago.

Figure 16 on the right shows the absolute and percentage savings in annual energy use by comparing the baseline duct leakage in 8 locations at the baseline belly leakage. The other conditions are the same as in the figure above. The columns represent absolute savings at two different duct leakage levels, while the markers represent percentage savings at the same duct leakage levels. Based on observation, the annual energy use at different duct leakage levels appears proportional to the duct leakage levels. The average percentage annual energy reduction across all locations is 2.7% at 0.08 duct leakage and 5.3% at 0.04 duct leakage.

Figure 16. Impact of duct leakage for single-wide homes with heat pump at 0.12, 0.08 and 0.04 cfm25/ft^2 leakage. Homes are for cases where belly is baseline leakage of 15 ACH50. Note: The legend ‘Abs’ and ‘Per’ in the right figure denotes ‘Absolute’ and ‘Percentage’, respectively.



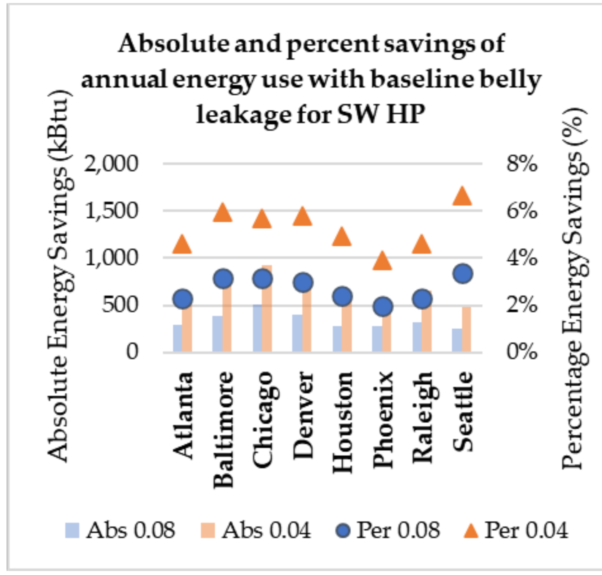
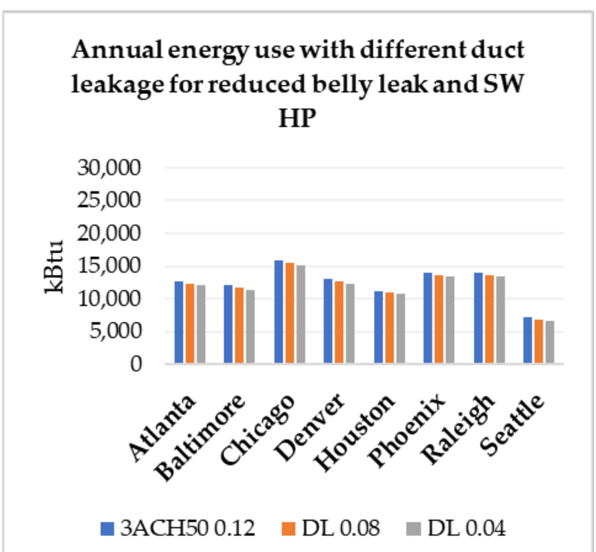


Figure 17 shows the annual HVAC system energy use modeled at different levels of duct leakage in 8 locations for a single-wide home using a single-speed HP system at the reduced belly leakage. Annual energy use varies by location from a low of 7,000 kBtu in Seattle to a high of 16,000 kBtu in Chicago.

Figure 17. Impact of duct leakage when belly is tight (3 ACH50) for single-wide homes with a heat pump at 0.12, 0.08 and 0.04 cfm25/ft^2 leakage. Note: The legend ‘Abs’ and ‘Per’ in the right figure denotes ‘Absolute’ and ‘Percentage’, respectively.



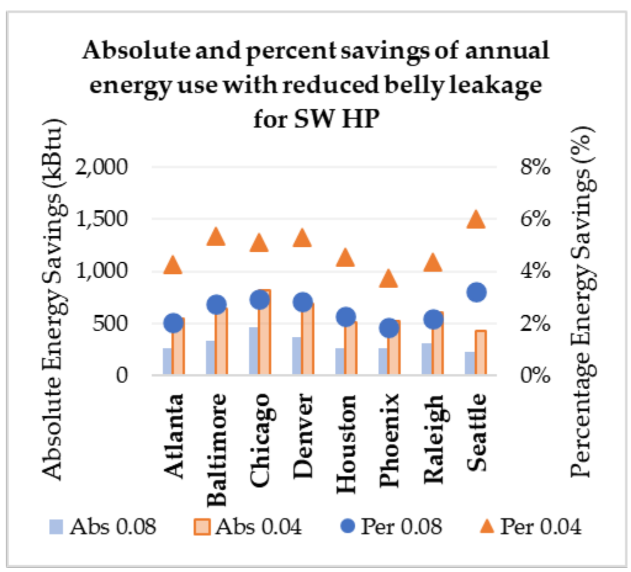


Figure 17 on the right shows the absolute and percentage savings in annual energy use by comparing the baseline duct leakage in 8 locations to the reduced belly leakage. The other conditions are the same as in the figure above. The columns represent absolute savings at two different duct leakage levels, while the markers represent percentage savings at the same duct leakage levels. Based on observation of 3 points regression, the annual energy use at different duct leakage levels appears proportional to the duct leakage levels.

The average percentage annual energy reduction across all locations is 2.5% at 0.08 duct leakage and 4.8% at 0.04 duct leakage. Based on above description, the duct leakage impact on annual energy consumption is bigger than this modeled belly leakage impact; however, if the real world starting leakage is greater, as modeled in Baltimore (see section above), then the belly tightening is more comparable with duct leakage.

ENERGY SAVINGS FOR VARIABLE-SPEED HP VS. SINGLE-SPEED HP

This section provides comparison of annual energy use between single-speed HPs and variable-speed heat pumps in all 8 locations with standard belly leakage. Figure 18 on the left presents annual HVAC system energy use with different heat pump types in 8 locations for a double-wide home at the standard belly leakage. The annual energy use varies with location from the lowest of 11,000 kBtu in Seattle to the highest of 27,000 kBtu in Chicago.

Figure 18. Energy use and savings of variable-speed vs. single-speed heat pumps for double-wide baseline homes. Note: The legend ‘Abs’ and ‘Per’ in the right figure denotes ‘Absolute’ and ‘Percentage’, respectively.

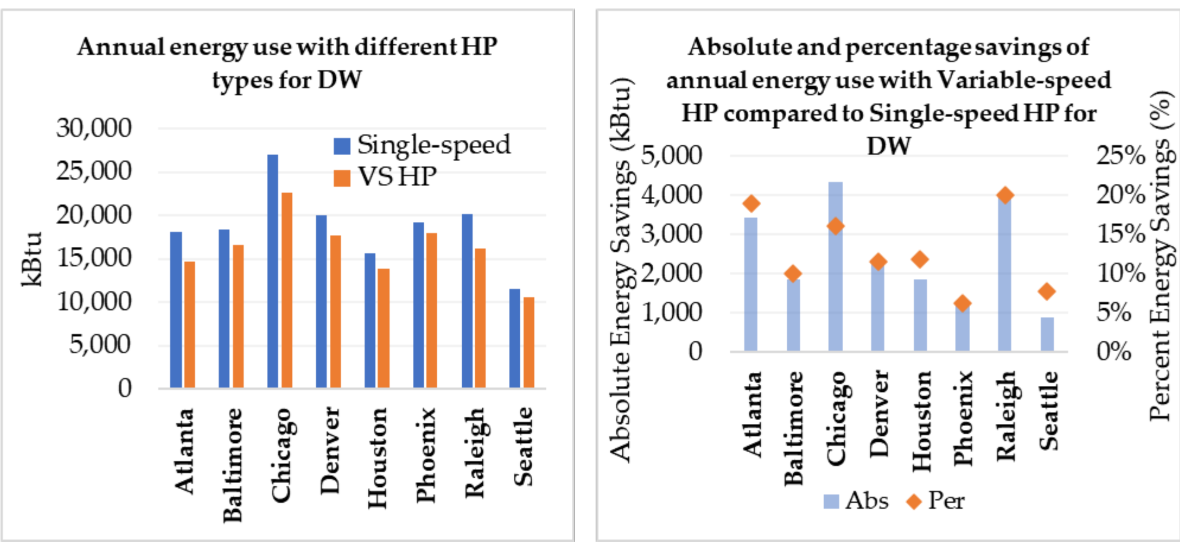


Figure 18 on the right presents absolute and percentage savings of double-wide annual energy use by comparing single-speed HPs with variable-speed heat pumps in 8 locations at the standard belly leakage with baseline envelope. The columns represent absolute savings, while the markers represent percentage savings. The annual energy use absolute differences vary from the lowest of 900 kBtu in Seattle to the highest of 4,350 kBtu in Chicago. The percentage savings of annual energy use vary from the lowest of 6.3% in Phoenix to the highest of 20.0% in Raleigh. The average percentage saving of annual energy use across all locations is 12.8%.

Figure 19 on the left shows the annual HVAC system energy use with different heat pump types in 8 locations for a single-wide house at the standard belly leakage. Annual energy use varies by location from a low of 7,200 kBtu in Seattle to a high of 16,000 kBtu in Chicago.

Figure 19. Energy use and savings of variable-speed heat pumps relative to single-speed heat pumps for baseline single-wide units. Note: The legend 'Abs' and 'Per' in the right figure denotes 'Absolute' and 'Percentage', respectively.

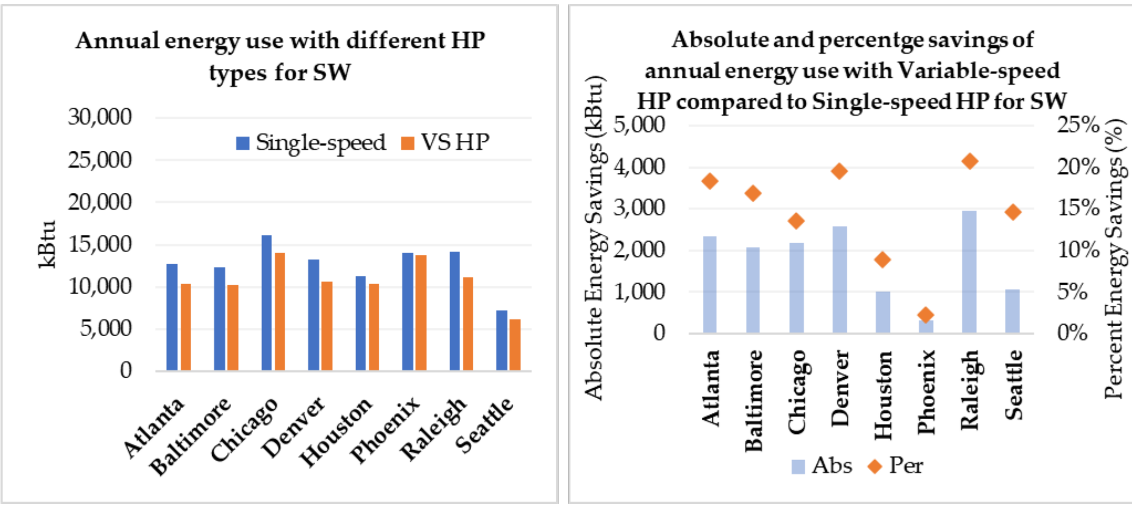


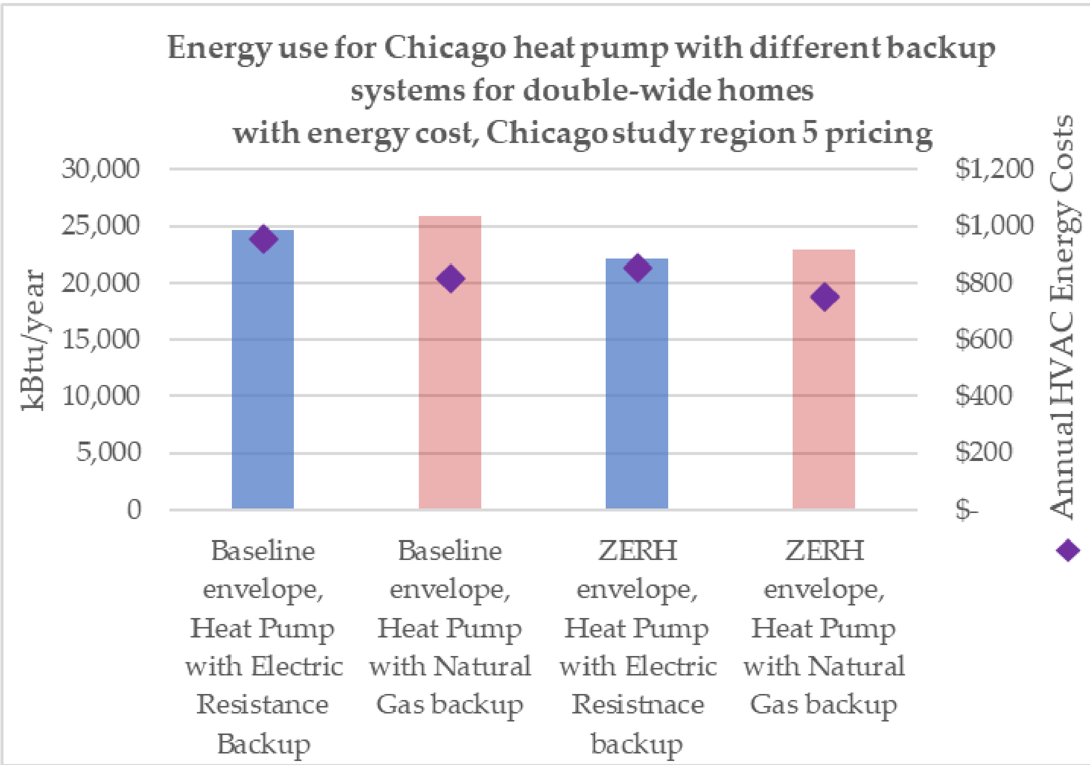
Figure 19 on the right shows the absolute and percentage savings of annual energy use by comparing single-speed HPs with variable-speed heat pumps in 8 locations at the standard belly leakage. The other conditions are the same as the figure above. The columns represent absolute savings, while the markers represent percentage savings. The absolute differences in annual energy use vary from a low of 322 kBtu in Phoenix to a high of 2,938 kBtu in Raleigh. The percentage savings in annual energy use range from a low of 2.3% in Phoenix to a high of 20.8% in Raleigh. The average percent savings of annual energy use is 14.4%.

The energy savings with variable-speed heat pumps are primarily due to system performance with higher cooling EER and heating COP especially when operating at lower speeds. Compared to double-wide homes, single-wide homes have smaller building loads and a slightly higher ratio of system capacity to load. Since systems in single-wide homes operate more often at lower speed compared to double-wide homes, greater energy savings are expected. This phenomenon is reflected in the savings results shown in Figures 18 and 19.

ENERGY COMPARISON OF NATURAL GAS BACKUP VERSUS ELECTRIC RESISTANCE FOR HEAT PUMPS.

As described earlier, for Chicago we ran both electric resistance and natural gas as backup for heat pumps. Figure 20 shows the difference in site energy use for two cases. Since the electric coil has a site-energy effective COP of 1 and the backup gas has an AFUE of 0.8, total site energy use is slightly (4.5% for baseline envelope; 3.5% for the ZERH envelope) lower for electric resistance backup compared to using a natural-gas furnace for backup. However, because natural gas is less expensive per delivered Btu, the natural gas backup results in lower HVAC operating costs.[8]

Figure 20. Annual energy use for Chicago double-wide home with heat pump and natural gas and electric resistance backup heating.



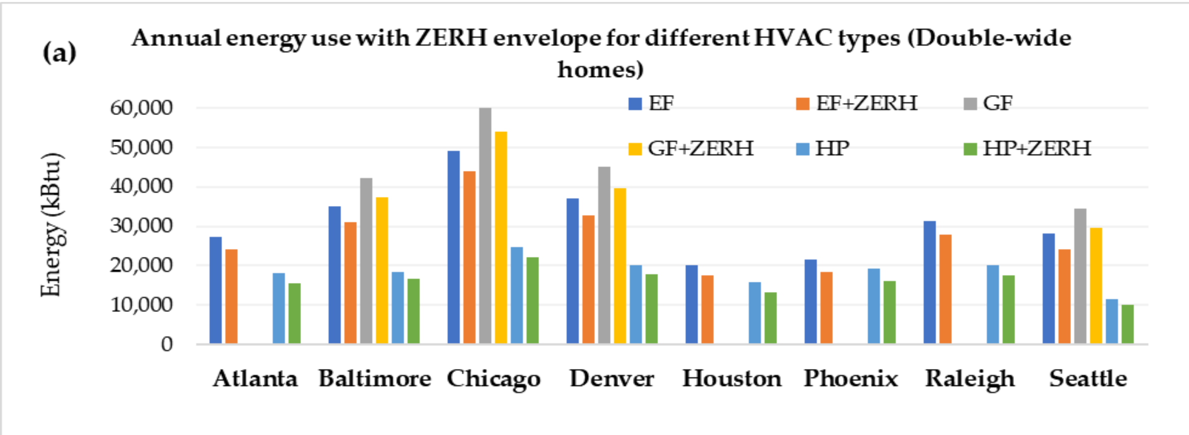
ENERGY SAVING FOR ENVELOPE IMPROVEMENT

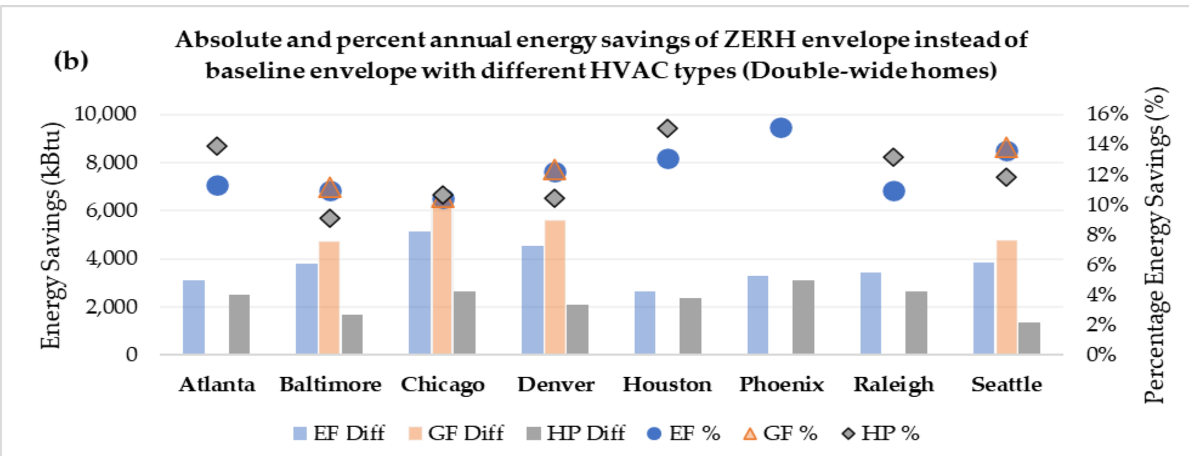
One of the important enhancements to the present study is the inclusion of the envelope specification required by the Zero Energy Ready Home standards. Figure 21 shows modeled annual HVAC energy for each location for three HVAC system types for the baseline and ZERH envelope specifications for a double-wide home and Figure 22 shows the same analysis for a typical single-wide home.[9]

[8] Regional utility pricing is explained in more detail in the cost-effectiveness section of the report.

[9] These results are based on modeled standard belly leakage levels.

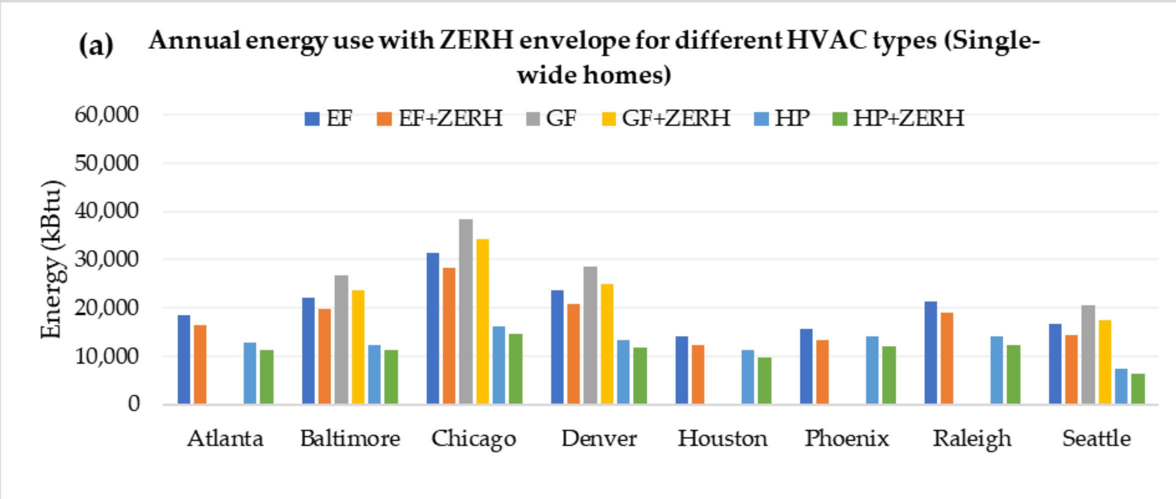
Figure 21. (a) Modeled annual energy use of a double-wide home for baseline and ZERH envelope specifications, by location and HVAC system type. (b) Absolute and Percent annual energy savings of ZERH envelope instead of baseline envelope with different HVAC types. Note: Heat pumps in this graph were modeled with electric resistance backup heat.

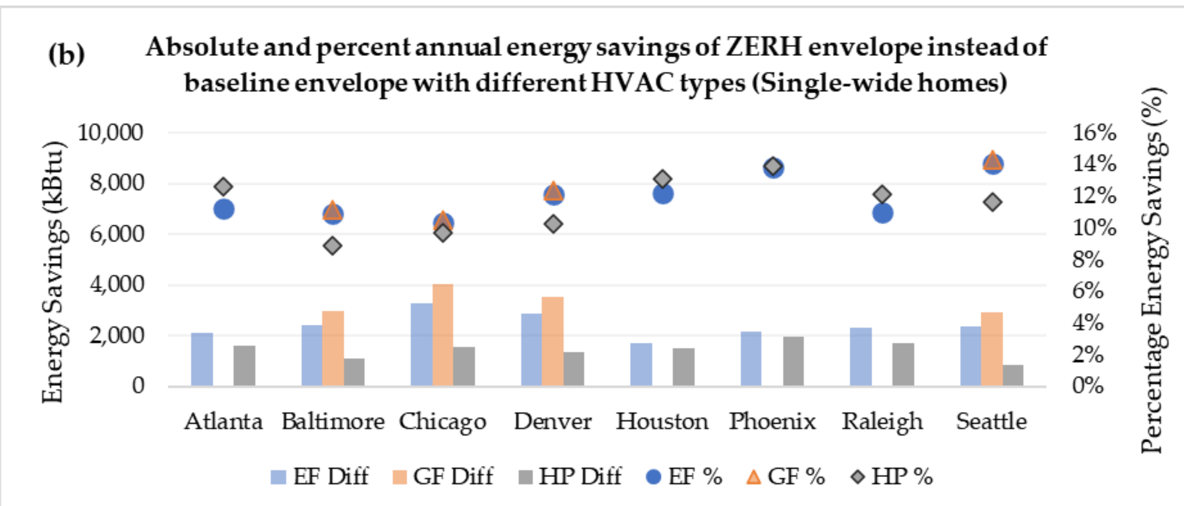




The modeling suggests ZERH envelope savings in the range of about 9 to 16 percent for double-wide homes and 9 to 14 percent for single-wide homes, depending on location and HVAC system type.

Figure 22. (a) Modeled annual energy use and savings from Zero Energy Ready Home envelope specifications for 3 different heating systems in single-wide homes. (b) Absolute and Percent annual energy savings of ZERH envelope instead of baseline envelope with different HVAC types in single-wide homes





As one might expect, the percentage savings of annual HVAC system energy use are consistent for both house types: single wide and double-wide and for the different heating types. Comparatively, the envelope improvements can provide much higher annual energy savings compared to duct leakage because duct energy losses from both conduction and leakage occur in the belly space except for crossover connections.

PEAK ENERGY SAVINGS

One of the outputs of the simulation was the peak hour energy use for the year. For the baseline electric homes this occurred on a winter morning for the TMY data run in all climates. Reducing peak electric use has value as it can reduce times of expensive (and often emissions-intensive) electric generation. The value is described under cost effectiveness. Figure 23 (a) shows the peak energy use for the modeled double-wide unit and Figure 23 (a) is the savings in peak energy use from the improved envelope for each of the HVAC system types. Figure 24 (a) and (b) shows equivalent information for the modeled single-wide unit.

Figure 23. (a) Peak hour HVAC energy use and (b) related peak energy savings for double-wide homes with different HVAC and envelope.

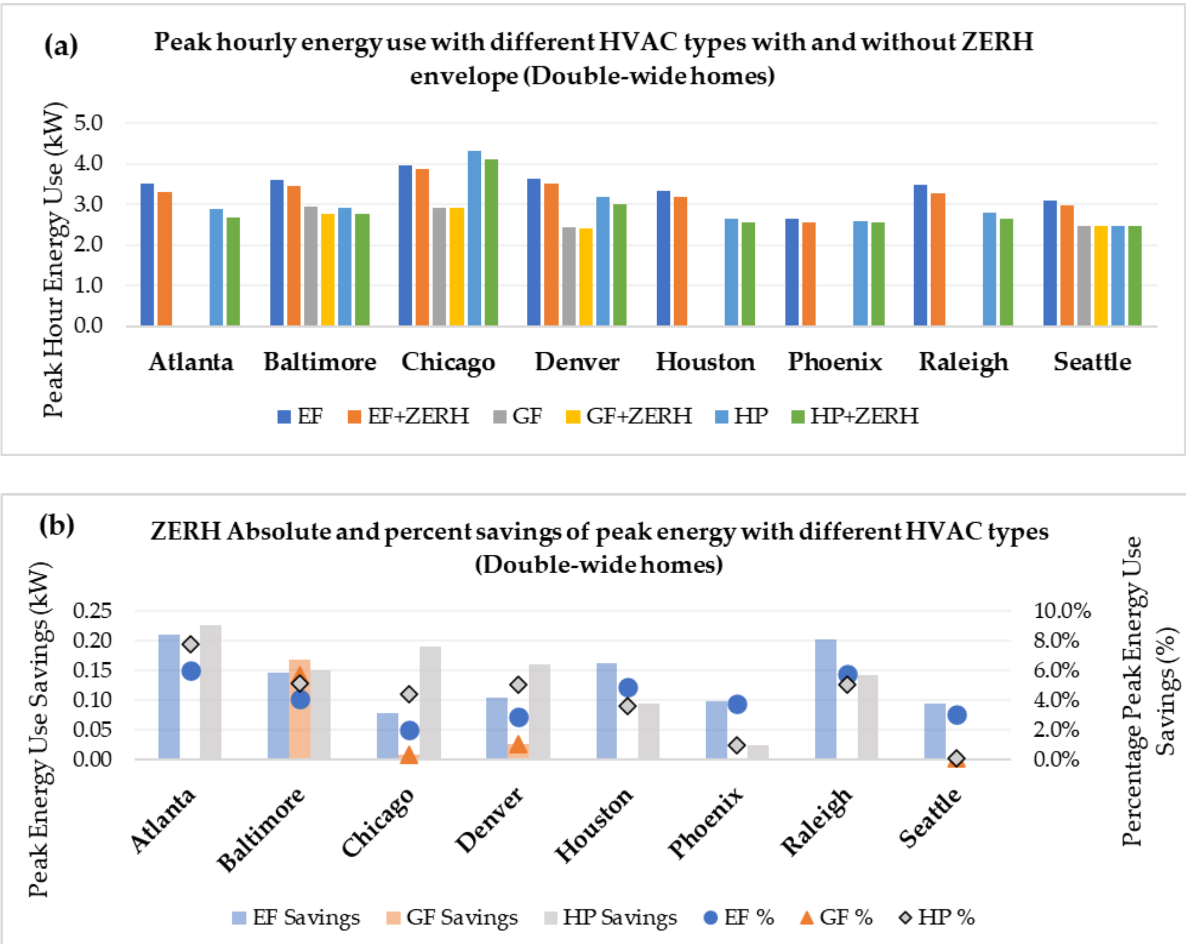
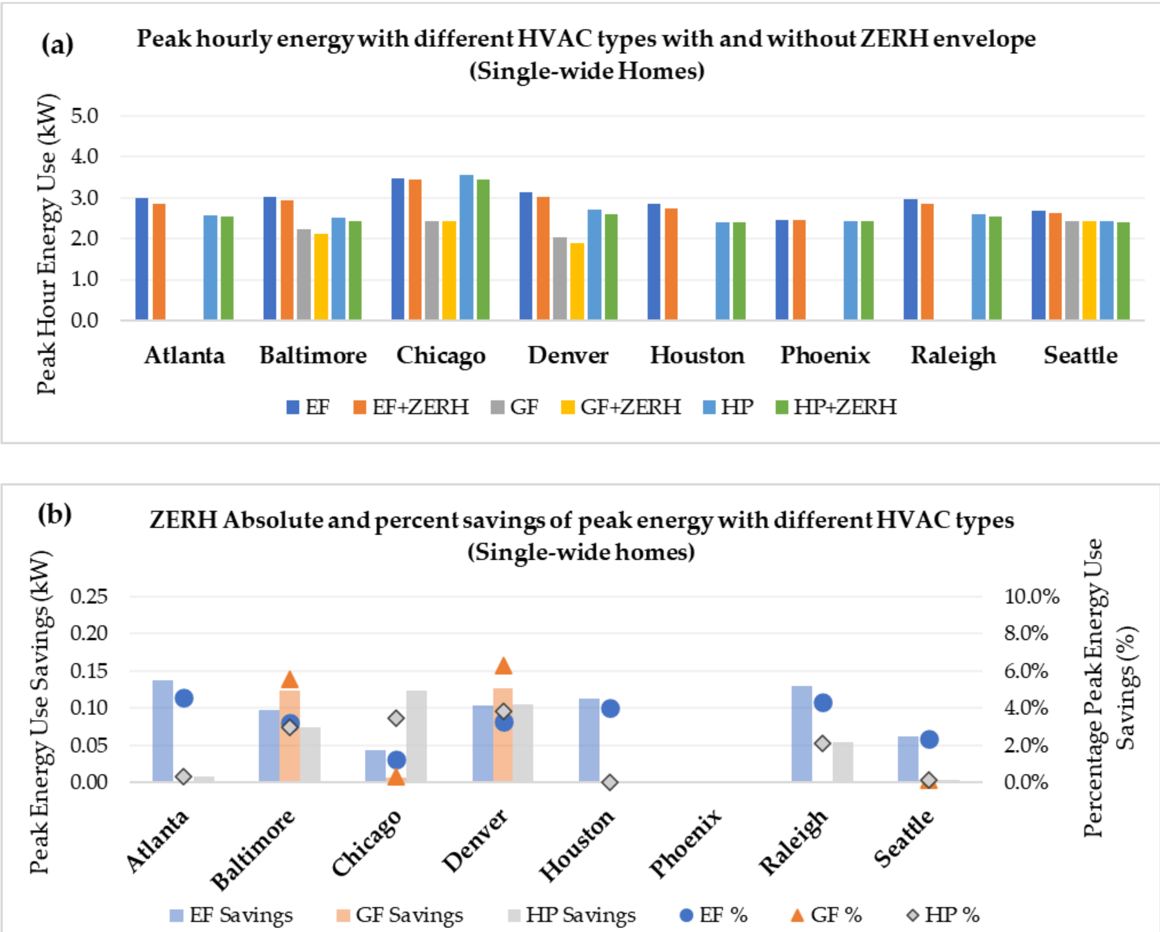


Figure 24. (a) Peak hour energy use and (b) peak energy savings for single-wide homes with different HVAC and envelope.



CO_2e EMISSION WITH DIFFERENT HVAC TYPES AND ENVELOPES

Additional post-processing was performed to calculate CO_2e emissions from annual HVAC system energy use with different HVAC system types and different envelope specifications. CO_2e is a value that equates the detriment of greenhosue gases to CO_2 such that, for example, 1 ton of methane is equivalent to 28 tons of CO_2e whereas one ton of CO_2 is 1 ton of CO_2e.

There are three HVAC system types: Electric furnace + AC, Gas furnace + AC, and Heat pumps. There are 2 different envelope specifications: baseline and zero energy ready home (ZERH).

CO_2e emission calculation procedure

1. Obtain hourly emission rates from electricity consumption (kg CO_2e per MWh at the point of end use) based on location, where the electric grid emissions are based on the zip code of the city modeled. These rates are computed consistent with RESNET methodology. The RESNET methodology uses forecasted regional electric grid

emissions averaged from 2025 to 2050. Fossil fuel emissions are based on household combustion fuels. RESNET uses the combined pre-combustion plus combustion CO_2e emission rates from ASHRAE Standard 189.1, Appendix J for the 100-year GWP time horizon. More details are provided in Appendix A of this report.

2. Obtain hourly emission rates from electricity use.
3. Calculate hourly CO_2e emission rate from natural gas use based on national value.
4. Output hourly CO_2e emssion rates combining electric and gas emissions.
5. Sum hourly values for annual emissions.

Figure 25 (a) shows the annual CO_2e emissions with three HVAC system types and envelope specifications in 8 locations for a double-wide home with standard belly leakage.

Figure 25. (a) Annual CO_2e emissions and (b) percentage reduction with ZERH envelope and 3 HVAC systems for double-wide homes.

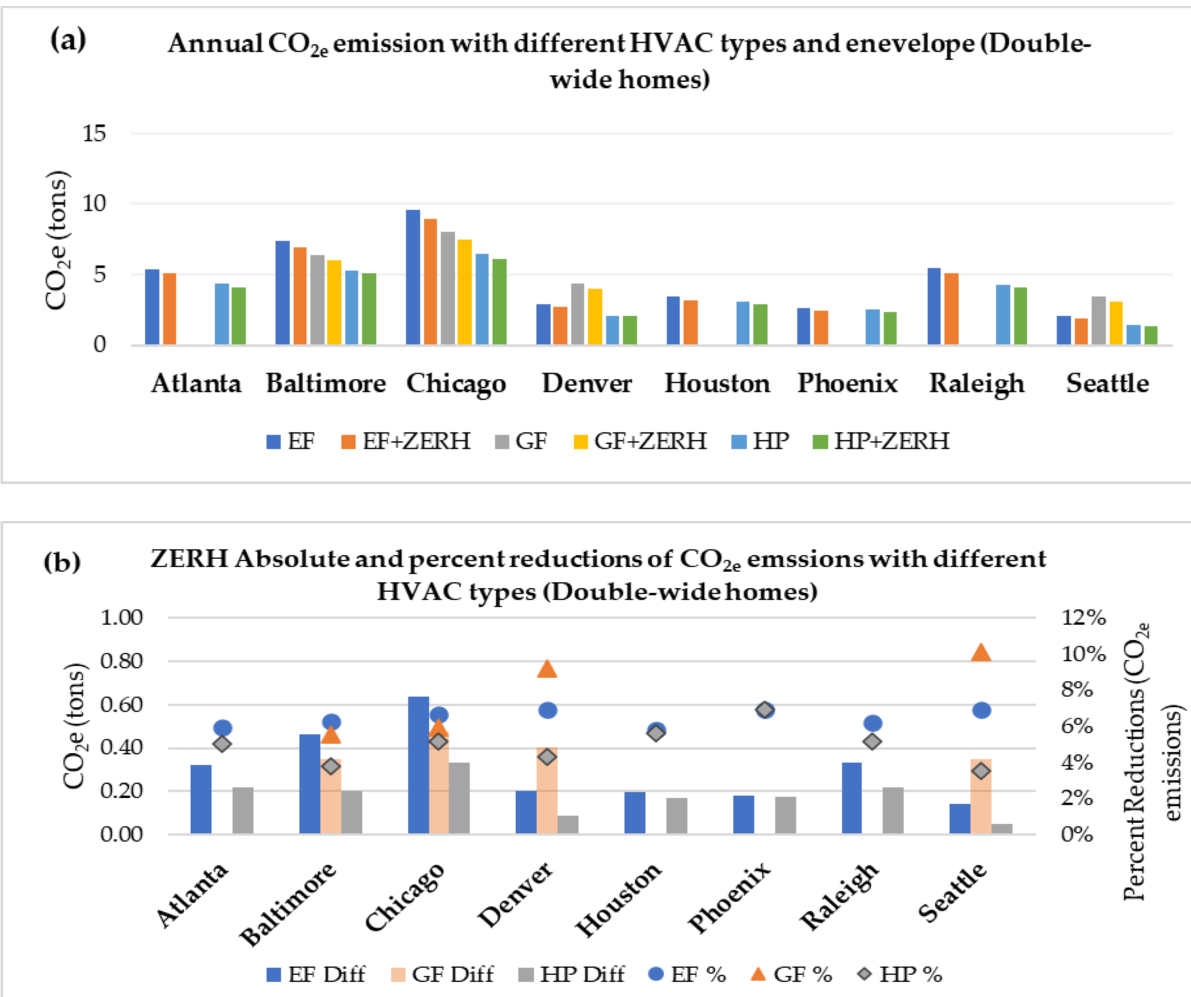
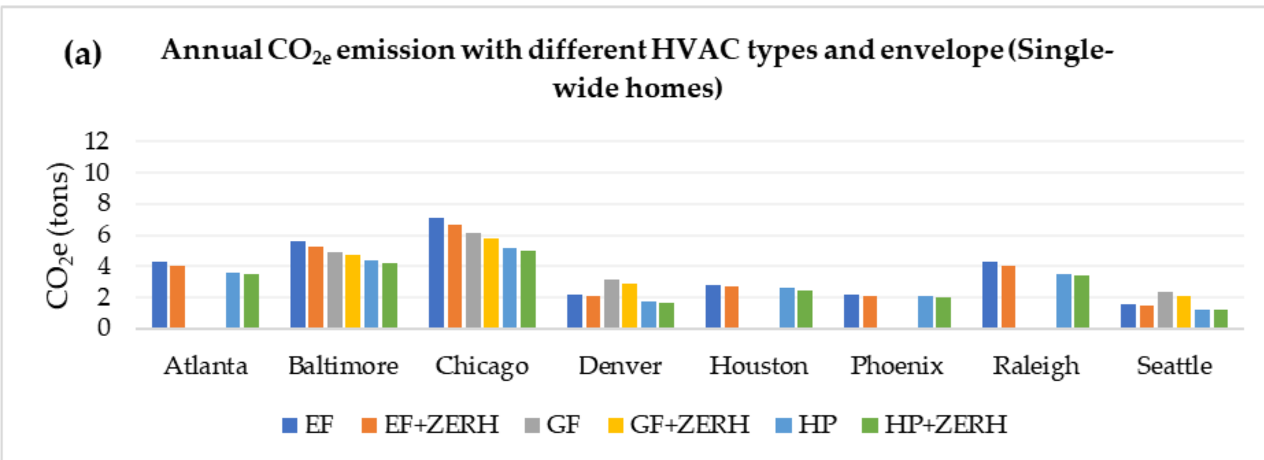
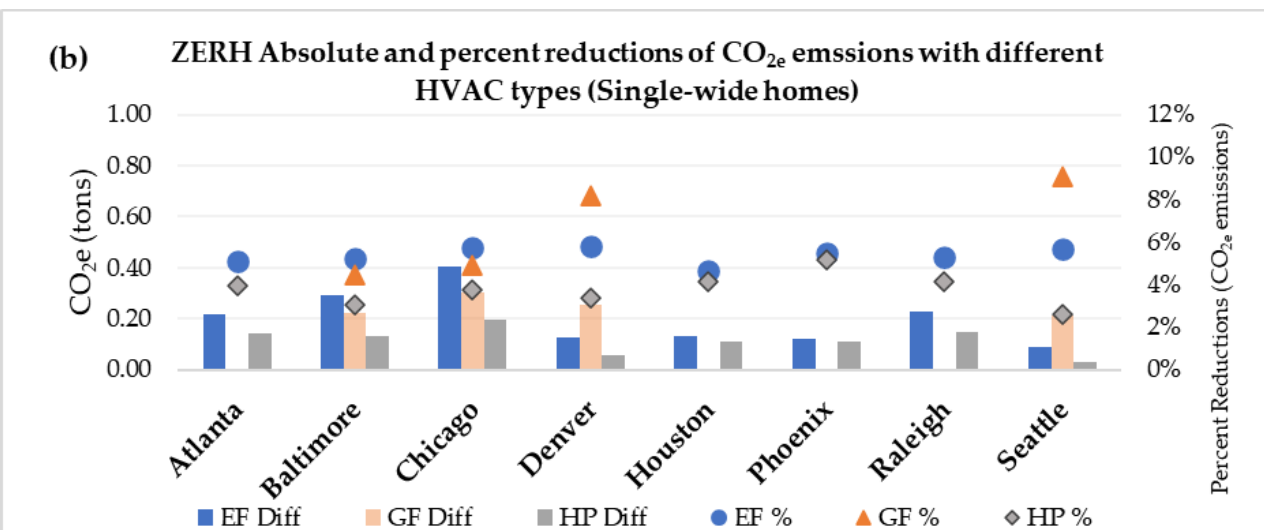


Figure 25 (b) shows the absolute and percentage differences of annual CO_2e emissions by comparing baseline envelope specifications with zero energy ready home (ZERH) envelope specifications in 8 locations at the standard belly leakage and three HVAC system types. By implementing the ZERH envelope, average annual $CO_{2}e$ emissions in eight locations are reduced by 6.5% for electric furnace + AC, 7.7% tons for gas furnace + AC, and 4.9% tons for heat pump, respectively.

Figure 26 (a) shows the annual $CO_{2}e$ emissions with three HVAC system types and envelope specifications in 8 locations for a single-wide home at standard belly leakage. Figure 26 (b) shows the absolute and percentage differences of annual $CO_{2}e$ emissions by comparing baseline envelope specifications with Zero Energy Ready Home (ZERH) envelope specifications in 8 locations at the standard belly leakage and three HVAC system types.

Figure 26. (a) Annual $CO_{2}e$ emissions and (b) $CO_{2}e$ emission percentage reductions with ZERH envelope and 3 HVAC systems for single-wide homes.





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 and configuration innovations. This section also rolls up results from the eight modeled locations into regional estimates of baseline energy costs, energy-cost savings for potential innovations and cost-effectiveness.

METHODS AND ASSUMPTIONS

Assessing the energy-cost savings and 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

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 27 shows the study regions, climate zones and modeling cities, and Table 7 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 Chicago 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. Thus additional modeling cities for this region were not pursued.

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 other weighting factors are our own estimates based on conversations with industry stakeholders. The prior modeling study (Pigg et al, 2021) provides a complete listing of the weighting factors used in the analysis.

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

Figure 27. Study regions, Building America climate zones, and selected energy-modeling locations used in the study. HUD thermals not shown, however zone 1 coincides with Region 1, HUD zone 2 with Regions 2 and 3 and HUD zone 3 with Regions 4, 5 and 6.

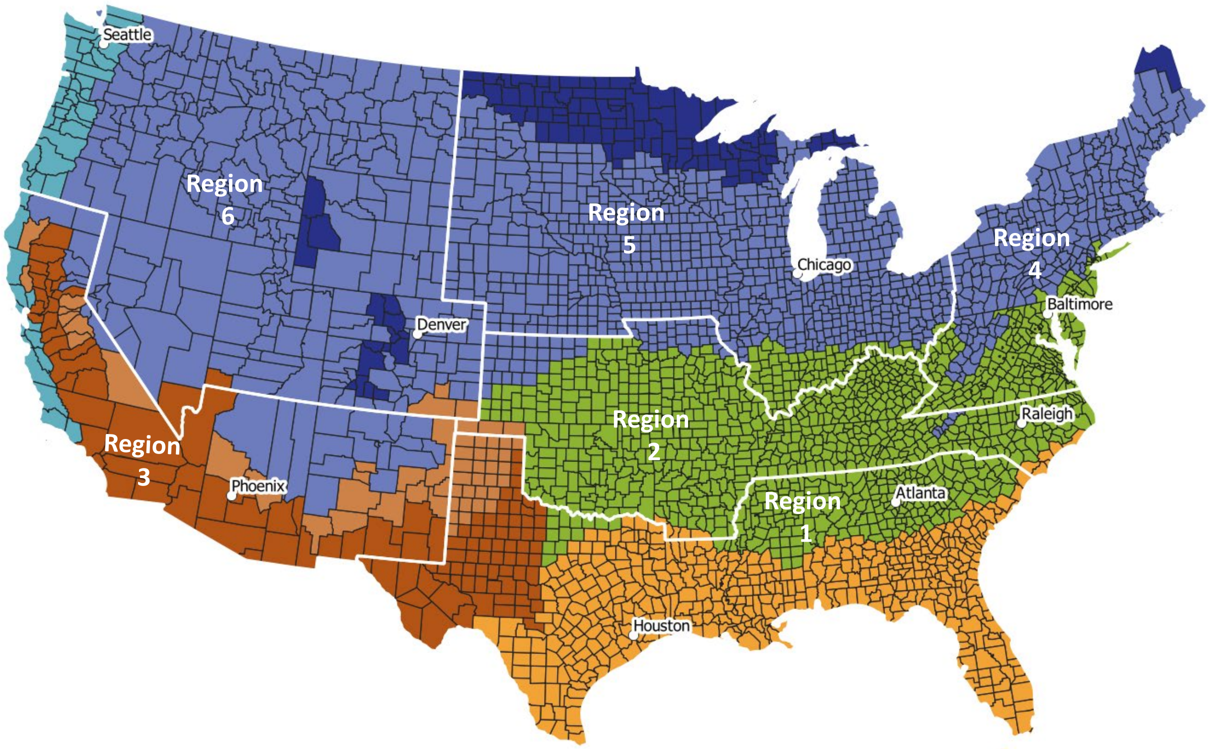


Table 7. Analysis weighting factors, by study region, HUD Thermal zone, Building America climate zone and home type.

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

Fuel-prices

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. The estimate of state-level fixed charges for electricity came from a public database[11] of electric utility rates, which we combined with EIA data on utility sales to estimate state-average fixed charges. For natural gas we used EIA data for heat content of natural gas consumed by state[12] and 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. The fixed charge for natural gas thus reported for each state averaged was 21 percent of the reported "all-in" cost per therm given by EIA. In recent years the fixed cost may have increased as some southern utilities charge more fixed cost to offset lower fuel charges and reduced demand due to more electrification. For example, Florida City Gas received approval of a rate structure that went in effect in June 2018 increasing its GS-100 (typical residential rate) from $9.50 per month to $15 per month. This monthly rate increased to $19 per month in May 2023. For the 2018 rate increase the distribution charge was reduced from $0.6578 per Therm to $0.41137 per Therm, whereas the rated increased from $0.40383 to $0.57421/Therm in the 2023 rate change.[13] On the counter side, using the per-therm cost may be generous to the gas economics as natural gas can be removed from homes all together if heating and water heating are done with electric heat pumps. At that point, the monthly fixed charge may be too steep for manufactured homeowners to keep for cooking, or potentially clothes drying. Switching to electric or propane at that point will make sense. Table 8 shows the regional fuel prices used in the analysis.

Table 8. Regional fuel prices.

Study region	Modeling City	Electricity		Natural Gas		Propane	Fuel Oil
		$/mo. (fixed)	¢/kWh	$/mo. (fixed)	¢/therm	$/gal.	$/gal.
1	Houston	$11.22	10.6	$12.28	97.3	$2.85	
	Atlanta	$13.13	11.2	$12.04	89.2	$2.59	
2	Raleigh	$12.84	9.9	$12.70	84.2	$2.35	
3	Phoenix	$14.67	15.3	$7.32	109.9	$1.94	
4	Baltimore	$8.68	12.0	$10.98	91.1	$2.84	$2.73

[11] https://openei.org/wiki/Utility_Rate_Database, Retrieved November 4, 2021
[12] https://www.eia.gov/dnav/ng/ng_cons_heat_a_EPG0_VGTH_btucf_a.htm
[13] Florida City Gas Notice to Customers, 2018 and 2023.

	Chicago	$11.97	11.4	$11.38	61.8	$1.95	
5	Baltimore	$11.14	14.9	$13.82	99.7	$2.73	
	Chicago	$9.59	13.2	$11.66	60.7	$1.88	
6	Denver	$12.70	9.6	$8.98	69.4	$1.96	
	Seattle	$10.95	9.5	$4.95	92.9	$1.94	

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 9). We escalated fuel prices using the latest supplement to NIST Handbook 135 (Lavappa and Kneifel 2021), using listed regional fuel-price indices that include an assumed 2 percent inflation. All results presented here are based on a 25-year lifetime.

Table 9. Life-cycle costing factors used in the current DOE rulemaking (DOE 2021) and adopted for this report.

Costing factor	Chattel loan	Real-estate mortgage	Cash purchase
Percent of home purchases	54.6%	15.4%	30.0%
Loan interest rate	9.0%	5.0%	
Down payment	20.0%	20.0%	
Loan fees	1.0%	1.0%	
Term (years)	15	30	
Discount rate	9.0%	5.0%	5.0%
Property-tax rate	0.9%		
Sales-tax rate	3.0%		

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. However, when tax credits and incentives are added in, they can shift the balance and make the innovation more attractive. For example a breakeven point of $2000 without any incentive indicates the consumer could spend any amount less that and come out ahead. If a tax credit or rebate of $1500 were applied, then that breakeven point would rise to $3500 and the customer could spend anything up to that amount and come out ahead.

Energy Cost Savings, Break-Even Incremental Costs, CO_2e Emissions and Peak Demand Evaluation

A series of comparisons are presented in the following tables and graphs to highlight differences in energy cost, break-even incremental costs, and CO_2e emissions. The four summary tables in this section provide the results of several pairs of simulation scenarios, summarizing annual heating and cooling energy costs (Table 11), break even incremental cost for heating and cooling (Table 12), CO_2e emissions (Table 13), and peak demand (Table 14). Results are broken down by study region and home type. Samples of these results have been plotted herein.

The simulated energy use results have been applied to regional fuel prices listed in Table 8 and the blended financing presented in Table 9 to estimate energy costs and incremental break even costs between scenarios. The break-even costs have been divided by a per dollar present value of $1.12.

Ten upgrade scenarios were considered (Table 10) which describes each pair of configurations being compared, with results shown in Table 11.

Table 10. Simulation scenario comparison pairs.

Scenario	Baseline system	Efficient system
1	Standard home envelope with a single-speed HP	Zero energy ready home (ZERH) with a single-speed HP
2	Standard home envelope with a variable-speed heat pump heating and cooling system (VSHP)	ZERH with a VSHP
3	Standard home envelope with an electric furnace (EF)	Standard home envelope with a single-speed HP
4	Standard home envelope with a single-speed HP	Standard home envelope with a VSHP
5	ZERH with a single-speed HP	ZERH with a single-speed HP and a tight belly
6	ZERH with a VSHP	ZERH with VSHP and a tight belly
7	ZERH with a single-speed HP and leaky ducts	ZERH with a single-speed HP and tight ducts
8	ZERH with a VSHP and leaky ducts	ZERH with a VSHP and tight ducts
9	ZERH with a single-speed HP and leaky ducts	ZERH with a single-speed HP, tight ducts, and tight belly
10	ZERH with a VSHP and leaky ducts	ZERH with a VSHP, tight ducts, and tight belly

As displayed in Table 11, the annual heating and cooling cost savings associated with the higher efficiency option are most pronounced when upgrading from the conventional house with an electric furnace to the same envelope with a single-speed HP. The annual savings are highest in study regions 4 ($536 for single-wide, $879 for double-wide) and 5 ($556 for single-wide, and $908 for double-wide), though homes with electric furnaces are estimated to constitute only about a quarter of shipments to these regions. (Later we look at the economics of heat pump upgrades for homes that would otherwise be heated with natural gas.) Other sizable energy cost savings are observed with a ZERH with a HP heating and cooling system over a conventional envelope with a HP and with a conventional envelope with a VSHP over same building with a single-speed HP.

Table 11. Annual heating and cooling energy cost savings for baseline versus efficiency options by study region and home type.

Annual Heating and Cooling Energy Cost Savings												
Scenario			1	2	3	4	5	6	7	8	9	10
	Baseline:		HP	VSHP	EF	HP	ZERH w HP	ZERH w VSHP	ZERH w HP, Leaky duct	ZERH w VSHP, Leaky duct	ZERH w HP, Leaky duct	ZERH w VSHP, Leaky duct
	Efficiency:		ZERH w HP	ZERH w VSHP	HP	VSHP	ZERH w HP, Tight belly	ZERH w VSHP, Tight belly	ZERH w HP, Tight duct	ZERH w VSHP, Tight duct	ZERH w HP, Tight duct, Tight belly	ZERH w VSHP, Tight duct, Tight belly
Single-Wide	Study Region	1	$48	$48	$112	$42	$3	$3	$9	$8	$10	$9
		2	$50	$41	$206	$85	$5	$2	$8	$7	$12	$9
		3	$88	$104	$68	$14	$6	$6	$12	$14	$16	$18
		4	$56	$36	$536	$86	$10	$6	$15	$12	$21	$16
		5	$57	$35	$556	$83	$10	$6	$14	$11	$21	$15
		6	$35	$25	$287	$65	$6	$3	$9	$6	$12	$9
Double-Wide	Study Region	1	$76	$75	$180	$72	$6	$5	$14	$12	$18	$16
		2	$77	$65	$322	$117	$9	$5	$15	$12	$21	$16
		3	$140	$166	$107	$54	$11	$11	$20	$21	$27	$28
		4	$93	$66	$879	$80	$21	$13	$32	$24	$46	$34
		5	$97	$67	$908	$78	$21	$13	$27	$24	$42	$34
		6	$50	$42	$472	$48	$11	$7	$15	$13	$22	$18

Visual comparisons of the estimated heating and cooling energy costs for the baseline envelope with an electric furnace, a heat pump, a variable-speed heat pump, and natural gas and propane furnaces (where gas equipment has been simulated) are compared in Figure 28 (for single-wide) and Figure 29 (for double-wide). The variation in space heating and cooling costs between single- and double-wide homes appears to follow a similar trend, with the observed variation being relative to the size of the home. The upgrade from electric furnace to HP is notably more pronounced in the colder climates. With natural gas prices currently relatively low, the cost for gas furnace configuration edges out a variable-speed heat pump in northern climates.

Figure 28. Estimated annual heating and cooling costs for baseline envelope with selected HVAC types, by study region, for single-wide homes.

• EF - Electric Furnace
• HP - Heat Pump
• VSHP - Variable Speed Heat Pump
• NG - Natural Gas Furnace
• Propane - Propane Furnace

Figure 29. Estimated annual heating and cooling costs for baseline envelope with selected HVAC types, by study region, for double-wide homes.

- EF - Electric Furnace
- HP - Heat Pump
- VSHP - Variable Speed Heat Pump
- NG - Natural Gas Furnace
- Propane - Propane Furnace

We also compared the heating and cooling energy costs for simulations involving a combination of HVAC system, duct and envelope upgrades:

- Home with baseline envelope with electric furnace
- Home with baseline envelope with a single-speed HP
- Zero energy ready home with a single-speed HP
- Zero energy ready home with a single-speed HP, tight belly, and tight ducts
- Zero energy ready home with variable-speed heat pump, tight belly, and tight ducts

The results depicted in Figure 30 shows the regionally weighted average energy costs for each of the above-mentioned simulation scenarios, for single-wide homes. Figure 31 provides the same for double-wide homes. These figures illustrate that transitioning from an electric furnace to a heat pump results in significant reductions in energy costs. While it's true that moving beyond a heat pump also reveals apparent energy savings, these savings come with the costs associated with implementing the respective energy-efficient measures.

Figure 30. Weighted regional average heating and cooling costs of baseline envelope with various systems, for single-wide homes.

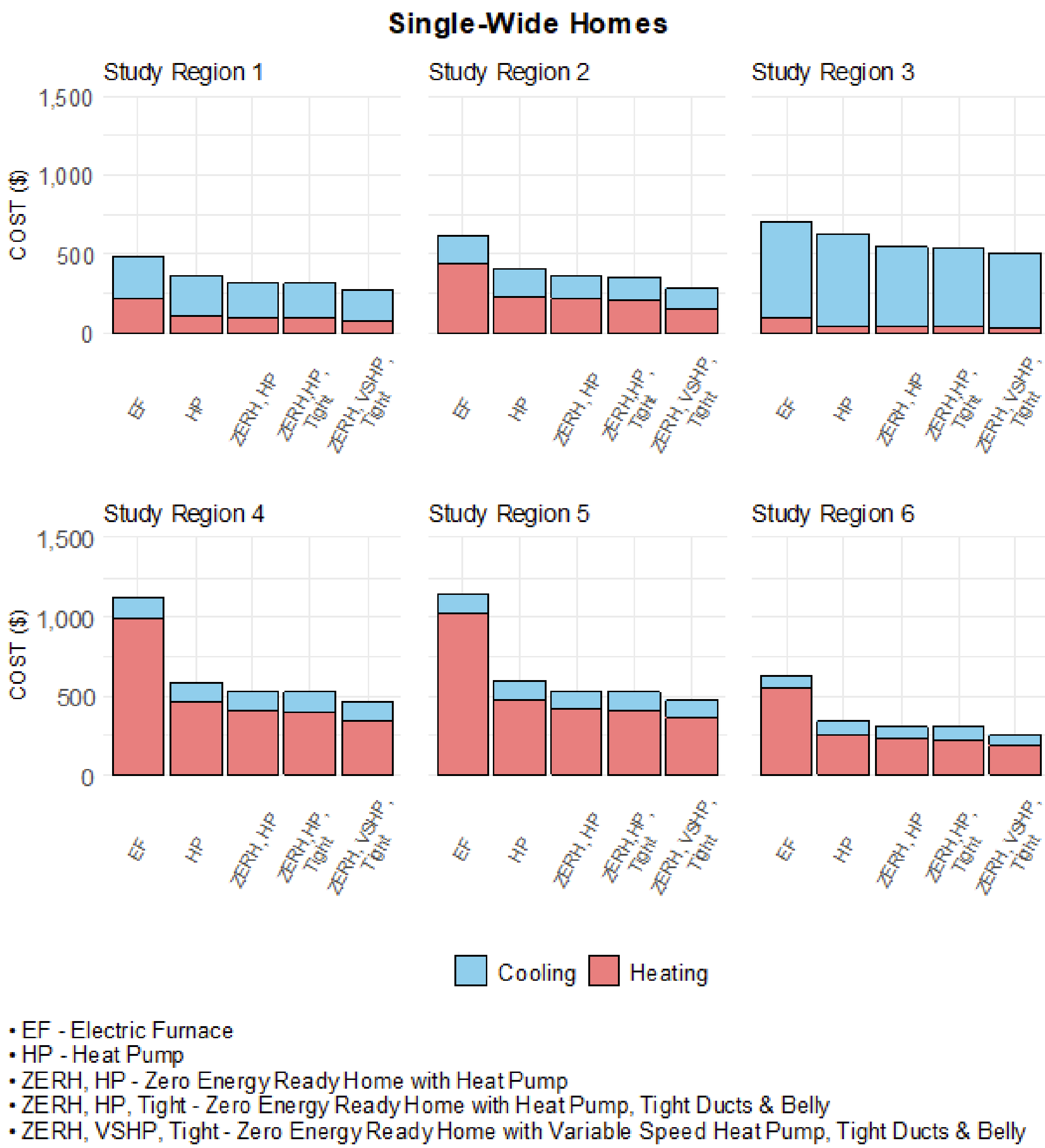
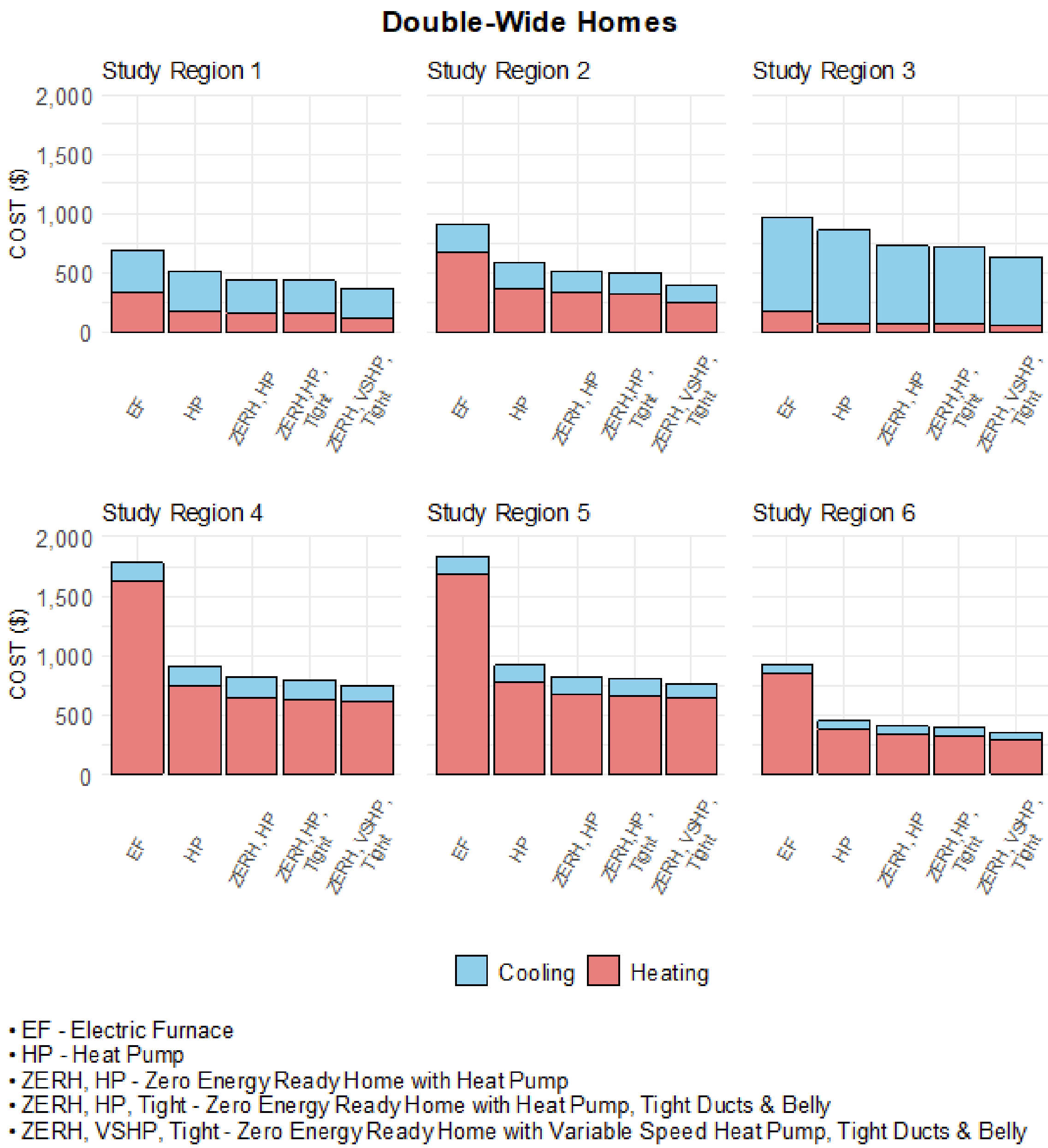


Figure 31. Weighted regional average heating and cooling costs of baseline envelope with various systems, for double-wide homes.



In addition to the energy cost analysis depicted above, percentage cost savings for the scenarios outlined in Table 10 were also assessed. The potential heating and cooling cost savings when transitioning from a standard envelope with a heat pump to an energy-efficient zero energy-ready home with a heat pump (scenario 1 in Table 10) are illustrated for all six study regions in Figures 32 and 33, for single-wide and double-wide homes, respectively. Similar trends in the cost savings are observed for single-wide and double-wide homes. In accordance with the climatic zones of the study regions, noticeable variation in heating and cooling cost savings is observed among them. Cooling cost savings are most substantial in the study regions characterized as hot or mixed climate (regions 1, 2 and 3), with the greatest savings anticipated in study Region 2 – with 17% savings for single-wide and 22% for double-wide homes. Estimated heating cost savings among the heating dominated climates (regions 4, 5, and 6) range from 12% to 13% for both home types.

Figure 32. Electric space heating and space cooling percentage annual operating-cost savings for a ZERH envelope compared to the baseline envelope in a heat-pump-conditioned home, by study region, for single-wide homes.

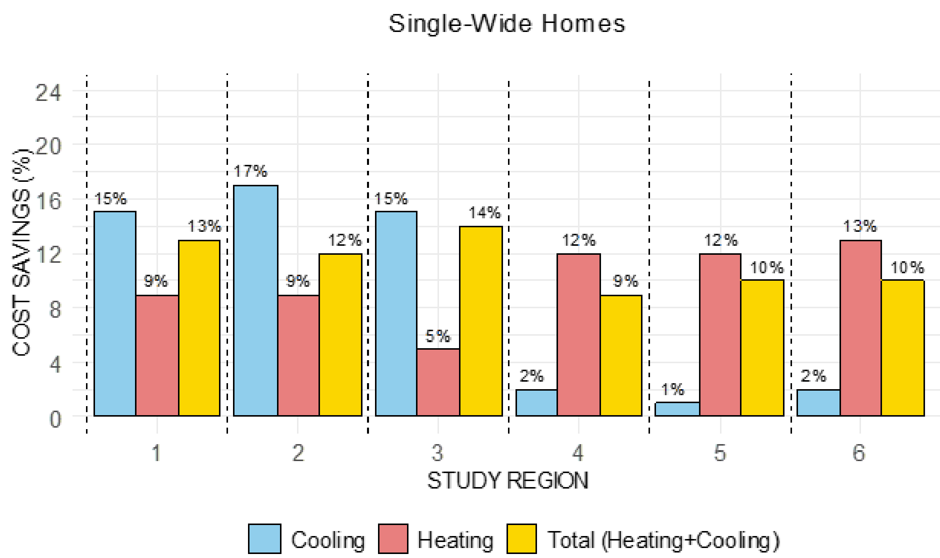
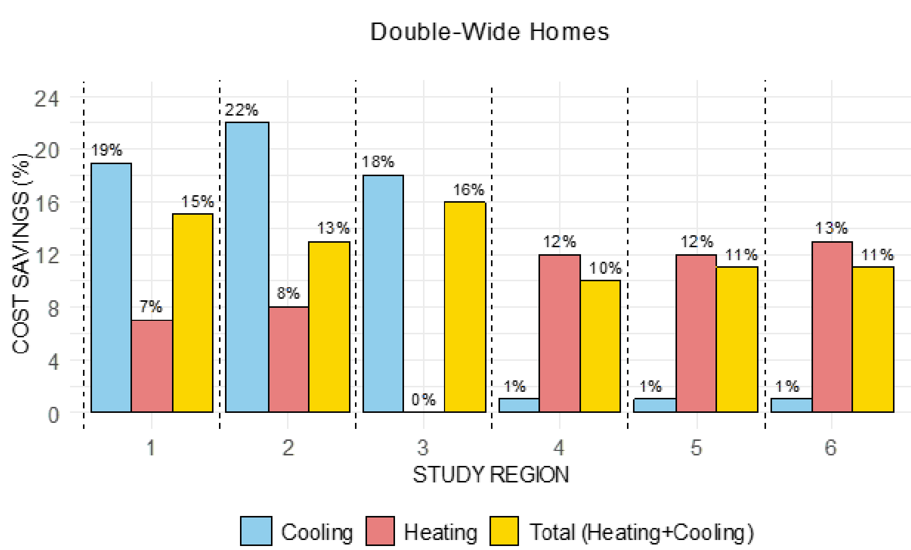


Figure 33. Electric space heating and space cooling percentage annual cost savings for ZERH envelope compared to the baseline envelope in a heat-pump-conditioned home, by study region, for double-wide homes.

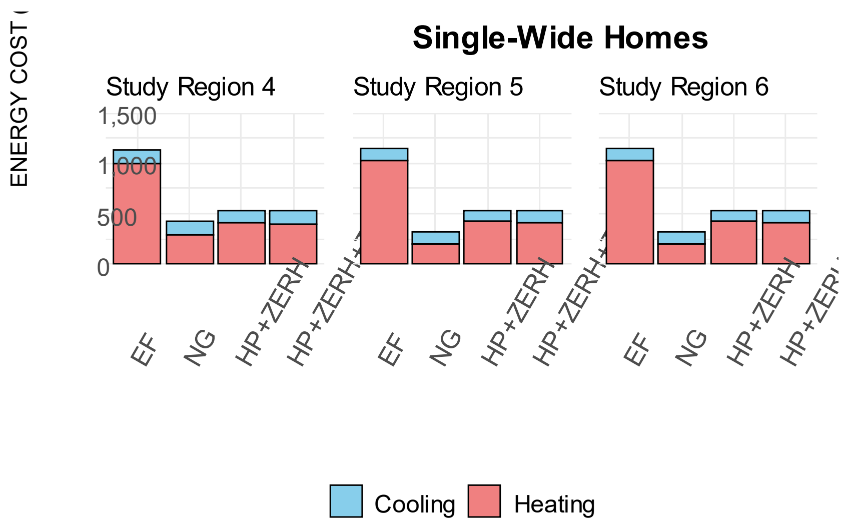


Cost effectiveness of natural gas, heat pump compared to electric furnace

Figure 34 provides a comparison of the operational energy costs in single-wide homes with the following options: a standard envelope home with an electric furnace, a standard envelope home with a natural gas furnace, a Zero Energy Ready Home (ZERH) with a heat pump, as well as a ZERH with a heat pump and tight envelope. The same are compared in Figure 35 for double-wide homes.

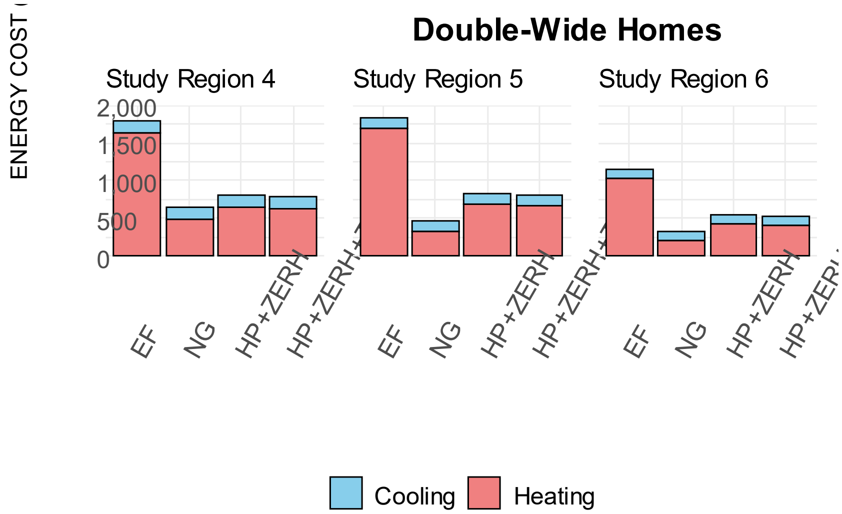
It's worth noting that the overall heating cost for the ZERH with heat pump are significantly influenced by the currently lower natural gas prices on a btu basis, leading to a projection of operating-cost favoring the natural gas furnace. For instance, although the site heating energy for a single-wide home in study Region 4 is significantly higher (30.1 MMBtu) for natural gas than for a ZERH with a single-speed heat pump (9.9 MMBtu), because of the much-cheaper per Btu cost of natural gas, the heating cost ends up being lower ($292) compared to the heat pump in a ZERH home ($405). However, it's important to highlight that natural gas is associated with higher CO_2e emissions when compared to heat pumps. Detailed CO_2e emission results are discussed in Figures 37 and 38 at the end of this section.

Figure 34. Operating-cost (heating, cooling) for standard envelope home with electric furnace, natural gas furnace, ZERH with single-speed HP and ZERH with single-speed HP and tight envelope, for single-wide homes.



- EF - Electric Furnace
- NG - Natural Gas Furnace
- HP+ZERH - Zero EnergyReady Home with HeatPump
- HP+ZERH+TE - Zero EnergyReady Home with Tight Envelope & HeatPump

Figure 35. Operating-cost (heating, cooling) for standard envelope home with electric furnace, natural gas furnace, ZERH with single-speed HP and ZERH with single-speed HP and tight envelope, for double-wide homes.



- EF - Electric Furnace
- NG - Natural Gas Furnace
- HP+ZERH - Zero EnergyReady Home with HeatPump
- HP+ZERH+TE - Zero EnergyReady Home with Tight Envelope & HeatPump

Incremental cost effectiveness of ZERH and heat pumps and tight "Belly" and ducts

Table 12 provides the break-even incremental cost for heating and cooling energy for the various efficiency options over a baseline condition. The estimated results for break-even costs for some measures are vastly different, depending on study region. The results suggest, for example, a break-even incremental cost of about $13,000 to upgrade from an electric furnace to a single-speed heat pump for a double-wide style home in study region 4 (Climate Zone 3, Northeast). By contrast, the estimated break-even incremental cost for the same improvement in study region 1 is only about $2,500. Another contrast of note is that for study region 3, the break-even expenditure is greater when upgrading from a conventional home with a HP to a ZERH with a HP ($1,231 for single-wide and $1,965 for a double-wide), than it is for upgrading from the same baseline to a conventional home with a VSHP ($203 for single-wide and $765 for a double-wide). In all of the other study regions, the differences between these same two efficiency measures are flat or reversed.

Table 12. Break-even incremental costs for heating and cooling energy for baseline versus efficiency options by study region and home type.

Break-even Incremental Cost for Heating and Cooling											
Home Type	Baseline:	HP	VSHP	EF	HP	ZERH w HP	ZERH w VSHP	ZERH w HP, Leaky duct	ZERH w VSHP, Leaky duct	ZERH w HP, Leaky duct	ZERH w VSHP, Leaky duct
	Efficiency:	ZERH w HP	ZERH w VSHP	HP	VSHP	ZERH w HP, Tight belly	ZERH w VSHP, Tight belly	ZERH w HP, Tight duct	ZERH w VSHP, Tight duct	ZERH w HP, Tight duct,	ZERH w VSHP, Tight duct,

											Tight belly	Tight belly
Single-Wide	Study Region	1	$648	$654	$1,526	$572	$46	$36	$116	$103	$142	$125
		2	$675	$563	$2,804	$1,156	$63	$34	$116	$93	$160	$119
		3	$1,231	$1,458	$956	$203	$84	$84	$167	$191	$227	$251
		4	$838	$537	$8,044	$1,293	$157	$87	$221	$174	$314	$233
		5	$757	$470	$7,369	$1,094	$139	$78	$192	$150	$275	$201
		6	$499	$352	$4,036	$912	$81	$43	$126	$91	$175	$126
Double-Wide	Study Region	1	$1,034	$1,018	$2,452	$973	$87	$66	$185	$168	$240	$213
		2	$1,048	$880	$4,381	$1,592	$123	$67	$198	$168	$283	$216
		3	$1,965	$2,330	$1,505	$765	$155	$149	$275	$299	$382	$394
		4	$1,395	$997	$13,189	$1,200	$315	$195	$473	$365	$690	$516
		5	$1,287	$884	$12,042	$1,027	$281	$174	$358	$317	$558	$453
		6	$700	$585	$6,634	$669	$151	$103	$208	$180	$306	$252

Figure 36 provides the incremental break-even costs for a heat pump and a variable-speed heat pump, over a baseline standard envelope home with an electric furnace. The inference from the figure is that study Regions 4 and 5 exhibit relatively higher break-even costs for both single-wide and double-wide homes; higher installed costs are warranted given the great heating cost savings projected in these regions. Note however that electric furnaces are only about a quarter of the shipments in those regions. In specific terms, for single-wide homes in study Region 4, the estimated incremental break-even cost when transitioning from an electric furnace to a heat pump is $8,044, and for a variable-speed heat pump, it is $9,336. For double-wide homes in Region 4, the break-even stands at $13,189 for a heat pump and $14,389 for a variable-speed heat pump.

Figure 36. Break-even incremental cost for heat pumps compared to Electric Furnace, by home type and regions.

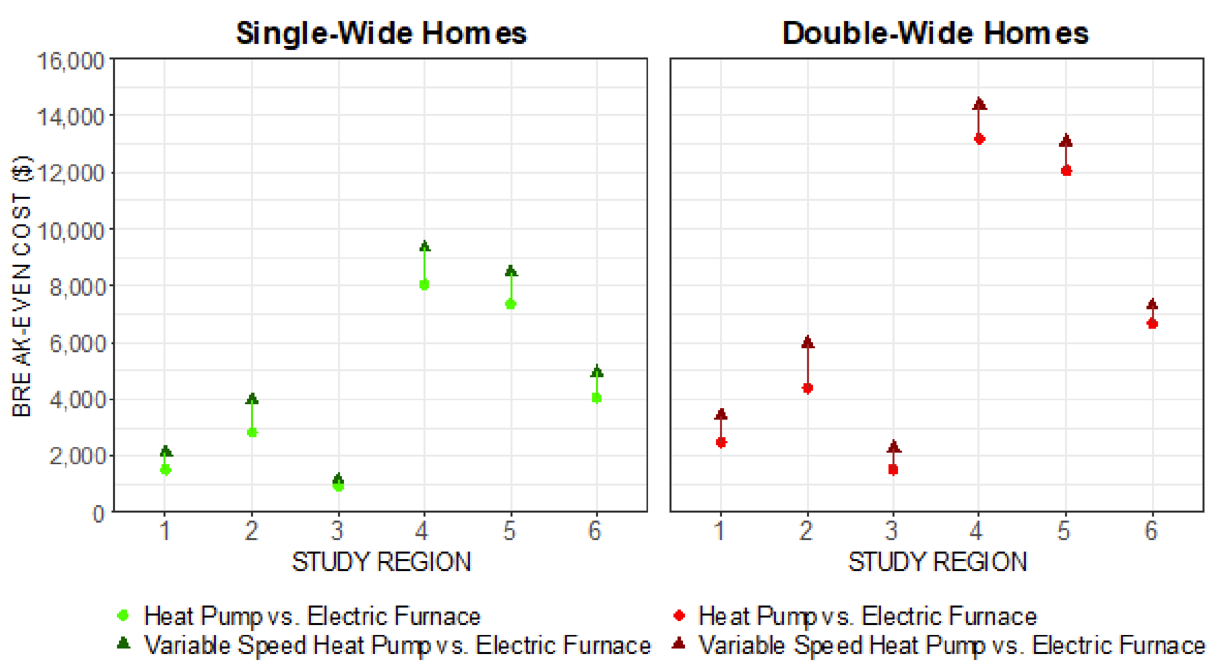
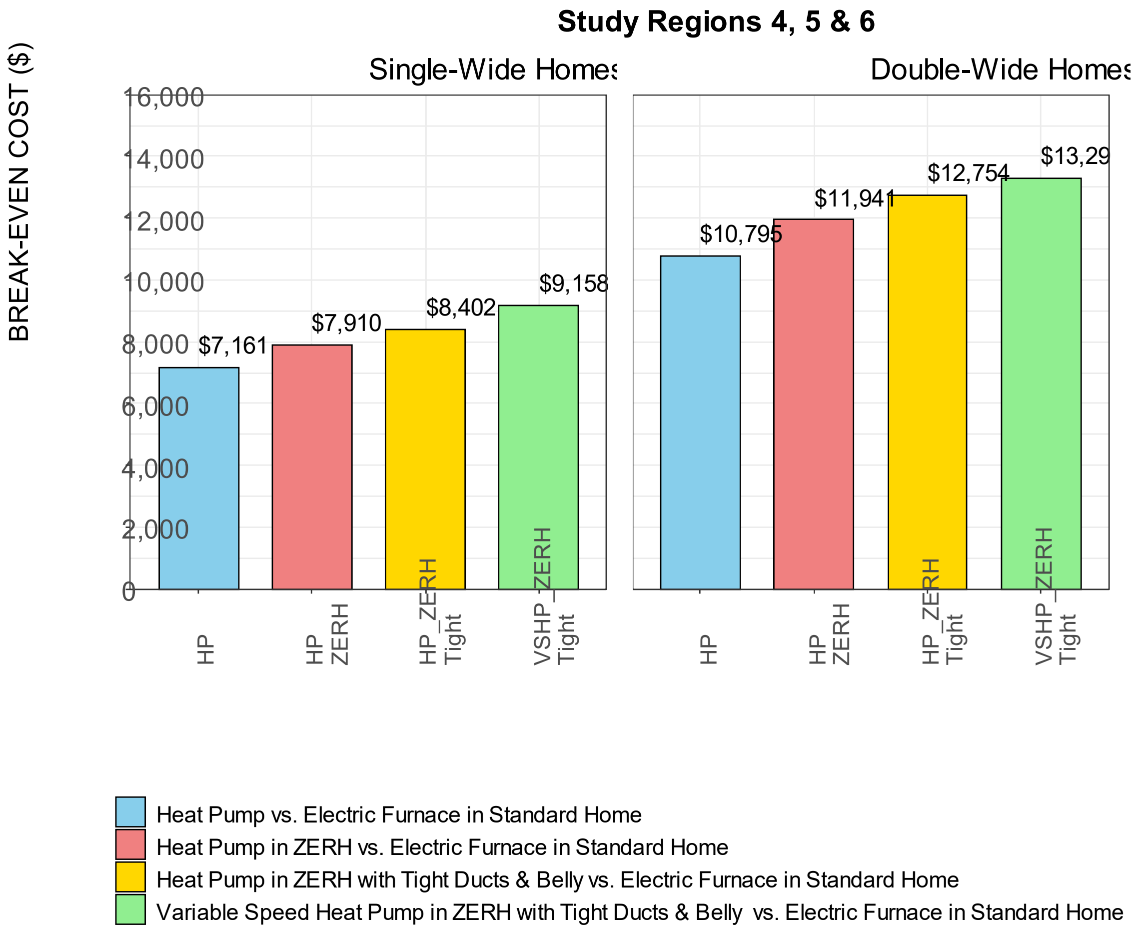


Figure 37 and Figure 38 present a comparison of the incremental break-even costs for various scenarios relative to a baseline of a standard home with an electric furnace. Weighted average results are provided for warm climate regions (study Regions 1-3, Figure 32) and for the cold climate regions (study Regions 4-6, Figure 33), for both single-wide and double-wide homes. The break-even incremental costs for double-wide homes are about 50% higher than the single-wide homes for the respective upgrades. As anticipated, the break-even costs increase as we progress towards the more energy-efficient options explored in the study. Also, in the colder regions, the break-even incremental first cost is far greater than in the warmer climates given like comparisons. For instance, in the context of double-wide homes in the warm climates, the transition from the baseline with an electric furnace to a single-speed heat pump is associated with a break-even incremental cost of $2,753. Opting for the most energy-efficient alternative considered in the study – a ZERH with a variable-speed heat pump, tight belly, and tight ducts – boosts the break-even cost to $5,442 in these regions. By contrast, assuming the same double-wide home in the cold climates, the transition from the baseline with an electric furnace to a single-speed heat pump is associated with a break-even incremental cost of $10,795, and the most energy-efficient alternative considered in the study has a break-even incremental cost of $13,291.

Figure 37. Incremental first cost at which a measure is a good choice from a consumer cost savings perspective. Weighted average of regions 1, 2 and 3 (warm climates).

Figure 38. Incremental first cost at which a measure is a good choice from a consumer cost-savings perspective. Weighted average of regions 4, 5 and 6 (cold climates).



CO_2e Emission Reduction for envelope and equipment improvements

We also investigated the impacts of various upgrades on CO_2e emissions. Differences in CO_2e emissions are provided for the ten pairs of simulation model results in Table 13. Overall, the most impactful CO_2e emissions reduction is seen in upgrading from a conventional home with electric furnace to one with a HP. For single-wide units the regional weighted average annual CO_2e emissions reduction ranged from 0.081 tons (study region 3) to 1.827 tons (study region 5) and for double-wide units the reduction range was from 0.131 tons (study region 3) to 2.973 tons (study region 5). Upgrading from a conventional home with a single-speed HP to one with a variable-speed heat pump is also impressive, with the highest reduction for double-wide units in study region 2, for an estimated reduction of 0.421 tons.

In Table 13 we have introduced an additional simulation comparison -- one between a baseline home with a gas furnace (GF) and the same home with a HP. The gas furnace model was not run in study regions where a gas furnace is not typical. We see substantial CO_2e emissions reductions in all three study regions where these can be compared. Study Region 4 reductions are 0.799 tons (SW) and 1.330 tons (DW); study Region 5 are 0.894 tons (SW) and 1.471 tons (DW); and study Region 6 are 1.342 tons (SW) and 2.153 tons (DW).

Table 13. Annual CO_2e emissions reduction for baseline versus efficiency options by study region and home type.

Annual CO_2e Emissions Reductions (tons)													
Home Type	Baseline:		HP	VSHP	EF	GF	HP	ZERH w HP	ZERH w VSHP	ZERH w HP, Leaky duct	ZERH w VSHP, Leaky duct	ZERH w HP, Leaky duct	ZERH w VSHP, Leaky duct
	Efficiency:		ZERH w HP	ZERH w VSHP	HP	HP	VSHP	ZERH w HP, Tight belly	ZERH w VSHP, Tight belly	ZERH w HP, Tight duct	ZERH w VSHP, Tight duct	ZERH w HP, Tight duct, Tight belly	ZERH w VSHP, Tight duct, Tight belly
Single-Wide	Study Region	1	0.116	0.112	0.322	n/a	0.127	0.009	0.007	0.021	0.019	0.027	0.024
		2	0.145	0.105	0.738	n/a	0.316	0.016	0.009	0.027	0.019	0.037	0.025
		3	0.108	0.126	0.081	n/a	0.023	0.008	0.008	0.016	0.018	0.021	0.023
		4	0.169	0.107	1.637	0.799	0.287	0.032	0.016	0.043	0.035	0.063	0.046
		5	0.186	0.115	1.827	0.894	0.290	0.034	0.018	0.045	0.037	0.068	0.049
		6	0.054	0.037	0.442	1.342	0.106	0.009	0.005	0.013	0.010	0.019	0.013
Double-Wide	Study Region	1	0.183	0.177	0.528	n/a	0.204	0.018	0.013	0.034	0.032	0.047	0.041
		2	0.221	0.169	1.167	n/a	0.421	0.031	0.017	0.045	0.036	0.066	0.049
		3	0.173	0.204	0.131	n/a	0.070	0.014	0.015	0.025	0.028	0.036	0.037
		4	0.283	0.195	2.677	1.330	0.271	0.065	0.038	0.094	0.071	0.139	0.100
		5	0.322	0.211	2.973	1.471	0.282	0.071	0.041	0.087	0.075	0.137	0.107
		6	0.073	0.061	0.705	2.153	0.075	0.016	0.011	0.021	0.018	0.032	0.026

Figures 39 and 40 provide summaries of CO_2e emissions for electric furnace, heat pump, and variable-speed heat pump, and natural gas where modeled, (all with the baseline envelope) across the six study regions, for both single-wide and double-wide homes.

As anticipated, across all study regions, both for single and double-wide homes, heat pumps and variable-speed heat pumps consistently exhibit lower CO_2e emissions when compared to electric and natural-gas furnaces. Although natural gas demonstrates cost savings advantages, Figures 37 and 38 underscore the environmental benefits of heat pumps in terms of CO_2e emissions in comparison to natural gas furnaces.

Figure 39. CO_2e emissions by equipment type and study region for single-wide homes.

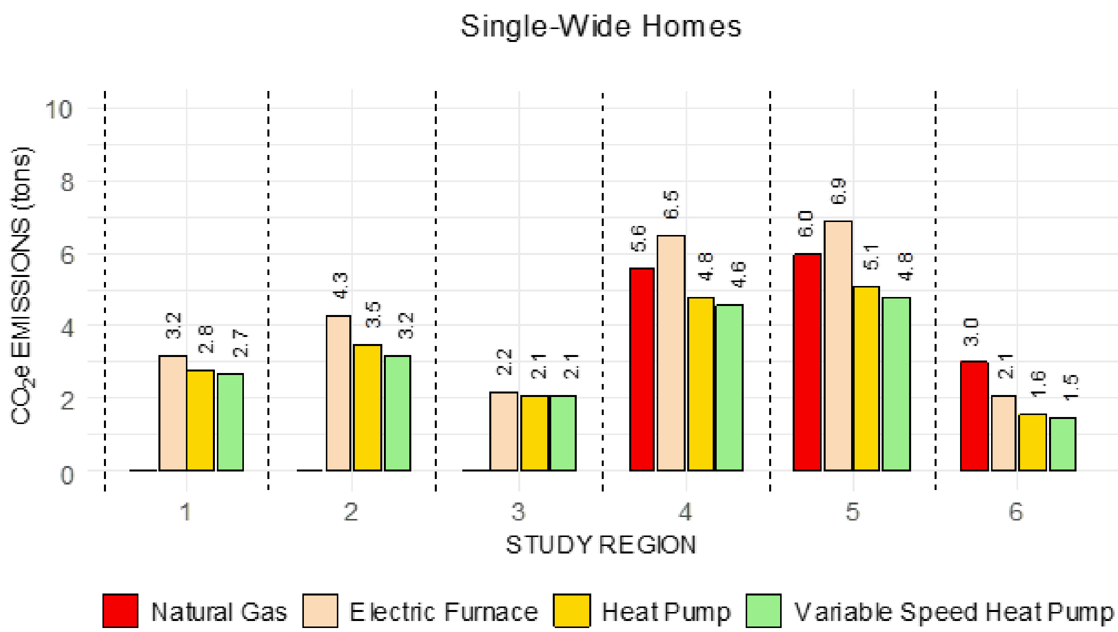
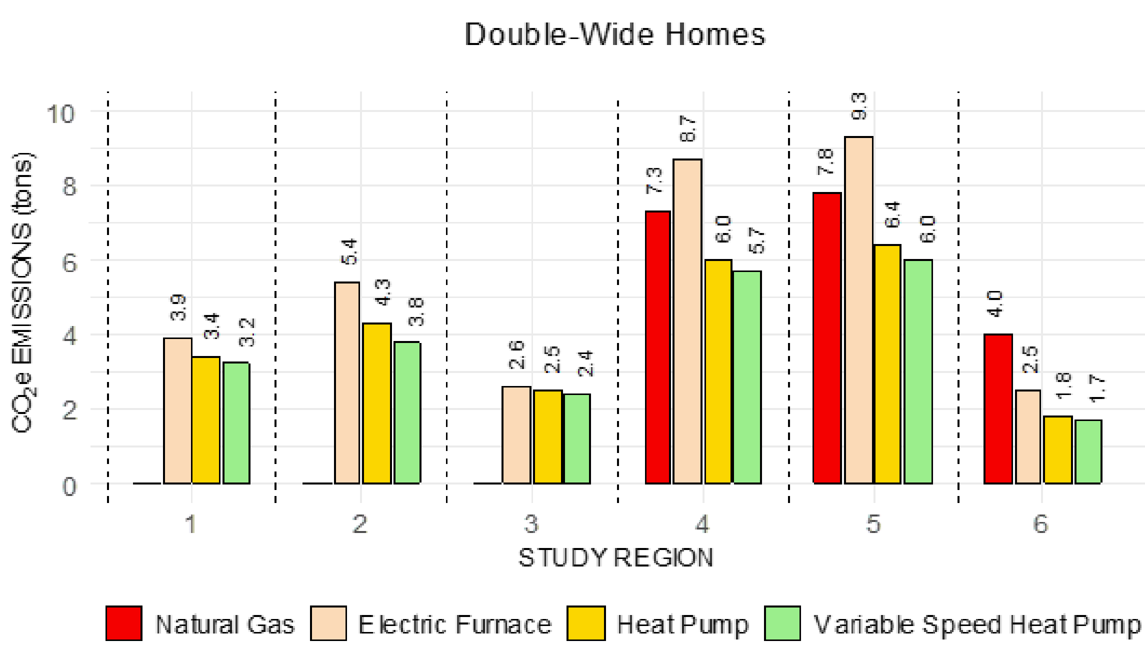


Figure 40. CO_2e emissions by equipment type and study region for double-wide homes.

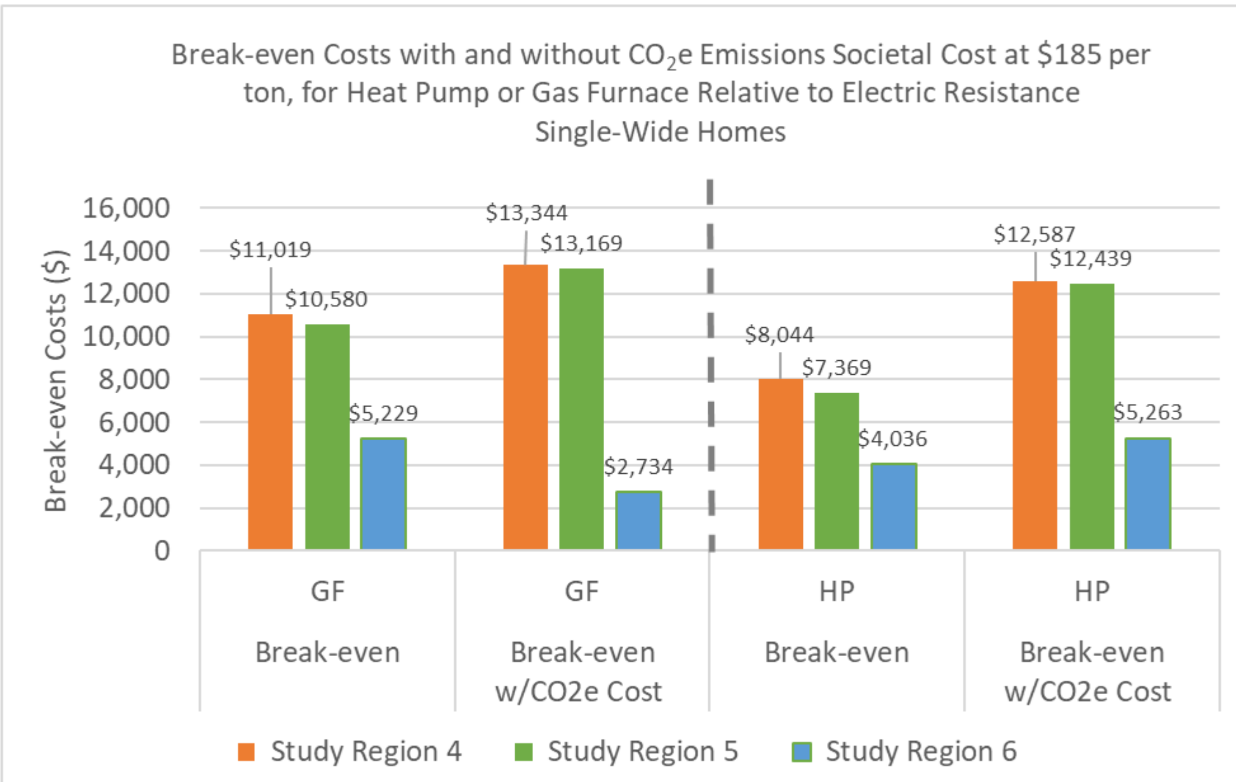


How much is reducing CO_2e worth? The U.S. currently uses $51 per ton of CO_2e[14] according to State of the Plant in its calculations of the social cost of carbon, while an article published by

[14] https://news.climate.columbia.edu/2021/04/01/social-cost-of-carbon/

Nature concludes $185 per ton is more appropriate.[15] If these societal costs are countered with rebates to consumers for envelope and HVAC solutions then the break-even costs shown in previous sections would increase. In Figures 41 and 42, for single-wide and double-wide respectively, we demonstrate the addition of societal costs at $185 per ton for the colder study regions. These figures present the break-even costs of the baseline homes with a gas furnace and then with a heat pump, both without societal costs (or rebates) compared to the break-even with societal costs added in. The societal cost of $185 per ton was taken to be consistent over 15 years for the purpose of estimating breakeven values in Figures 41 and 42.

Figure 41. Break-even costs with and without CO_2e emissions societal cost at $185 per ton, baseline envelope with single-speed heat pump or gas furnace, versus electric resistance for single-wide homes.



[15] Kevin Rennert, "Comprehensive evidence implies a higher social cost of CO2,", Nature, published online Sept. 1, 2022, https://www.nature.com/articles/s41586-022-05224-9

Figure 42. Break-even costs with and without CO_2e emissions societal cost at $185 per ton, baseline envelope with single-speed heat pump or gas furnace, versus electric resistance for double-wide homes.

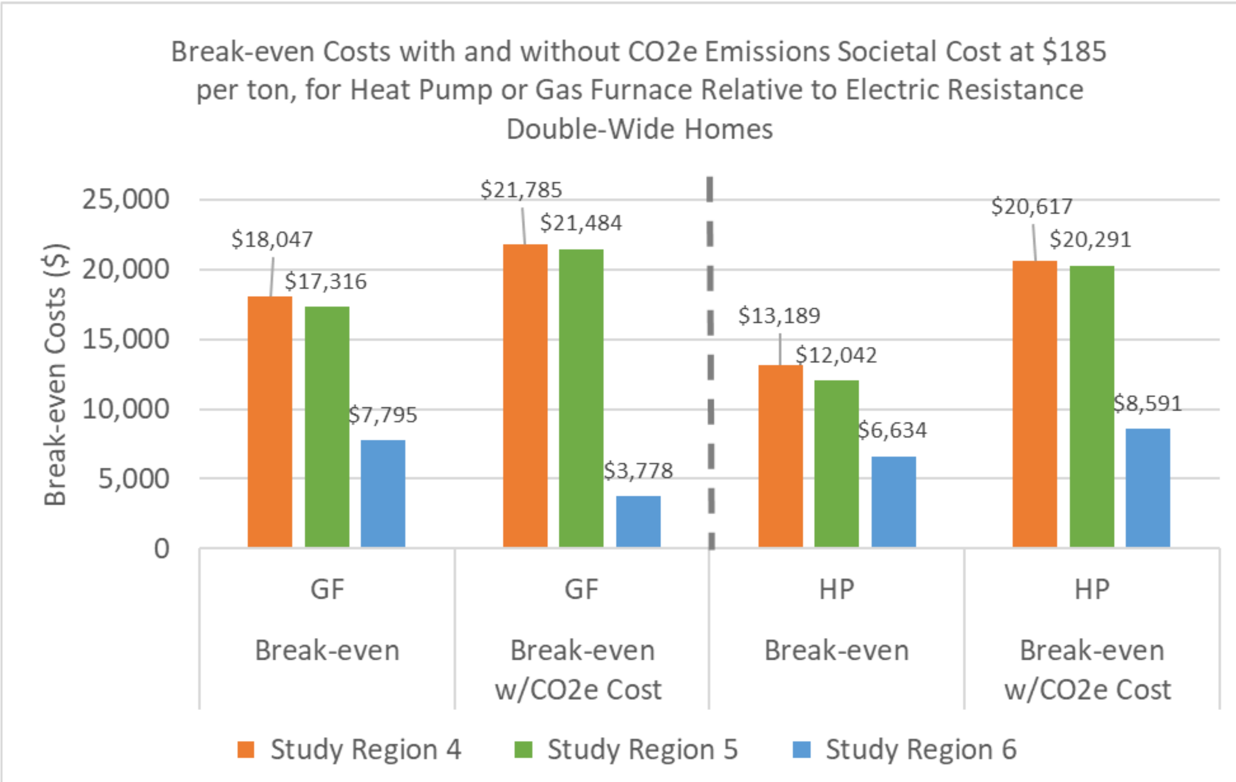
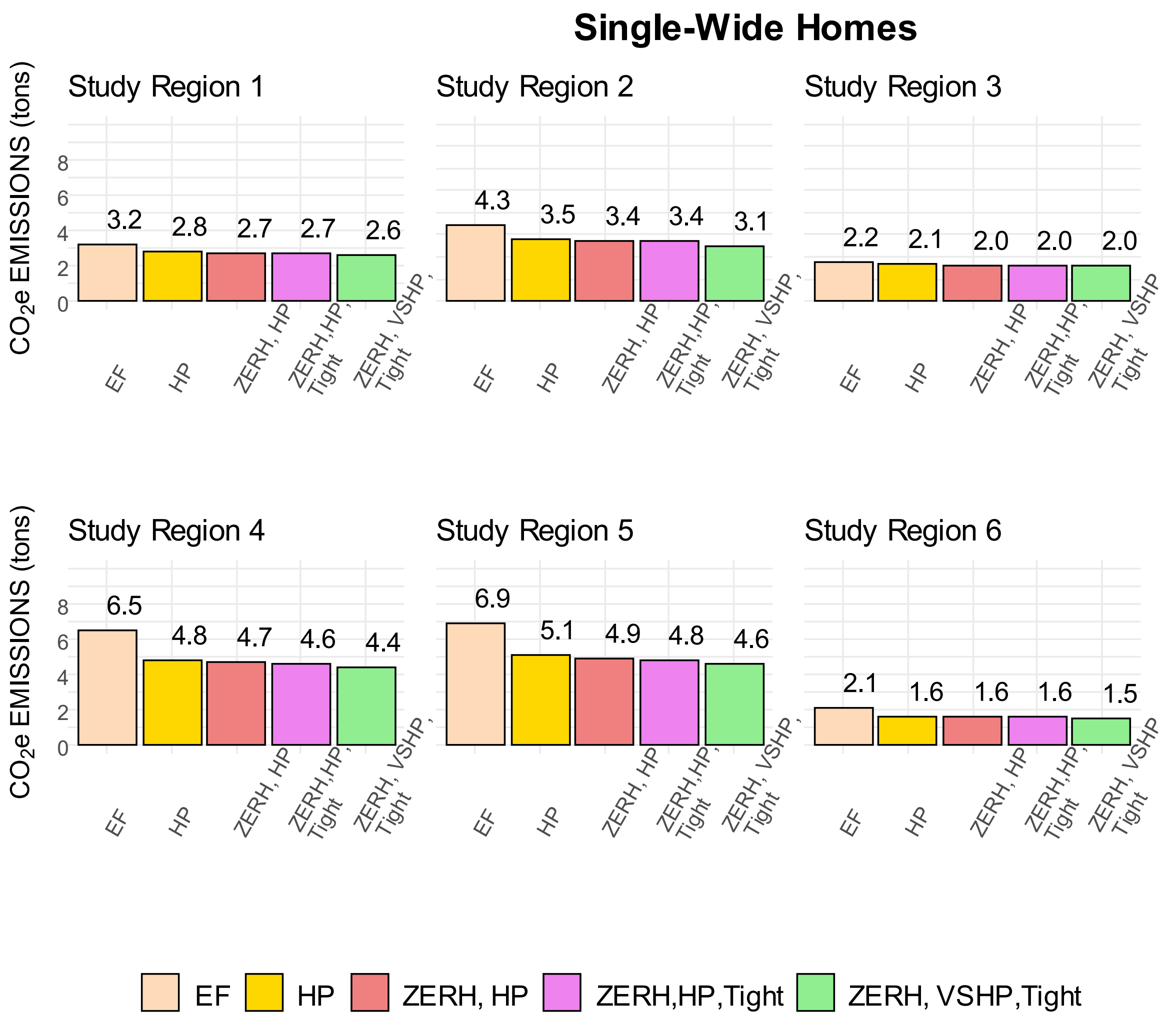


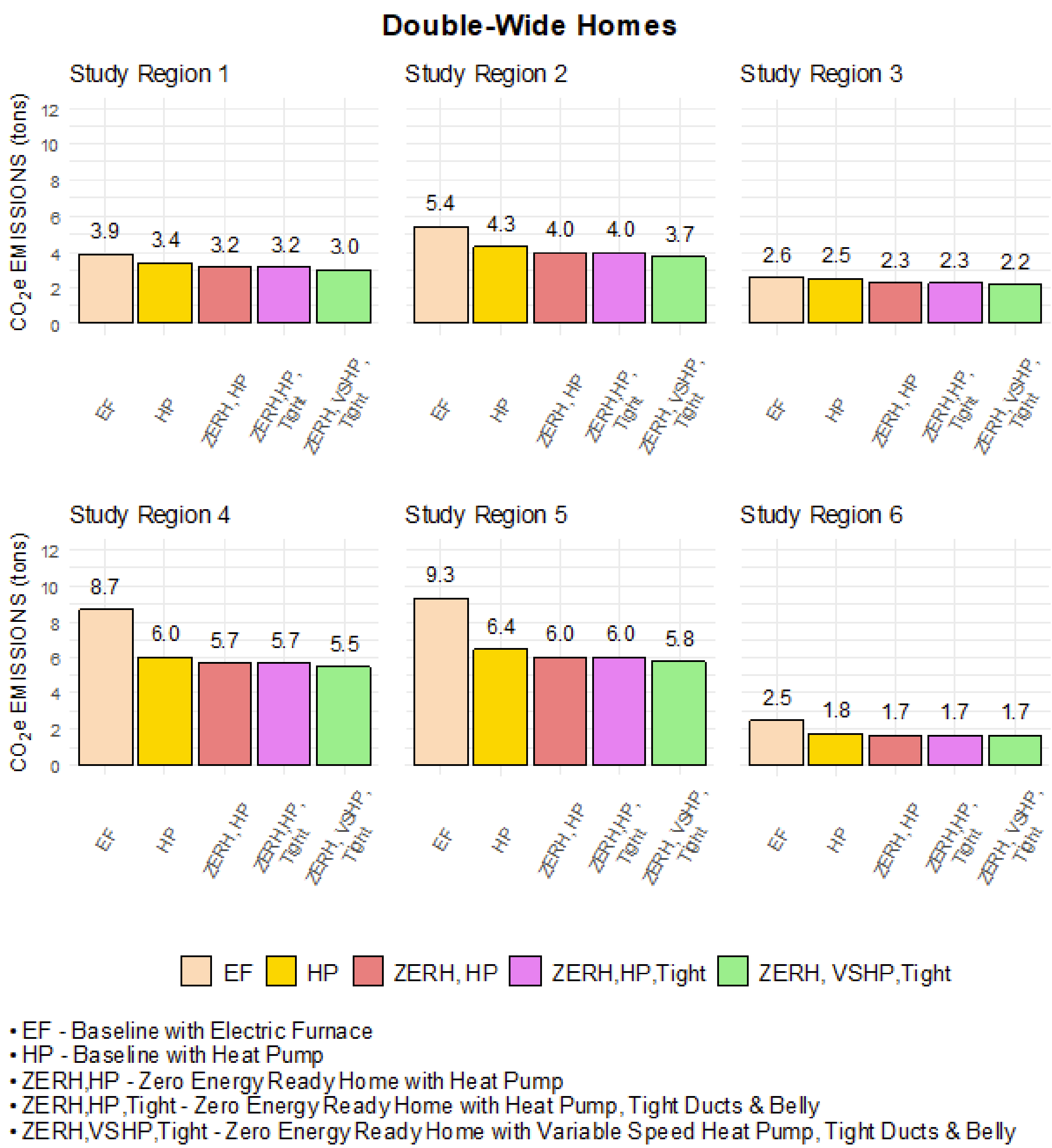
Figure 43 (single-wide) and Figure 44 (double-wide) depict the projected step-wise improvement of increasingly lower emission options relative to a baseline home with an electric furnace. This figure again illustrates that heat pumps exhibit superior characteristics in terms of CO_2e emissions when compared to electric furnaces. For single-wide homes, upgrading from an electric furnace to a heat pump is estimated to result in a reduction of 0.08 (4%) to 1.83 (27%) CO_2e emissions (tons), depending on Study Region. For the double-wide homes the CO_2e emissions reduction per Study Region ranges from 0.13 (5%) to 2.97 (32%). Moreover, when upgrading from an electric furnace to the most efficient technology considered in this study (a variable-speed heat pump installed in a ZERH with a tight belly and tight ducts), the per Study Region CO_2e emissions reduction is even more substantial, as much as 2.33 (34%) for single-wide homes and 3.64 (39%) for double-wide homes, with the greatest improvement consistently in Study Region 5.

Figure 43. Annual whole house CO2e emissions by equipment type and home type for single-wide homes.



• EF - Baseline with Electric Furnace
• HP - Baseline with Heat Pump
• ZERH,HP - Zero Energy Ready Home with Heat Pump
• ZERH,HP,Tight - Zero Energy Ready Home with Heat Pump, Tight Ducts & Belly
• ZERH,VSHP,Tight - Zero Energy Ready Home with Variable Speed Heat Pump, Tight Ducts & Belly

Figure 44. Annual whole house CO_2e emissions by equipment type and home type for double-wide homes.



Electric demand reduction for envelope and equipment improvements

One of the simulation outputs was peak hourly demand for space conditioning. For the base electric homes this occurred in winter mornings regardless of climate. The peak electrical demand could occur in summer or winter. The peak hourly electrical demand for single-wide simulation runs ranged from 8,111 Watts to 12,155 Watts. The peak ranged from 8,073 to 14,680 Watts for double-wide homes. Table 14 presents the results for peak demand reductions for the most relevant simulation by study region. Savings of over 1 kW occur in study Regions 1, 2, and 6 for moving from an electric resistance furnace to a heat pump. With a heat pump in place, the ZERH modeled envelope improvement yield regionally weighted averages between 0 to 398 W for single-wide and between 85 W and 637 W for double-wide units – with the greatest savings indicated for the cold climates. Implemented across manufactured homes in an area these reductions could be meaningful to a utility. The value of the savings will vary by utility. In regulated states, the value to the utility will largely depend on regulations. A 2020 Lawrence Berkeley study put the 2017 first cost value of demand savings from efficiency programs at $568/kW to $2553/kW depending on the location of the nine states they studied. The southern states studied were on the lower end of this range. [16] We note that the weather files used for simulation are TMY which is based on history and may not represent current temperature extremes or peaks given climate change. Actual peak savings will vary and may tend to be higher than what is represented here.

Table 14. Peak demand for baseline versus efficiency options by study region and home type.

Peak Demand Reduction (Watts)												
Home Type	Baseline:		HP	VSHP	EF	HP	ZERH w HP	ZERH w VSHP	ZERH w HP, Leaky duct	ZERH w VSHP, Leaky duct	ZERH w HP, Leaky duct	ZERH w VSHP, Leaky duct
	Efficiency:		ZERH w HP	ZERH w VSHP	HP	VSHP	ZERH w HP, Tight belly	ZERH w VSHP, Tight belly	ZERH w HP, Tight duct	ZERH w VSHP, Tight duct	ZERH w HP, Tight duct, Tight belly	ZERH w VSHP, Tight duct, Tight belly
Single-Wide	Study Region	1	8	2	1,490	(39)	0	0	5	5	5	5
		2	188	223	1,266	(116)	2	4	29	50	30	51
		3	(0)	(1)	52	(74)	0	(0)	(0)	(0)	-	(0)
		4	352	244	560	118	47	58	138	137	169	171
		5	398	363	0	44	71	86	196	192	243	242
		6	297	(9)	1,313	947	48	(2)	170	5	195	3
Double-Wide	Study Region	1	436	125	2,280	504	48	12	55	42	66	43
		2	484	415	2,330	178	48	2	44	30	44	30
		3	85	139	215	125	13	30	36	51	45	60
		4	597	396	194	633	152	109	298	202	403	276
		5	637	591	0	183	153	163	328	291	439	402
		6	317	201	1,776	1,407	61	(2)	180	11	218	10

Note that there is no reduction observed in study Region 5 when upgrading from the electric furnace to the single-speed heat pump as the heat pump modeled did not run during the peak hour due to the cold temperature despite the cold climate heat pump modeled running to -22 F. In the other cities modeled there were peak winter savings as the heatpump was able to operate at the coldest temperatures.

[16] Peak Demand Impacts from Electricity Efficiency Programs

Figures 45 and 46 illustrate the savings of ZERH in each region relative to a baseline home with heat pump.

Figure 45. Peak electric demand for baseline with single-speed HP and ZERH with single-speed HP by study region for single-wide homes.

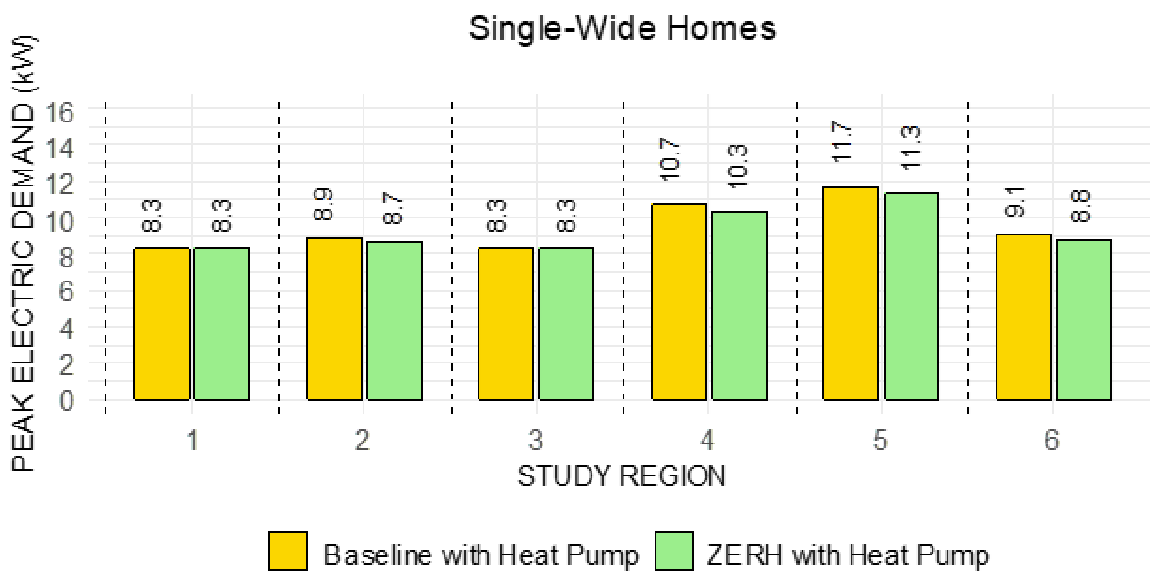
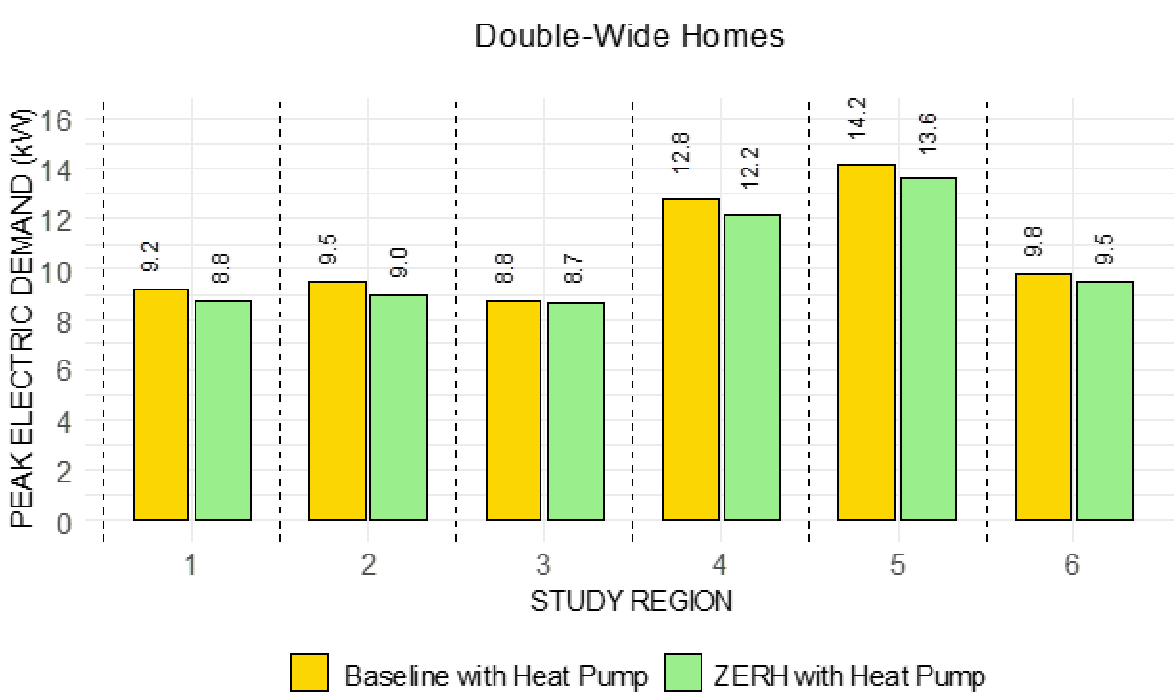


Figure 46. Peak electric demand for baseline with single-speed HP and ZERH with single-speed HP by study region for double-wide homes.



CONCLUSIONS

In summary of the analysis derived from simulation results and economic evaluations, several key conclusions emerge. These findings shed light on the advantages of heat pumps over electric resistance furnaces, the potential benefits of variable-speed heat pumps, the impact of belly and duct leakage on energy savings, and the efficacy of Zero Energy Rated Home in reducing energy consumption. Additionally, the assessment extends to the consequential CO_2e emission reductions associated with higher efficiency HVAC systems and improved building envelopes. The following sections provide more information on these conclusive insights.

Heat pumps represent a significant improvement over electric resistance furnaces

The energy savings achieved through the use of heat pumps, compared to electric furnaces, for double-wide homes vary from 11% in Phoenix to 59% in Seattle, with the most substantial absolute savings in Chicago, exceeding 24,000 kBtus. In the case of single-wide homes, the savings are 10% and 57% in Phoenix and Seattle, respectively, with Chicago experiencing absolute savings just over 15,000 kBtu. The adoption of heat pumps results in a reduction in energy consumption, leading to annual cost savings ranging from approximately $70 to $900. These savings are contingent on the study region and home type, with the greatest cost benefits observed in colder climates and for double-wide homes. Given the significant electrical savings, installing heat pumps emerges as the preferred choice over electric resistance heat.

Variable-speed heat pumps are advantageous, though cost savings over single-speed heat pumps are currently small

In general, variable-speed heat pumps have higher efficiencies than single-speed HPs for both cooling and heating. The range of electrical savings across eight sites from this study is 5% and around 500 kBtu in Phoenix to 20% and almost 3000 kBtu in Raleigh. Higher efficiency variable-speed heat pumps have a higher initial cost compared to single-speed HPs, and the return on investment for this more efficient option may take several years. For variable-speed heat pumps, the cost effectiveness evaluation suggests annual cost savings of $17 to $117, depending on study region and home type. Variable-speed heat pumps offer the added advantage over single-speed HPs by efficiently meeting larger heating loads in cold climates, even with capacities that would otherwise be oversized for corresponding cooling loads. VSHPs have the additional advantages of running at lower speeds for smaller loads which can prevent short cycling which can lead to comfort problems from elevated relative humidity.

Belly leakage impacts energy savings and more field research is needed

An important distinction between this and prior envelope modeling research is the simulation of the belly area as a thermal zone. In prior research conducted by this team, all ducts are embedded in the belly zone. In the previous study, the belly zone and the living space are assumed to be combined as a single thermal zone and only ducts in either the crawl space or the attic are modeled. All duct conduction and leakage losses occur in the unconditioned zone. Since the present study requires that all ducts be embedded in the belly space, all duct conduction and leakage losses occur only in the belly space.

The impact of annual HVAC system energy consumption using a baseline belly zone air tightness of 15 ACH50 and tightening it to 3 ACH50 was rather minor across all eight cities. The authors recognized that this tightening represents a small hole. Subsequently, new simulations were conducted for Baltimore baseline belly zone air tightness of 60 ACH50. This greater range of simulated tightening resulted in about 6% site energy savings in double-wide homes and 4% in single-wide savings. Research on the hole sizes and air tightness of the belly zones in actual sited manufactured homes is needed for more precise predictions of energy use differences.

Duct leakage impacts energy savings, though tighter ducts need to be standard practice

Based on the limited field data available, savings of 2 to 3% may be achieved by tightening the ducts in single-wide and some double-wide units. This savings represents the difference when going from a Qn of 0.08 to 0.04. Homes with a baseline of leaky crossover connections may expect savings of 6% when tightened. When a ZERH envelope with a single-speed HP is upgraded to tighter ducts, the annual cost savings could be as high as $46, depending on study region and home type. The economic viability of energy savings only becomes apparent when tighter ducts are adopted as a standard practice.

Zero Energy Rated Home Envelope reduces energy use with meaningful cost savings

The ZERH envelope measures total cost savings ranged from a low of 9% to 16% depending on building type and study region. If the envelope measures were applied to a home with heat pump, savings could be as low as under 1,000 kBtuh in a single-wide unit in Seattle or over 6,000 kBtu for a gas furnace home in Chicago. In terms of economics, the ZERH envelope measure suggests annual energy cost savings ranging from $25 to $166, depending on baseline assumptions, study region, and home size. The improved envelope can lead to additional costs savings when the ZERH improvement leads to HVAC downsizing. Regional percentage cost savings achieved with the ZERH envelope for double-wide homes is presented in Figure C-1. This example assumes single-speed HP systems.

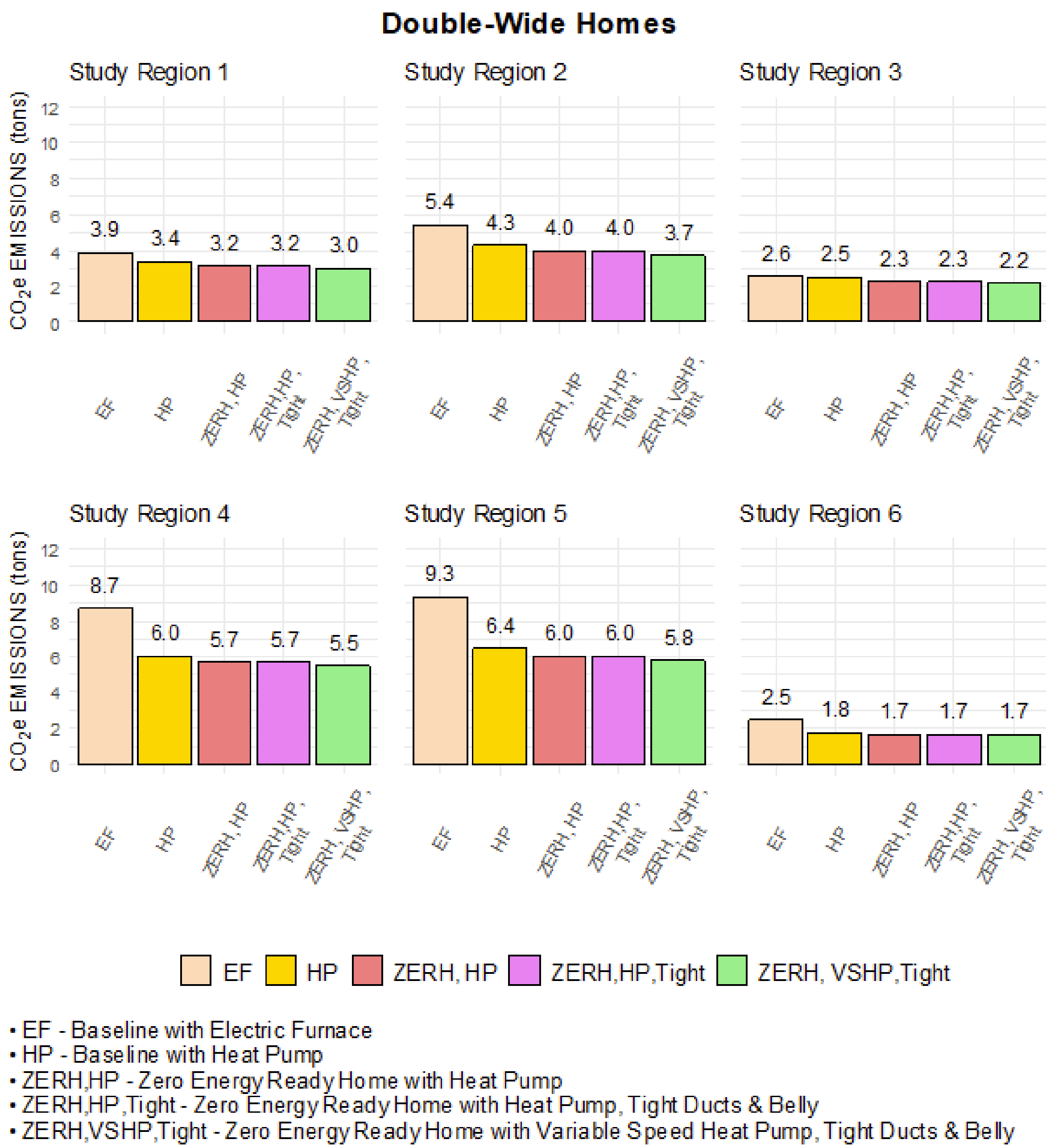
Figure C-1. The percentage of cost savings for the Zero Energy Ready Home envelope improvements. All homes in this example were modeled with heat pumps.

Impactful CO_2e emission reduction with higher efficiency HVAC Types and Envelopes

The annual predicted CO_2e emissions averaged from 2025 to 2050 in eight simulated cities with a ZERH envelope for double-wide homes are reduced by about 6.5% for electric furnace + AC, 8% for gas furnace (6 cities simulated) + AC, and 5% for heat pump, respectively. Among the eight locations with ZERH envelope for single-wide homes, these average reductions are 5% for electric furnace + AC, 7% for gas furnace + AC, and 4% for heat pump, respectively.

Figure C-2 provides the CO_2e emissions, by study region, for double-wide homes, demonstrating the reductions moving from measure to measure and differences among study regions. Cumulatively these measures are estimated to save 3.5 tons of CO_2e per double-wide house in study region 5, where the baseline CO_2e missions are the highest. Based on the above analysis, the CO_2e emission reduction with ZERH construction is significant.

Figure C-2. Simulated annual CO_2e emissions from combinations of HVAC and other improvements for double-wide homes by study region.



DISCUSSION

What is the impact of this research on home manufacturers and policy makers?

Based on the simulated savings and break-even economics we could conclude placing ductwork in the belly and not the attic in southern climates likely saves first cost as well as energy, and manufactures should consider making the switch. Duct sealing programs are beneficial but perhaps only cost effective to consumers in all regions if done as part of routine practice if starting from the level present in homes tested for this project. Heat pumps are cost effective for homes located in the South that will have central air conditioners, as the first cost upgrade is rather minor. Heat pumps are also likely more cost effective than electric resistance for consumers in northern regions due to the large savings.

In regions where the cost of natural gas is much lower than electricty per energy unit, upgrading from a natural gas furnace to an electric heat pump based on consumer financial return may be a challenge. The challenge is particularly great in homes with no central AC system. However, in cold locations where the per unit electricity cost is low (for example some areas in the northwest), it may be cost effective for a consumer to upgrade to a heat pump. Also, gas prices historically flucatuate more greatly than electricty, and costs may not remain low.

There are also potential benfits for reducing peak winter morning utility demand for upgrading from electric resistance to heat pumps in all climates except perhaps the very coldest where heat pumps may not operate on peak days. Similarly, there may be great benefit to society from reduced greenhouse gas emissions by incorporating envelope and HVAC improvements. How can these benefits be directly passed on to the consumer to help cover the increased first cost?

From a manufacturers viewpoint that needs to sell product, what can be done?

There are some buyers for whom any increase in price puts them out of the market. For many, manufactured homes are the lowest cost new home option avilable. Therefore it may be impracticial to mandate any high cost improvements which could potentially cause other societal problems with housing shortages. This is where incentives come into play. Federal, state, and utility programs could help incentivize manufacturers to build heat pump ready homes and tighten and test ductwork. Such programs could also require some field test and verification of whole home, belly, and duct tighness to overcome issues that occur during transport and installation.

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APPENDIX A: CO_2E EMSSION METHODOLOGY

RESNET's New CO_2e Index

Adopted from ASHRAE 90.2 Annual Meeting
Toronto, Ontario, Canada June 27, 2022

Philip Fairey

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UNIVERSITY OF CENTRAL FLORIDA

Background

- RESNET's CO_2e Index is an initiative of the RESNET Board of Directors' Load Flexibility Task Group (LFTG)
- The LFTG is tasked by the RESNET Board to address time of use issues related to home energy ratings
- Carbon emissions from electricity generation are directly related to time of use because electricity generation fuel mix varies with demand
- All RESNET-accredited HERS Software tools perform hourly energy use simulations
- NREL has developed forward-looking hourly electricity generation emission rate data that can be used to evaluate carbon emissions
- Long-range carbon emission estimates for buildings are critical to efforts to combat global climate change.

IPCC 6th Assessment Report Potential for "irreversible change"

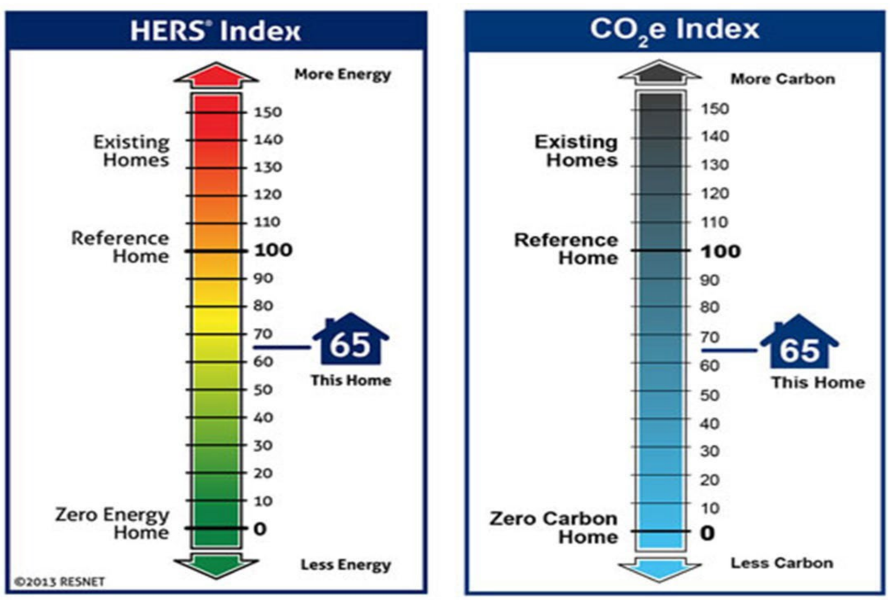
What is RESNET Doing About Climate Change?

- RESNET has created a CO_2e Index to accompany its Energy Rating Index (ERI / HERS Index)
- The CO_2e Index provides a mechanism for Home Energy Raters to evaluate the long-term CO_2e emissions of a dwelling unit
- What is CO_2e?
- CO_2e is an expression of the impact of all Green House Gasses (GHGs) expressed in terms of their Carbon Dioxide equivalent
- What are the other GHGs that are considered in CO_2e?
- Methane (CO_2 from natural gas): 29.8 times the equivalent of CO_2
- Nitrous Oxide (N_2O): 273 times the equivalent of CO_2
- Both pre-combustion (upstream) and combustion emissions are accounted by RESNET's CO_2e Index.

CO_2e Index Concept

- Create the CO_2e Index using hourly energy simulation results from accredited HERS software tools so that time of use is properly considered
- Use forward-looking CO_2e emission rates for electricity generation so that future emissions are not overstated
- Use combined pre-combustion (upstream) and combustion emission rates for electricity and natural gas
- Use IPCC AR6 Global Warming Potential (GWP) values for the 100-year time horizon
- Make no alterations to the calculation of the HERS Index/ERI
- Configure the CO_2e Index Reference Home the same as the Energy Rating Reference Home except using electricity for all energy end uses.

Value Added for the Energy Rating Index



What CO_2e Emission Rates are Used?

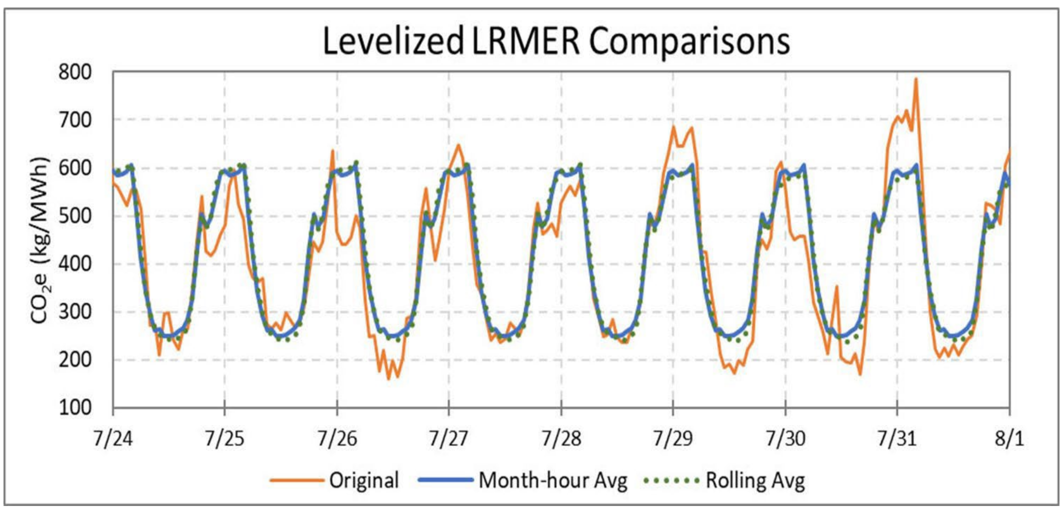
- For electricity, RESNET uses the levelized, month-hour, Long-Run Marginal CO_2e Emission Rates (LRMER) for the low renewable- energy cost scenario from the 2021 Cambium database with the following constraints
  - Combined pre-combustion plus combustion CO_2e emissions
  - Emission rates levelized over 2025-2050 time frame
  - AR6 global warming potentials (GWP) for 100-year time horizon
  - 3% social discount rate (out-year emissions count less than near term emissions)
- For household combustion fuels, RESNET uses the combined pre- combustion plus combustion CO_2e emission rates from ASHRAE Standard 189.1, Appendix J for the 100-year GWP time horizon.

What is the 2021 Cambium Database?

- Extensive database with projected hourly electric-sector generation and emissions data for years 2022 through 2050
- Multiple scenarios (e.g. BAU, High RE Cost, Low RE Cost, 95% decarbonized by 2050, etc.)
- Data for 134 regions covering the contiguous United States
- Virtual replication of EPA eGRID sub regions
- Several emissions metrics: Average, short-run marginal, and long-run marginal
- Multiple GHG emissions: CO_2 and CO_2e (CO_2 + CO_2 + N_2O)
- Combustion and pre-combustion emissions data
- Busbar and end use load data

What are Month-Hour CO_2e Emission Rates?

Original emission rates are developed using 2012 weather data. To make the emissions data more relevant to TMY3 weather data, month-hour averages are used so that estimates are not based on irrelevant 2012 weather peaks and valleys. Note also that month-hour and 14-day rolling average data are very similar.



Importance of Forward-Looking Generation Data

- The electric grid is changing in response to increasing cost of fossil fuels coupled with decreasing cost of renewable energy
- Estimating CO_2e emissions from an operational-only short- run perspective neglects how new electric loads (e.g. EVs) can be served by new non-emitting generators
- Utility scale photovoltaic generation is now less costly that combined cycle natural gas generation
- Wind generation is rapidly growing in areas with good wind resources

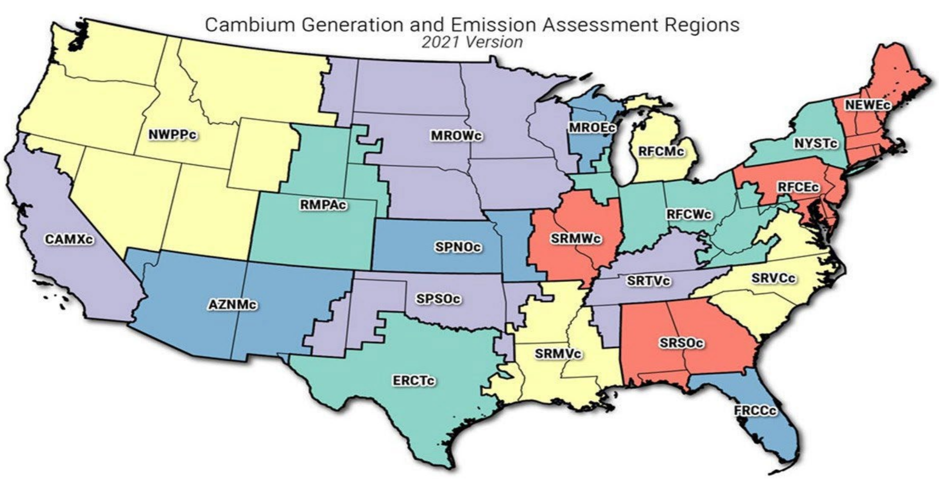
- More coal and oil-fired generation plants are closing or being reconfigured to use natural gas in response to relative cost increases and greenhouse gas reduction initiatives
- Failing to account for these grid changes into the future would over estimates both the long-term CO_2e emissions and the long-term CO_2e savings with respect to electricity generation.

Levelized Long-Run Marginal Emission Rates

- Very similar to annualized life-cycle cost calculations
- Uses Cambium Grid and Emission Assessment (GEA) region CO_2e long-run marginal emission rates (lrmer_CO_2e)
- NREL calculation spreadsheet tool is available here: https://data.nrel.gov/submissions/183
- RESNET specifications:
  - Start year = 2025
  - Evaluation period = 25 years
  - Discount rate*[17] = 3%
- Emissions calculated = combustion & pre-combustion CO_2e
- AR6 100-year GWP time horizon values

What are the Geographic Regions?

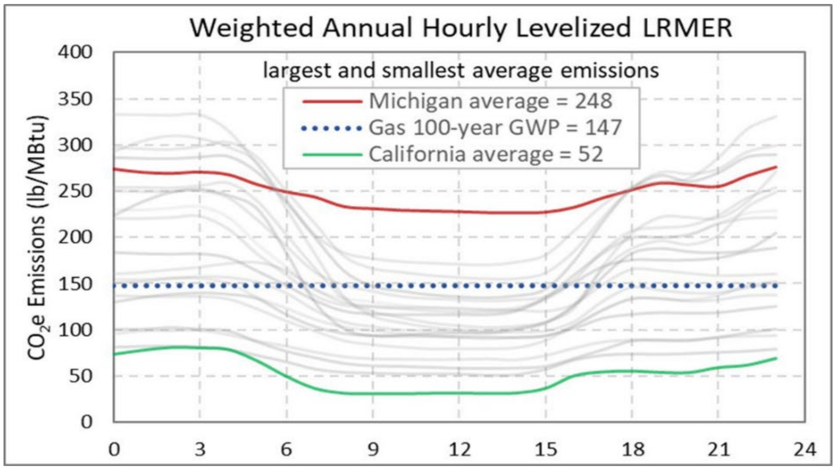
Cambium Generation and Emission Assessment (GEA) regions are almost identical to the EPA eGRID sub-regions. Cambium data are hourly, forward-looking projections while eGRID data are annual, retrospective empirical data.



[17] Discount rate is a societal discount rate that provides greater value for CO_2e emission savings that occur earlier in the evaluation period than for those that occur later in the evaluation period.

What do the Emission Rate Data Look Like?

The largest annual average electric CO_2e emission rate is in Michigan. The smallest is in California. The average of these two is 150 lb/MBtu, which is very close to the natural gas emission rate of 147 lb/MBtu.



How is the CO_2e Index Calculated?

CO_2e Index = ACO_2 / ($ARCO_2$ * IAF_{RH}) * 100

where:

ACO_2 = annual hourly CO_2e emissions from Rated Home

$ARCO_2$ = annual hourly CO_2e emissions from CO_2e Index Reference Home

IAF_{RH} = Index Adjustment Factor for Reference Home

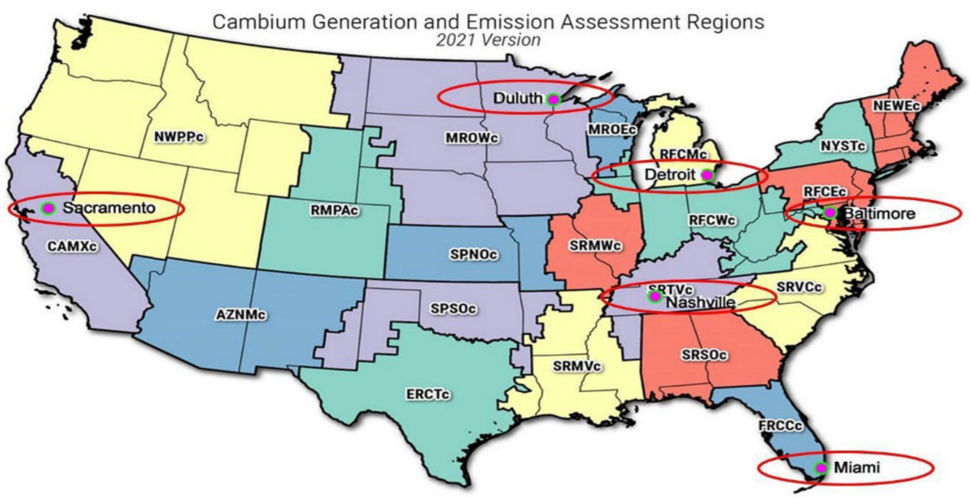
- For all electric homes, a CO_2e Index of 100 would represent the same thing as HERS Index of 100. In other words, the home has the same level of CO_2e emissions as an all-electric home configured to the 2006 IECC minimum requirements with 2006 vintage minimum standard equipment, lighting and appliances
- For mixed-fuel homes configured to these 2006 standards, the CO_2e Index will be greater than 100.

Some Limited EnergyGauge® Simulations

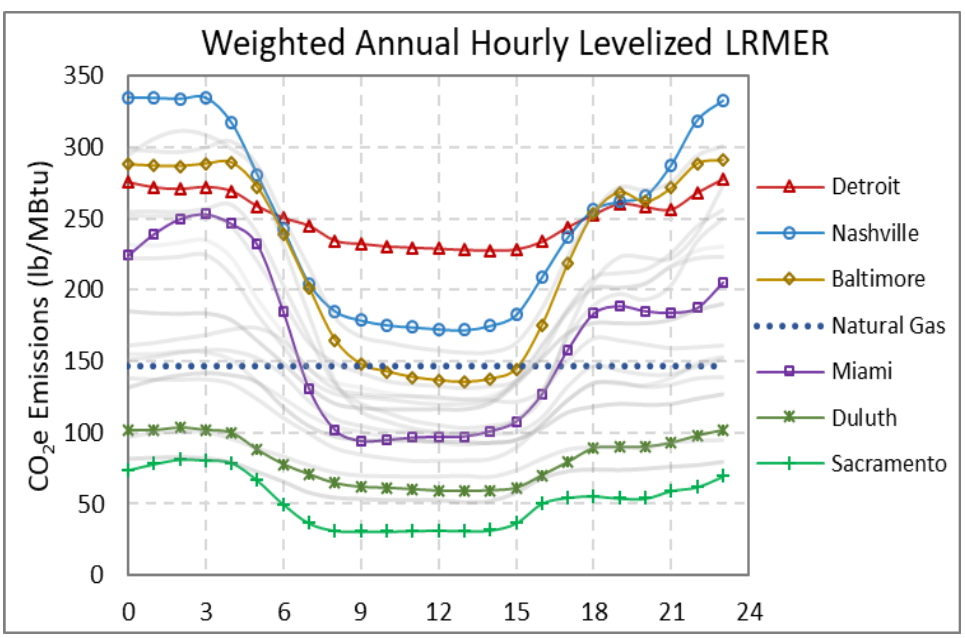
- 2,400 ft2, 2-story, 3-bedroom, vented-crawlspace, frame homes in six locations: Detroit, MI; Nashville, TN; Baltimore, MD; Miami, FL (slab-on- grade); Duluth, MN; and Sacramento, CA.
- Same home geometries used by RESNET's Software Consistency Committee (SCC) for software comparisons.

- Envelope energy features meet minimum 2018 IECC Table R402.1.2 R-value requirements.
- Four equipment, lighting and appliance configurations:
    - Base: HERS Reference HVAC, DHW, Lighting & Appliances
    - HE: High efficiency HVAC, DHW, Lighting & Appliances
    - PV: HE case with 4 kWp-dc PV system
    - **PVbatt**: PV case with a Tesla Powerwall (13.5 kWh)
- Both mixed-fuel and all electric homes are simulated.

Six Different GEA Regions & Climates

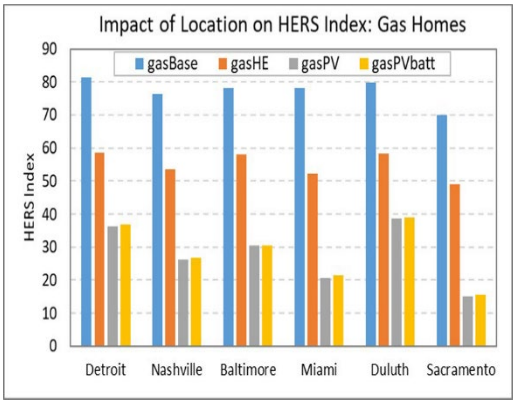


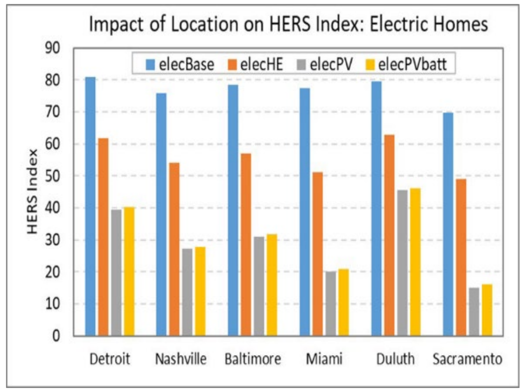
Why do These Locations Matter?



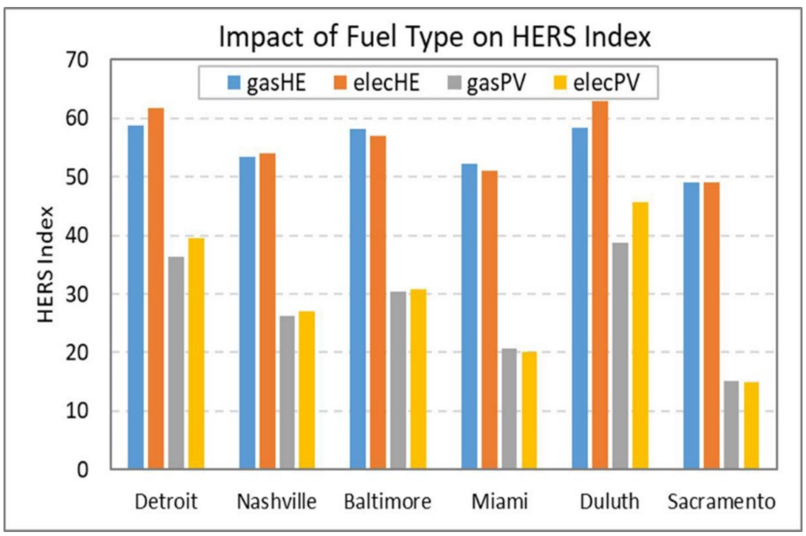
Impact of Location on HERS Index

Similar HERS Index values in all six locations for both fuel types



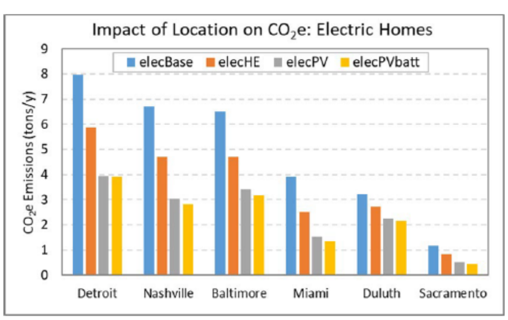


Impact of Fuel Type on HERS Index

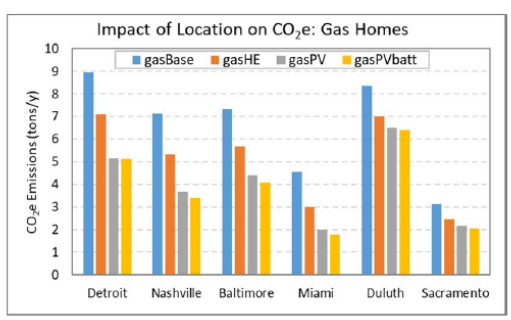


Impact of Location on CO_2e Emissions

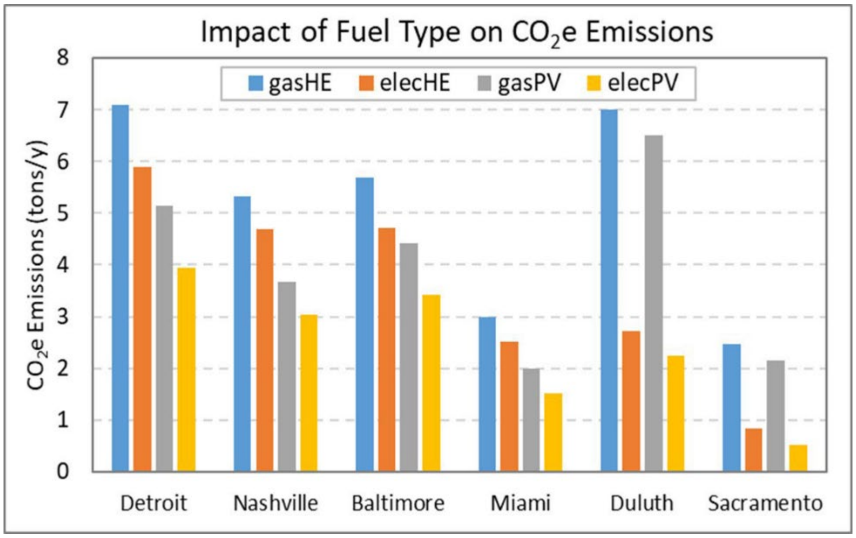
Electric home CO_2e emissions are relatively small in Duluth and Sacramento



Compared to electric home emissions, gas home emissions are large in Duluth and Sacramento

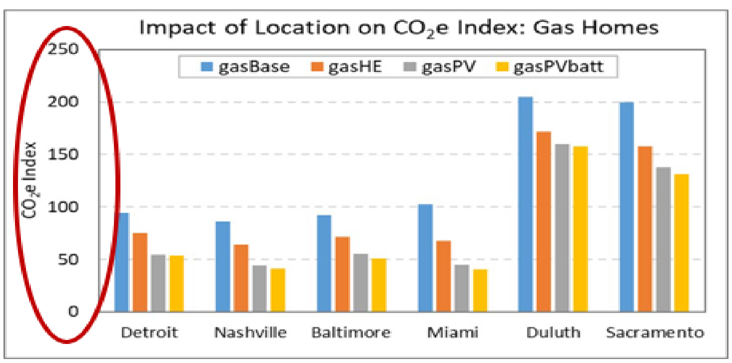


Impact of Fuel Type on CO_2e Emissions

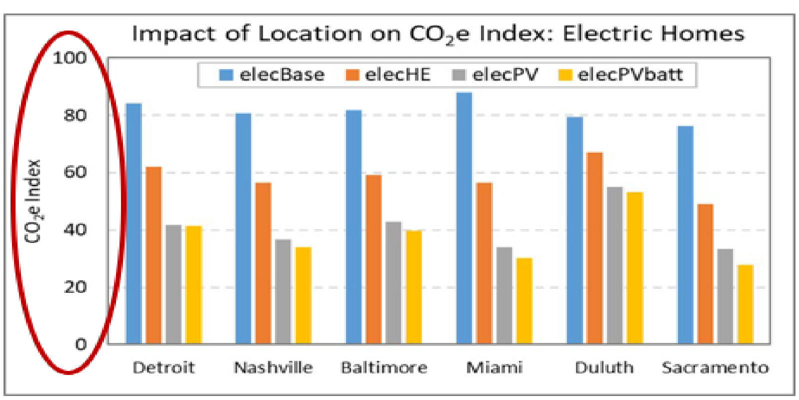


Impact of Location on CO_2e Index

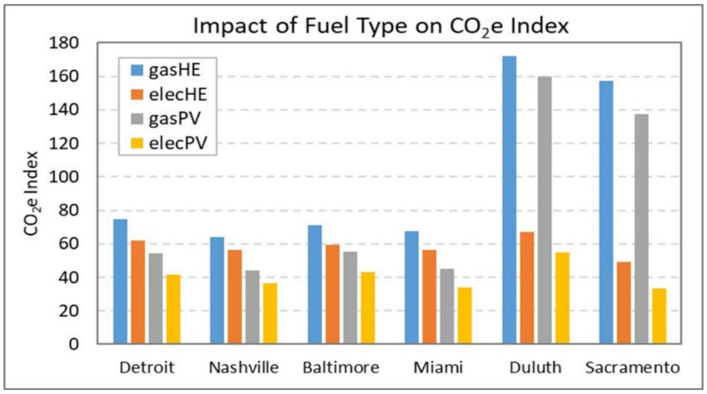
Very large impact in Duluth and Sacramento for gas homes (note y-axis differences)



Similar impact in all locations for electric homes (note large y-axis differences)



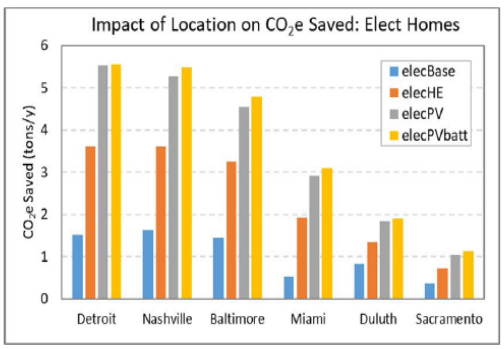
Impact of Fuel Type on CO_2e Index

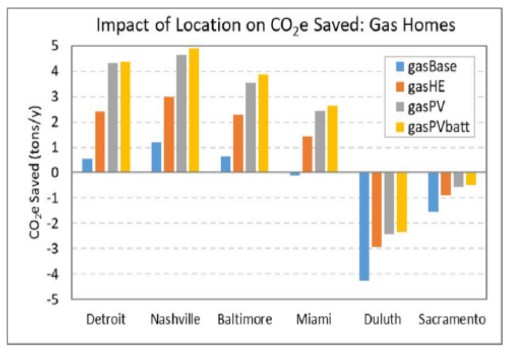


Impact of Location on CO_2e Saved

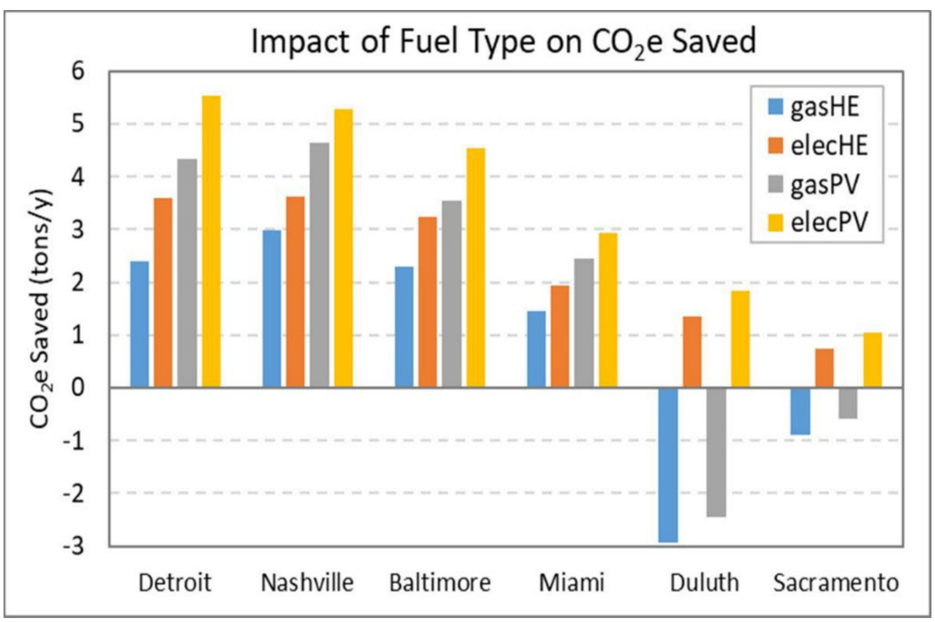
Electric home CO_2e emission savings relative to the CO_2e Reference Home are smallest in Duluth and Sacramento

For gas homes, CO_2e emission savings relative to the CO_2e Reference Home are negative in Duluth and Sacramento



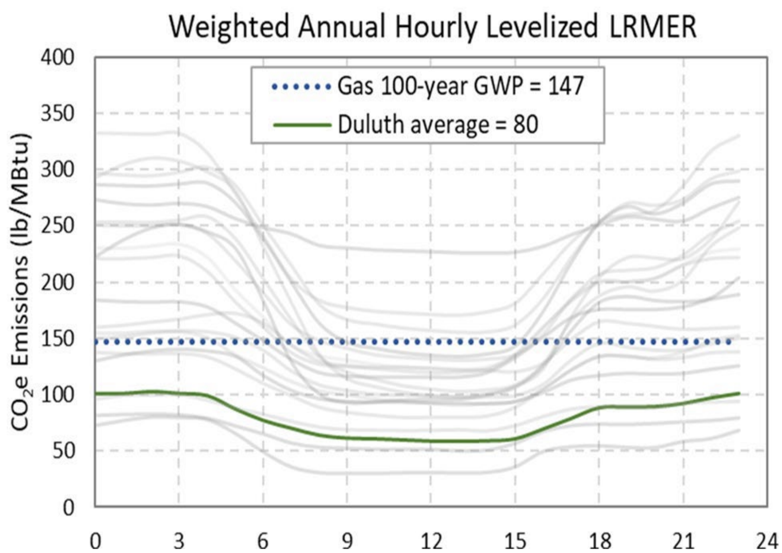


Impact of Fuel Type on CO_2e Saved

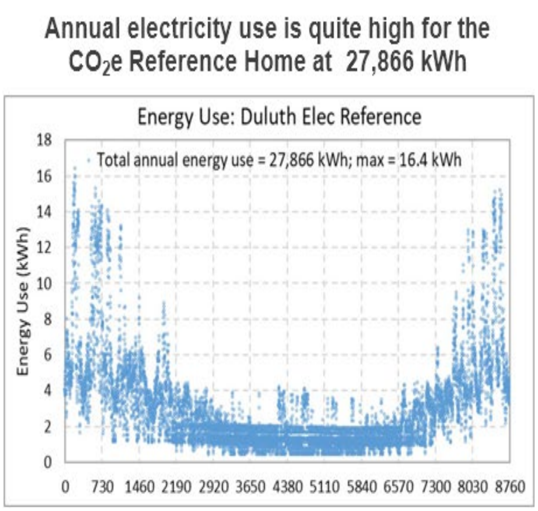


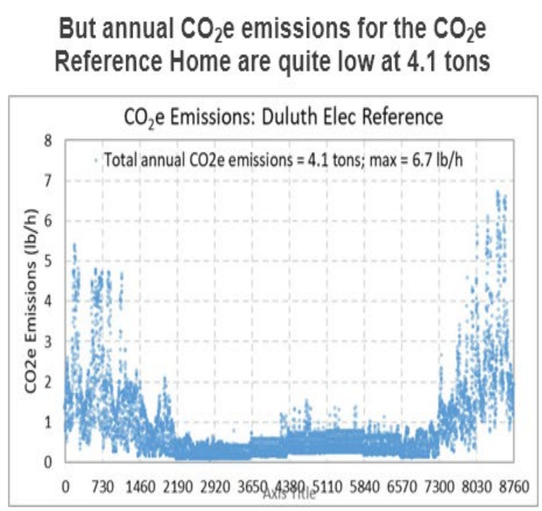
Let's Take A Closer Look at Duluth

- Duluth is located in a GEA region predicted to have large quantities of wind power in coming years
- As a result, forward-looking, levelized long-run emission rates are quite low, averaging only 80 lb/MBtu with gas emission rates significantly greater at 147 lb/MBtu
- Duluth is a very cold climate with large gas space heating energy consumption resulting in large gas emissions.

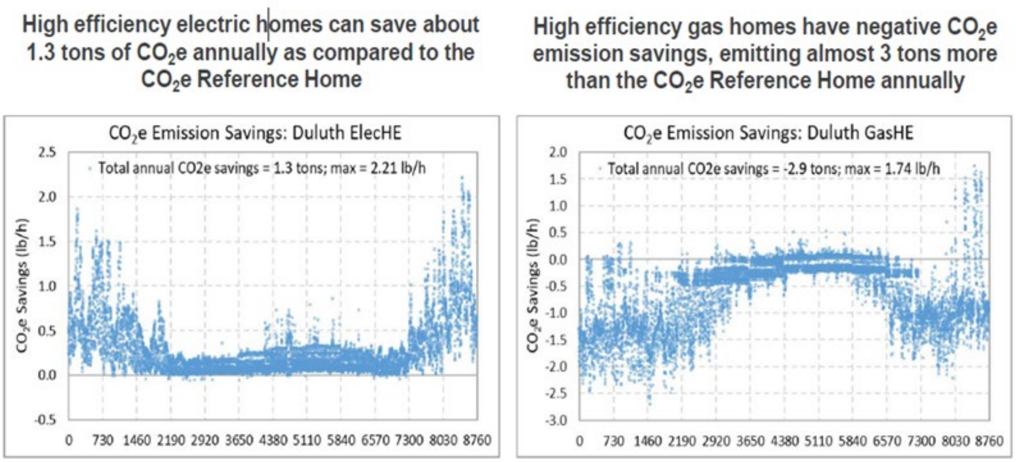


Duluth CO_2e Reference Home





Duluth Hourly CO_2e Emission Savings



Reference vs. Rated Home Emissions

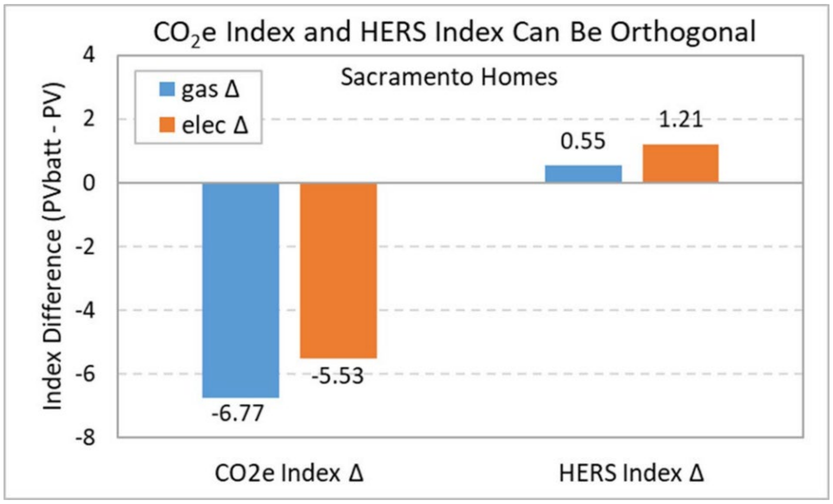
The CO_2e Reference Case emissions in Duluth are significantly smaller than the emissions of all four of the mixed-fuel homes. Note that the conditions for Sacramento are quite similar but the heating requirement is significantly smaller.

CO_2e Emissions (short tons)									
Location	Reference Case	Mixed-fuel homes				Electric Homes			
		gasBase	gasHE	gasPV	gasPVbatt	elecBase	elecHE	elecPV	elecPVbatt
Detroit	9.483	8.944	7.093	5.152	5.100	7.966	5.881	3.940	3.923
Nashville	8.313	7.132	5.333	3.681	3.408	6.693	4.694	3.042	2.833
Baltimore	7.962	7.326	5.676	4.418	4.070	6.509	4.714	3.411	3.162
Miami	4.432	4.542	2.987	1.989	1.791	3.901	2.507	1.509	1.343
Duluth	4.069	8.343	7.000	6.512	6.411	3.232	2.722	2.234	2.161
Sacramento	1.563	3.125	2.461	2.151	2.045	1.189	0.831	0.521	0.435

Carbon and Energy Can be Orthogonal

Energy Storage

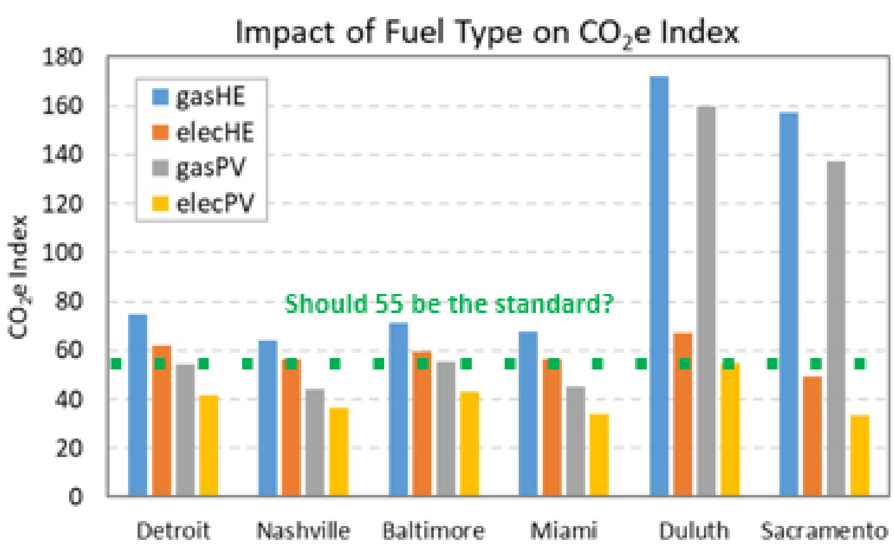
- When battery storage is included in the PV analysis, there is a 10% round trip energy loss associated with the electric energy storage
- While energy storage will normally decrease the CO_2e Index, it will also normally increase the HERS Index
- For these Sacramento homes, the CO_2e Index is considerably reduced while the HERS Index is increased, by more than a point in the electric home.



CO_2e Index Summary

- CO_2e Index calculated using the 2021 Cambium low RE cost scenario, levelized, Long-Run Marginal Emission Rates (LRMER) for CO_2e applied to Rated Home energy end uses as compared against the size adjusted CO_2e emissions for the CO_2e Index Reference Home energy end uses
- CO_2e Savings calculated using the same 2021 Cambium data applied against Rated Home energy end uses subtracted from the CO_2e emissions for the size adjusted CO_2e Index Reference Home energy end uses
- CO_2e Index Reference Home configured identically to the Energy Rating Reference Home except using electricity for all energy end uses
- ERI/HERS Index calculation is not changed

Should a CO_2e Index Standard be Established?



Appendix - References

1. RESNET MINHERS Standard Addendum 66f, PDS- 02
2. BSR/RESNET/ICC 301-2022, Addendum B-202x, PDS-01
3. Cambium Online Database: https://cambium.nrel.gov/
4. Cambium Documentation:
5. Gagnon, Pieter; Frazier, Will; Hale, Elaine, Cole, Wesley (2022): Long-run Marginal Emission Rates for Electricity - Workbooks for 2021 Cambium Data. National Renewable Energy Laboratory, Golden, CO. https://data.nrel.gov/submissions/183