Modeled Results of Four Residential Energy Efficiency Measure Packages for Deriving Advanced Building Construction Research Targets

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1 National Renewable Energy Laboratory
2 Lawrence Berkeley National Laboratory

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Office of Energy Efficiency & Renewable Energy
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June 2023

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List of Acronyms

ABC	Advanced Building Construction
ACH50	air changes per hour at 50 Pa
ASHP	air-source heat pump
ERV	energy recovery ventilator
EUI	energy use intensity
HRV	heat recovery ventilator
HSPF1	heating seasonal performance factor (pre-2023 version of the metric)
HVAC	heating, ventilating, and air conditioning
IECC	International Energy Conservation Code
MSHP	mini-split heat pump
NPV	net present value
SEER1	seasonal energy efficiency ratio (pre-2023 version of the metric)
SHGC	solar heat gain coefficient

Executive Summary

The Advanced Building Construction (ABC) Initiative from the U.S. Department of Energy Building Technologies Office is working to accelerate industrialized construction innovations for decarbonizing buildings. To inform performance and cost targets for research under the ABC Initiative, this analysis used the ResStock™ tool to evaluate the energy savings, utility bill impacts, and carbon emissions impacts of four simulated upgrade packages with specific target performance levels on a large sample of residential dwelling units (approximately 550,000) representative of the U.S. housing stock.

The four upgrade packages simulated were:

1. *All Equipment Swap-Outs*: Replacing the end-use equipment with high-efficiency electric equipment.
2. *Market-Ready Envelope*: Swapping out end-use equipment and upgrading the building envelope with market-ready solutions.
3. *IECC Envelope*: Swapping out end-use equipment and upgrading to the 2021 International Energy Conservation Code (IECC) residential prescriptive path building envelope requirements.
4. *PHIUS Envelope*: Swapping out end-use equipment and upgrading to the 2021 PHIUS standard building envelope requirements.

The key takeaways from the analysis are:

- Equipment-only upgrades are estimated to lead to increased utility bills in about 10% of dwelling units (using 2019 prices). However, we only assessed one model of ducted variable-speed heat pump, which did not meet typical “cold climate” heat pump specifications. This finding will be very sensitive to the details of the heat pump efficiency level and installation configuration being modeled.
- Equipment-only bill increases are related to price of electricity relative to natural gas, heating oil, and propane prices. The results presented here use 2019 prices, and results will change with fluctuations in the prices of these fuels.
- Building envelope upgrades can significantly mitigate these bill increases, with negative bills occurring in 4%, 2%, and 1% of homes for the *Market-Ready Envelope*, *IECC Envelope*, and *PHIUS Envelope* packages, respectively.
- If implemented prior to installing the heat pumps, these envelope packages can significantly reduce required heat pump capacities and potentially avoid electrical and ductwork upgrades, saving on upfront investment costs.
- The net present value of utility bill savings from this analysis can be used to inform cost compression targets for the ABC Initiative.
- All package performance levels are expected to reduce carbon equivalent emissions in every state, regardless of future grid scenario.

These findings and subsequent analysis were used to inform the forthcoming *Market Guidance to Scale Zero-carbon Aligned Residential Buildings*. Subsequent work will be necessary to explore additional sensitivities, including heat pump efficiency levels and cold climate performance.

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Introduction

Residential buildings account for 21% of total electricity consumption [1] and 20% of carbon emissions [2] in the United States. Substantially decarbonizing new and existing residential buildings is necessary to meet the urgency of climate change; however, care must be taken so that the process addresses energy cost burdens and historical inequities in underserved communities, instead of exacerbating them.

The Advanced Building Construction (ABC) Initiative from the U.S. Department of Energy Building Technologies Office is working to accelerate industrialized construction innovations for decarbonizing buildings. To inform research targets for the ABC Initiative, this analysis evaluated the energy savings, utility bill impacts, and carbon emissions impacts of four simulated upgrade packages with specific target performance levels on a large sample of residential dwelling units (approximately 550,000) representative the U.S. housing stock. Motivating research questions for our work include:

- What are the expected energy savings and carbon emissions reductions resulting from different package performance levels in different regions and building segments?
- How do these savings vary geographically and across different segments of the building stock?
- What are the expected energy bill impacts of swapping out all fossil-based end-use equipment with electric equipment, with and without envelope upgrades?
- What cost targets for ABC innovations would be required for customers or financing organizations to break even, based on modeled package annual energy cost savings?

Methodology

Workflow Overview

Figure 1 shows the workflow we used for this analysis, which includes four main steps: (1) define analysis inputs, (2) run simulations, (3) post-process results, and (4) visualize and interpret results.

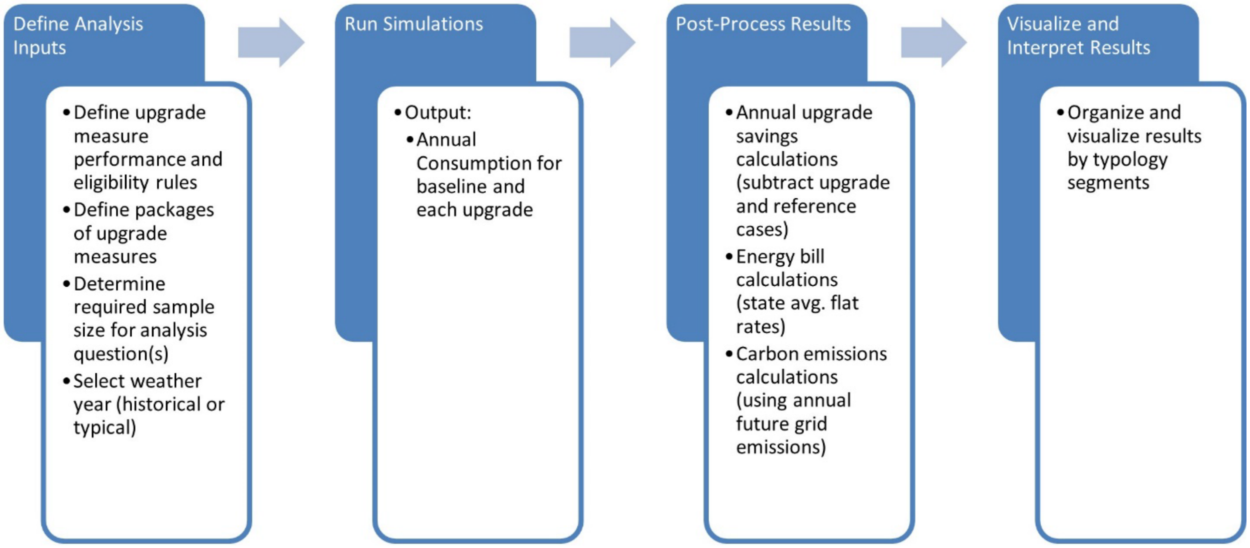

Figure 1. Analysis workflow

1. Define Analysis Inputs

First, upgrade package performance levels were defined with guidance from the ABC analysis working group, including representatives from RMI (formerly Rocky Mountain Institute), Association for Energy Affordability, Vermont Energy Investment Corporation, Phius (formerly Passive House Institute US), Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory, and Building Technologies Office. Because the Building Technologies Office and many state, local, and industry stakeholders see building electrification as a key element of building decarbonization, the working group decided that all upgrade packages should include swapping out all major fossil-based end-use equipment for high-efficiency electric equipment (described in Table 1). These equipment swap-outs are the basis for the first package. The working group decided to also include upgrades to high-efficiency LED lighting and major electric appliances like refrigerators, because they are "low-hanging fruit" that could be easily added to a retrofit program.

For the remaining three packages, the working group decided to apply three different levels of thermal envelope upgrades alongside the equipment swap-outs, to understand the impact of the envelope upgrades on equipment sizing, energy bills, and carbon emissions. The *Market-Ready Envelope* package includes a few shallow envelope improvements. The *IECC Envelope* package goes deeper by upgrading insulation, windows, and air sealing to 2021 International Energy Conservation Code (IECC) residential prescriptive path building envelope requirements. The *PHIUS Envelope* package goes even deeper by upgrading insulation, windows, and air sealing to the 2021 PHIUS standard. These packages are described in more detail in Package Definitions.

In summary, the four retrofit packages considered in the study were:

1. *All Equipment Swap-Outs*: Replacing the end-use equipment with high-efficiency electric equipment.
2. *Market-Ready Envelope*: Swapping out end-use equipment and upgrading the building envelope with market-ready solutions.

3. *IECC Envelope*: Swapping out end-use equipment and upgrading to the 2021 IECC residential prescriptive path building envelope requirements.
4. *PHIUS Envelope*: Swapping out end-use equipment and upgrading to the PHIUS standard building envelope requirements.

These packages, with performance levels that vary by climate region, were applied to the entire stock of residential dwelling units in the contiguous United States, including mobile homes and high-rise multifamily buildings. We acknowledge that certain aspects of the packages, such as installing ductless heat pumps to serve high-rise multifamily buildings, may not be feasible in real life. However, modeling the packages in all building types is still useful for understanding the potential impacts of alternative upgrade solutions.

2. Run Simulations

Second, we simulated the retrofit packages using the National Renewable Energy Laboratory's ResStock™ tool capable of modeling the existing residential building stock with a high degree of granularity. For more details on the ResStock methodology for building stock characterization and sampling, see Wilson et al. [3].

The state of ResStock for this analysis was August 2, 2021,[1] which includes all changes made to ResStock as part of an extensive calibration and validation effort in 2019–2021 [4].

3. Post-Process Results

Third, we analyzed the results and computed various metrics including site energy use intensity (EUI) and utility bill savings. We calculated the site EUI of the dwelling units for each upgrade package. For calculating the annual utility bill savings from the upgrade packages, we first calculated the utility bill for each package using state average flat rates (described in the Methodology for Utility Bill Calculation section). We then calculated the annual upgrade savings for each upgrade by comparing the utility bill of the upgrade with the reference case.

4. Visualize and Interpret Results

This step involved organizing the results by typology segments (as defined in Reyna et al. [5]) to gain insights into the variation by climate zone, building type, vintage, and other parameters. We then visualized and interpreted the results in different ways.

Package Definitions

Package 1: All Equipment Swap-Outs

The *All Equipment Swap-Outs* package includes upgrades that replace all major fossil-fuel-using equipment with high-efficiency electric equipment counterparts, including equipment for space heating, water heating, cooking, and clothes drying. It also upgrades all lighting to 100% LED (83 lumens/watt) and upgrades all major appliances to performance levels representing ENERGY STAR® or ENERGY STAR Most Efficient as of 2021 (see details in Table 1). This choice makes the package more expensive while also making the savings better compared to a

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[1] The state of the ResStock GitHub repository for the analysis can be found at https://github.com/NREL/resstock/tree/run/abctypology.

more bare-bones electrification package. Miscellaneous gas end uses such as pool heaters and gas fireplaces are not changed. The components of this package are listed in Table 1.

In this package, all water heaters are replaced with an 80-gallon heat pump water heater with Uniform Energy Factor (UEF) 2.4. We acknowledge that many homes may not be able to fit 80-gallon heat pump water heater tanks, especially if they are currently served by small 30-gallon electric tanks or central hot water boilers, but chose to model a single technology for simplicity. Modern heat pump water heaters typically have ratings around 3.4, so water heater energy savings for this analysis are conservative.

For heating, ventilating, and air conditioning (HVAC), homes with existing ducts receive a ducted air-source heat pump (ASHP), whereas homes without ducts receive a ductless air-source heat pump with mini-split form factor (MSHP). The modeled ducted ASHP retains about 50% of maximum heat output at 5°F and 25% at −15°F, so this is not considered a cold climate heat pump. The modeled ductless MSHP retains about 25% at −5°F. Both heat pump models were autosized to have their nominal capacity sized based on the larger of heating and cooling design loads while taking into account the heat pump’s reduced capacity at the design temperature. Ducts located in unconditioned space are upgraded to 10% leakage, R-8 insulation.

Table 1. Details of *All Equipment Swap-Outs* Package

Package Upgrades	Upgrade Details	Upgrade Condition
Heat pump water heater	80 gal; UEF around 2.4	All homes
Heat pump HVAC	Ducted ASHP, SEER1[a] 22, 10 HSPF1[b] • Sized for larger of design heating or cooling load • Retains about 50% of maximum heat output at 5°F and 25% at −15°F (not cold climate heat pump) • Backup electric resistance used to supplement when necessary and below 0ºF	Homes with ducts
	Ductless MSHP, SEER1 17, 9.5 HSPF1 • Sized for larger of design heating or cooling load • Retains about 25% of maximum heat output at −5°F • Backup electric resistance used to supplement when necessary	Homes without ducts
Duct sealing/insulation	All ducts in unconditioned space sealed to 10% leakage and insulated to R-8	All homes
Lighting	100% LED (83 lumens/watt)	All homes
Dryer	ENERGY STAR Most Efficient, heat pump, ventless (CEF[c] = 5.2)	All homes
Refrigerator	ENERGY STAR (EF[d] 21.9, 348 rated kWh/yr)	All homes
Clothes washer	ENERGY STAR Most Efficient (IMEF[e] = 2.92)	All homes
Dishwasher	ENERGY STAR (144 rated kWh/yr)	All homes
Cooking range	Induction cooktop and electric resistance oven (Cooktop_ef = 0.84, Oven_ef = 0.11)	All homes

[a] Seasonal energy efficiency ratio (pre-2023 version of the metric); [b] heating seasonal performance factor (pre-2023 version of the metric); [c] combined energy factor; [d] energy factor;
[e] integrated modified energy factor.

Package 2: Market-Ready Envelope

This package includes all the upgrades in the *All Equipment Swap-Outs* package plus additional envelope upgrades listed in Table 2. These *Market-Ready Envelope* upgrades include attic air-sealing and attic insulation, R-6.5 wall insulation, and low-e storm windows. Each of the upgrades have necessary existing conditions in order to be applied, and thus not all the upgrades are necessarily applied in every home.

Table 2. Details of *Market-Ready Envelope* Package

Package Upgrades	Upgrade Details	Upgrade Condition
Attic floor air-sealing and insulation	R-values follow 2021 IECC	Homes with vented attic and attic R-value less than 2021 IECC
R-6.5 wall insulation with re-siding	R-6.5 of continuous wall insulation—e.g., 1 inch of rigid polyisocyanurate board installed under new siding or over masonry	Homes older than 1990 with less than R-19 wall insulation
Low-e storm window	Exterior low-e storm windows	Homes with single- and double-pane windows

Homes with vented attics and attic floor R-values less than those specified in the 2021 IECC code receive the attic air-sealing and insulation upgrade. Because attic floor insulation often cannot be applied at full thickness near eaves, as shown in Figure 2 [6], a derate is applied to determine the effective attic insulation level used in modeling the packages for each climate zone (see Table 3). The derate was calculated using attic perimeter insulation calculations in BEopt [7] based on average attic perimeters from ResStock.

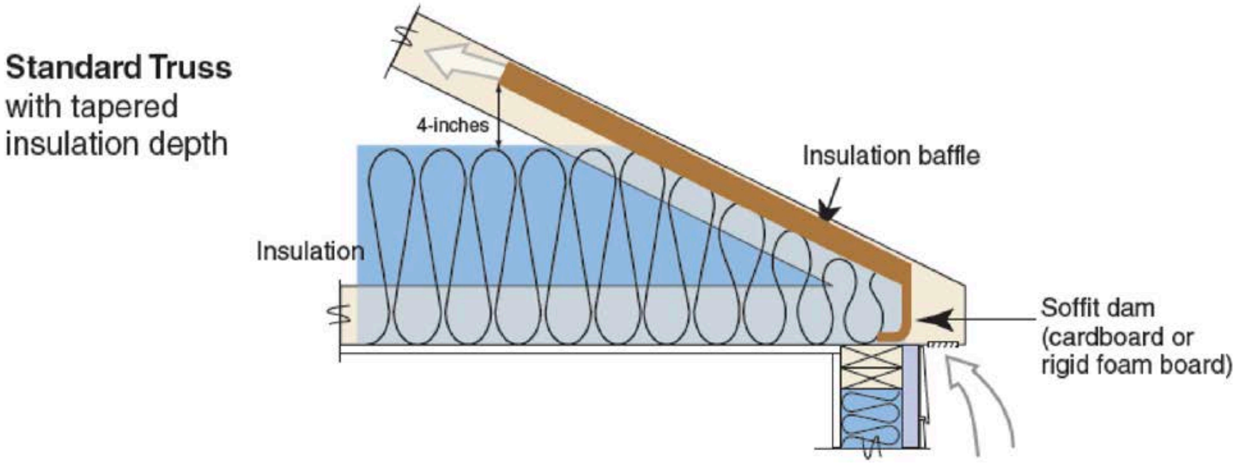


Figure 2. Standard roof trusses are narrow at the eaves, preventing full insulation thickness over the top plate of the exterior walls.

Source: Georgia Department of Community Affairs [6]

The attic insulation level for each climate zone is specified in Table 3.

Table 3. Attic Insulation for *Market-Ready Envelope* Upgrade

Climate Zone	Attic Floor R-value, Nominal	Attic Floor R-value, Effective
1	30	29
2–3	49	44
4–7	60	51

Similarly, exterior low-emissivity (low-e) storm windows are added to the homes with preexisting single- and double-pane windows. These exterior storm windows can reduce the air infiltration and conductive heat transfer associated with the window. The U-value and solar heat gain coefficient (SHGC) for windows with and without low-e storm windows are shown in Table 4.

Table 4. Window Properties With and Without Addition of Low-E Windows

Primary Window Type	Without Storm Window		With Low-E Storm Window	
	U-Value	**SHGC**	**U-Value**	**SHGC**
Single-pane, clear, metal frame	1.16	0.76	0.69	0.59
Single-pane, clear, non-metal frame	0.84	0.63	0.40	0.48
Double-pane, clear, metal frame	0.76	0.67	0.38	0.51
Double-pane, clear, non-metal frame	0.49	0.56	0.29	0.42

R-6.5 continuous wall insulation with re-siding is added in homes meeting two conditions. First, the vintage of the homes should be earlier than 1990 so that the siding is at least 30 years old. Second, the wall insulation of the home should be less than R-19. This upgrade is a generic performance level that can be achieved with currently available or emerging insulation materials, but agnostic of the specific technology used. Rigid polyisocyanurate insulation board (1-inch thickness) would be a typical example of a product achieving this performance level.

All three upgrades in the *Market-Ready Envelope* package have associated reductions in air infiltration. The air leakage reduction from each upgrade of *Market-Ready Envelope* is provided in Table 5 [8, 9]. The whole-home air leakage reduction due to the upgrades is calculated using Equation 1:

$$\left(1-(1-r_1)\times(1-r_2)\times(1-r_3)\right) \tag{1}$$

Where r_1, r_2, and r_3 represent the air leakage reduction from each upgraded envelope component.

For instance, let us consider a home with single-pane windows and no storm windows and a vented crawlspace where all three of these upgrades apply. In this case, the air leakage reduction from attic air sealing is 8%, R-6.5 wall insulation upgrade is 13%, and low-e storm window upgrade is 21%. Thus, the whole-home air leakage reduction is calculated to be 37%.

Table 5. Air Leakage Reduction

Upgraded Envelope Component	Vented Crawlspace	Other Than Vented Crawlspace
Attic air-sealing and insulation	8%	13%
R-6.5 wall insulation with re-siding	13%	19%
Window upgrade for single-pane without storm window	21%	30%
Window upgrade for double-pane or single-pane with storm window	7%	10%

Energy recovery ventilators (ERVs) or heat recovery ventilators (HRVs) are provided in homes with post-retrofit air infiltration rates less than 7 ACH50 (air changes per hour at 50 Pa). The efficiency of ERV and HRV upgrades are provided in Table 6, based on the forthcoming Phius Ventilator Product Certification.

Table 6. Efficiency of Ventilation System by Climate Zone[a]

Climate Zone	Ventilation System	Sensible Recovery Efficiency	Total Recovery Efficiency
1A	ERV	NR[b]	60%
2A	ERV	60%	60%
2B	ERV	50%	60%
3A	ERV	70%	60%
3B	HRV	70%	NR
3C	HRV	60%	NR
4A	ERV	80%	50%
4B	HRV	75%	NR
4C	HRV	70%	NR
5A	HRV	85%	NR
5B	HRV	80%	NR
6 (6A and 6B)	HRV	85%	NR
7 (7A and 7B)	HRV	85%	NR

[a] Values are based on calculation of the recovery efficiency needed to deliver 60 ºF air with outside air at the coldest average month temperature. Using calculations from 1,000 climate locations, the table values are halfway between the maximum and the mean value for locations in each zone, rounded to the nearest 5%. Source: Phius Ventilator Product Certification (forthcoming).

[b] Not reported; total recovery efficiency is not reported for HRVs.

Package 3: IECC Envelope

This package includes all the upgrades in *All Equipment Swap-Outs* plus envelope upgrades achieving performance levels consistent with the 2021 IECC Residential prescriptive path [10, 11], including the insulation of wall, floor, foundation wall, and window U-values and SHGCs (Table 7). *IECC Envelope* upgrades are applied to all the residential buildings with lower efficiency envelopes than *IECC Envelope* specifications, and are also applied to mobile homes and multifamily buildings with more than three stories. We recognize that there may not yet exist easy or practical methods to achieve these performance levels via retrofit at scale; the purpose of this analysis is to explore the hypothetical savings that could be achieved from a package that achieves a similar envelope performance level, even if some of the specifics are different.

Table 7. Details of *IECC Envelope* Package Upgrade, Based on 2021 IECC Prescriptive Path Specifications

Climate Zone	Window U-factor	Window SHGC	Ceiling R-value	Wall R-value	Floor R-value	Foundation Wall R-value
1	0.40	0.25	30	13	13	0
2	0.40	0.25	49	13	13	0
3	0.30	0.25	49	20	19	5
4 except Marine	0.30	0.40	60	20	19	10
5 and Marine 4	0.30	0.40	60	20	30	15
6	0.30	0.40	60	30	30	15
7 and 8	0.30	0.40	60	30	30	15

In this package, envelope air leakage is reduced to 3 ACH50 for homes with a leakage rate greater than 3 ACH50. ERV and HRV upgrades are included as detailed in the *Market-Ready Envelope* upgrade package.

Package 4: PHIUS Envelope

This package includes all the upgrades in package 1 (*All Equipment Swap-Outs*) with the addition of the *PHIUS Envelope* upgrades (Table 8). The building envelope in this package is aligned with the 2021 PHIUS prescriptive specification [12]. This package is applied to all residential buildings with lower efficiency envelopes than what is specified in PHIUS, including mid- and high-rise residential buildings. The air leakage rate is reduced to 1 ACH50, and it is assumed that there are no duct losses in crawlspaces or attics as these spaces are fully brought within the thermal envelope. As with the *IECC Envelope* package, we recognize that there may not yet exist easy or practical methods to achieve these performance levels via retrofit at scale; the purpose of this analysis is to explore the hypothetical savings that could be achieved from a package that achieves a similar envelope performance level, even if some of the specifics are different.

Table 8. Details of *PHIUS Envelope* Package

Climate Zone	Window U-factor	Window SHGC	Ceiling R-value	Wall and Floor R-value	Foundation Wall R-value	Slab Edge R-value
1A	0.5	0.25	R-51	R-22	R-7	2-ft R-7
2A	0.28	0.25	R-56	R-27	R-10	2-ft R-10
2B	0.29	0.25	R-56	R-27	R-13	2-ft R-13
3A	0.23	0.25	R-61	R-31	R-13	2-ft R-13
3B	0.28	0.25	R-60	R-30	R-14	2-ft R-14
3C	0.32	0.25	R-59	R-30	R-10	2-ft R-10
4A	0.19	0.25	R-66	R-36	R-17	2-ft R-17
4B	0.18	0.25	R-67	R-37	R-17	2-ft R-17
4C	0.24	0.4	R-65	R-35	R-16	2-ft R-16
5A	0.16	0.4	R-72	R-42	R-21	2-ft R-21
5B	0.17	0.4	R-69	R-39	R-19	2-ft R-19
6A	0.13	0.4	R-77	R-46	R-24	2-ft R-24
6B	0.14	0.4	R-75	R-44	R-23	2-ft R-23
7A	0.12	0.4	R-82	R-51	R-30	2-ft R-30
7B	0.12	0.4	R-82	R-51	R-30	2-ft R-30

Methodology for Utility Bill Calculation

We calculated utility bills based on the electricity, natural gas, propane, and residential fuel oil used. In all cases, we used 2019 tariff data downloaded in late June and early July 2021.

For electricity bill calculations, we used OpenEI's Utility Rate Database [13] to calculate the customer-weighted national average fixed monthly electricity charge as:

$$\frac{\sum Fixed\ electric\ charge\ x\ Number\ of\ customers}{\sum Number\ of\ customers} \tag{2}$$

across all utilities in the database. We also downloaded state average residential electricity data from the U.S. Energy Information Administration [14], including total revenue (in thousands of dollars), total sales (in megawatt-hours), and total customers (quantity), which allowed us to calculate the variable electricity rate for each state:

$$\frac{Total\ Revenue-(Fixed\ Cost*Number\ of\ Customer)}{Total\ Sales} \tag{3}$$

This methodology resulted in a fixed residential electric utility customer cost of \$10/customer/month, which we used throughout the United States, and a fixed (not time-sensitive or tiered) per-unit residential electric utility customer rate for each state that varied from \$0.087/kWh in Washington state to \$0.204/kWh in Connecticut.

For natural gas bill calculations, we used the American Gas Association's value of $11.25/customer/month [15] for the fixed portion of the utility bill (generally referred to as the "customer charge"). We downloaded 2019 data by state on price [16], consumption [17], and number of customers [18], and then calculated the volumetric rate for each state as:

$$\frac{(Consumption * Price) - (Fixed\ Cost * Number\ of\ Customers)}{Total\ Sales} \tag{4}$$

The results ranged from $0.43/therm in New Mexico to $1.47/therm in Florida. The $135/year gas customer charge is only applied to homes that use some amount of natural gas. Thus, it is not included in energy costs for the upgrade packages that result in homes becoming all-electric. For this purpose, we ignore miscellaneous gas end uses such as pool heaters and gas fireplaces.

For residential fuel oil and propane bill calculations, we used weekly data from the U.S. Energy Information Administration covering the 2018–2019 winter [19, 20]. We averaged the available weeks for each state. When state-level data were not available, we used data from the state's Petroleum Administration for Defense District (PADD). When these data were not available, we used the U.S. national average.

Results

We simulated the U.S. residential building stock with a sample of 550,000 dwelling units for the baseline and all four package upgrades using ResStock. We leveraged high-performance computing at the National Renewable Energy Laboratory to perform the simulation and post-processing of the results. This section describes the comparative analysis of the package upgrades comparing site EUI and utility bill savings.

Site Energy Use Intensity

The site EUI (kBtu/sf) for each residential building is calculated using Equation 5:

$$Site\ EUI = \frac{Total\ site\ energy\ (kBtu)}{Total\ conditioned\ area\ (sf)} \tag{5}$$

The median (± standard deviation) site EUI for each upgrade package across different climate zones and vintages is shown in Figure 4.

A map of the Building America climate zones is shown in Figure 3 for reference. The high standard deviations signify that the variability in the distribution of site EUI values is large. In comparing the site EUI for upgrade packages with the baseline case, we observe that the reduction in site EUI was largest for the *All Equipment Swap-Outs* package. The additional reductions from the envelope packages are smaller, although this is partially explained by the order in which the packages are applied. As expected, upgrading the building envelope results in the site energy consumption (and thus the site EUI) decreasing. The reduction in site EUI is most pronounced in the Cold & Very Cold climate region.

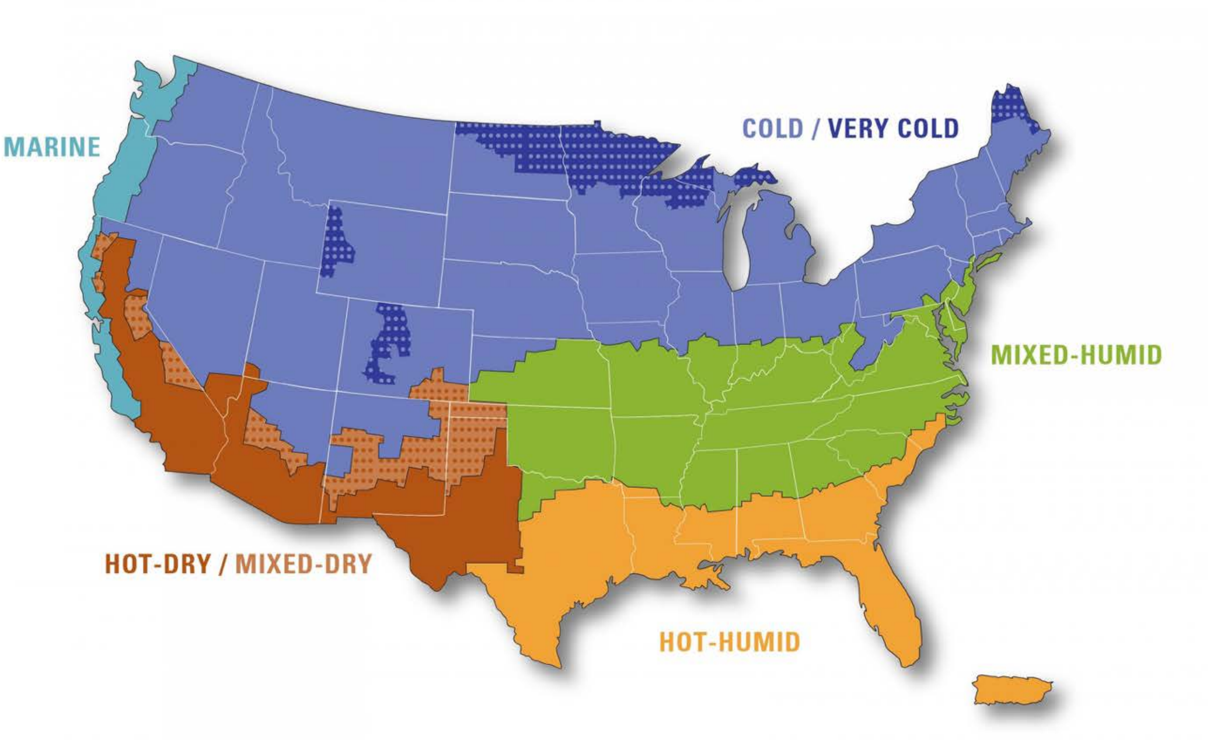
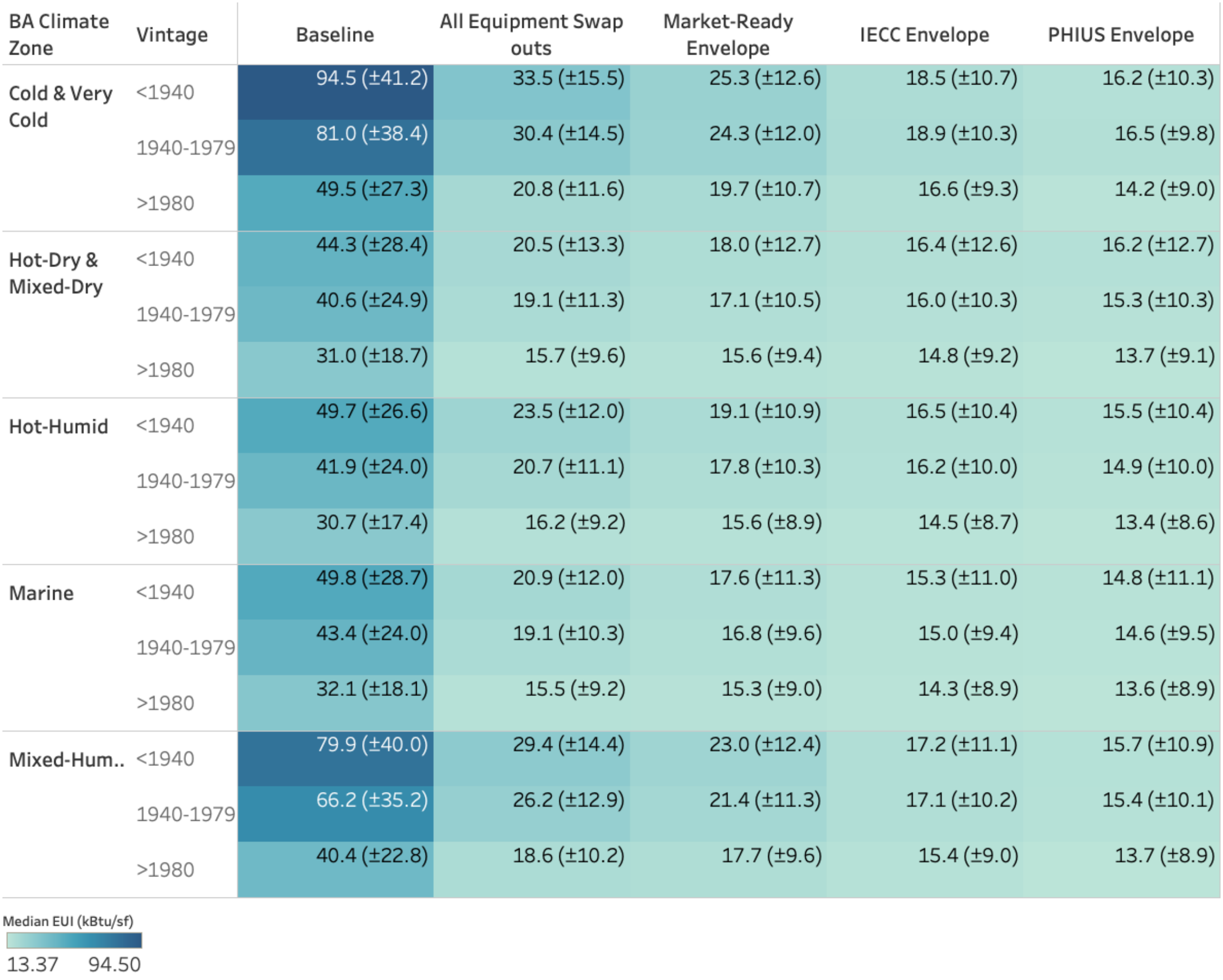


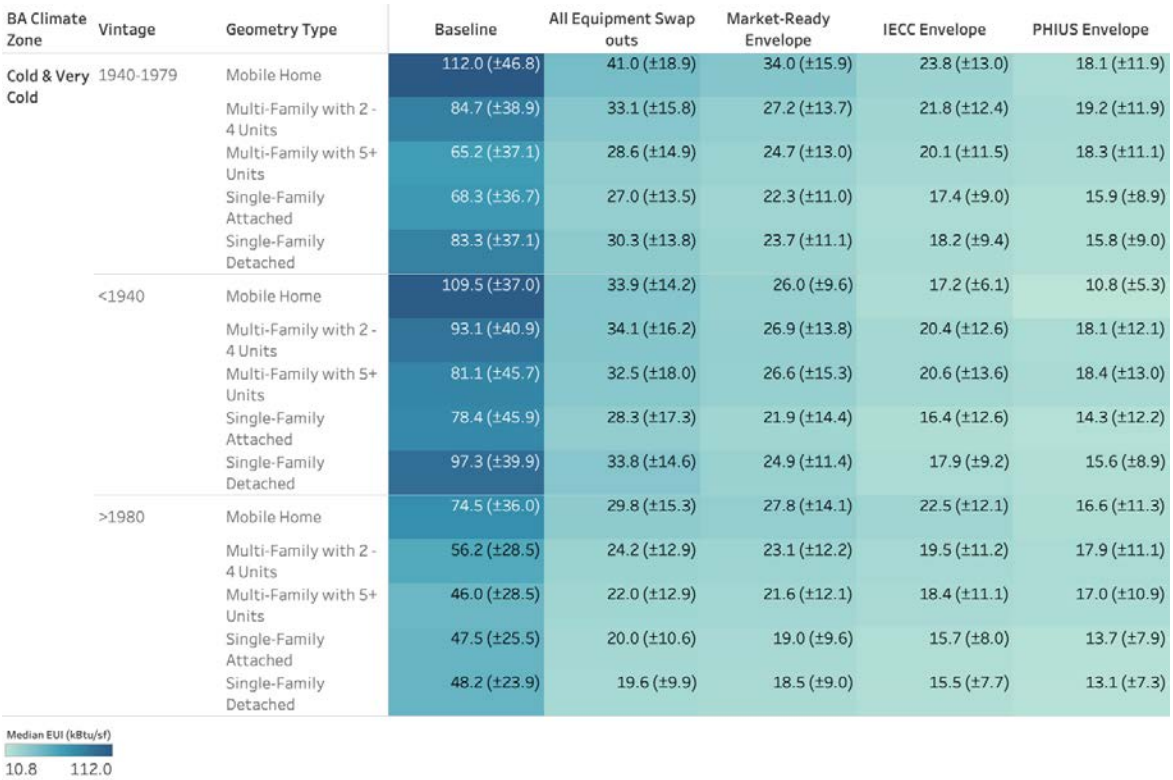
Figure 3. Building America climate zone map



BA Climate Zone	Vintage	Baseline	All Equipment Swap outs	Market-Ready Envelope	IECC Envelope	PHIUS Envelope
Cold & Very Cold	<1940	94.5 (±41.2)	33.5 (±15.5)	25.3 (±12.6)	18.5 (±10.7)	16.2 (±10.3)
	1940-1979	81.0 (±38.4)	30.4 (±14.5)	24.3 (±12.0)	18.9 (±10.3)	16.5 (±9.8)
	>1980	49.5 (±27.3)	20.8 (±11.6)	19.7 (±10.7)	16.6 (±9.3)	14.2 (±9.0)
Hot-Dry & Mixed-Dry	<1940	44.3 (±28.4)	20.5 (±13.3)	18.0 (±12.7)	16.4 (±12.6)	16.2 (±12.7)
	1940-1979	40.6 (±24.9)	19.1 (±11.3)	17.1 (±10.5)	16.0 (±10.3)	15.3 (±10.3)
	>1980	31.0 (±18.7)	15.7 (±9.6)	15.6 (±9.4)	14.8 (±9.2)	13.7 (±9.1)
Hot-Humid	<1940	49.7 (±26.6)	23.5 (±12.0)	19.1 (±10.9)	16.5 (±10.4)	15.5 (±10.4)
	1940-1979	41.9 (±24.0)	20.7 (±11.1)	17.8 (±10.3)	16.2 (±10.0)	14.9 (±10.0)
	>1980	30.7 (±17.4)	16.2 (±9.2)	15.6 (±8.9)	14.5 (±8.7)	13.4 (±8.6)
Marine	<1940	49.8 (±28.7)	20.9 (±12.0)	17.6 (±11.3)	15.3 (±11.0)	14.8 (±11.1)
	1940-1979	43.4 (±24.0)	19.1 (±10.3)	16.8 (±9.6)	15.0 (±9.4)	14.6 (±9.5)
	>1980	32.1 (±18.1)	15.5 (±9.2)	15.3 (±9.0)	14.3 (±8.9)	13.6 (±8.9)
Mixed-Hum..	<1940	79.9 (±40.0)	29.4 (±14.4)	23.0 (±12.4)	17.2 (±11.1)	15.7 (±10.9)
	1940-1979	66.2 (±35.2)	26.2 (±12.9)	21.4 (±11.3)	17.1 (±10.2)	15.4 (±10.1)
	>1980	40.4 (±22.8)	18.6 (±10.2)	17.7 (±9.6)	15.4 (±9.0)	13.7 (±8.9)

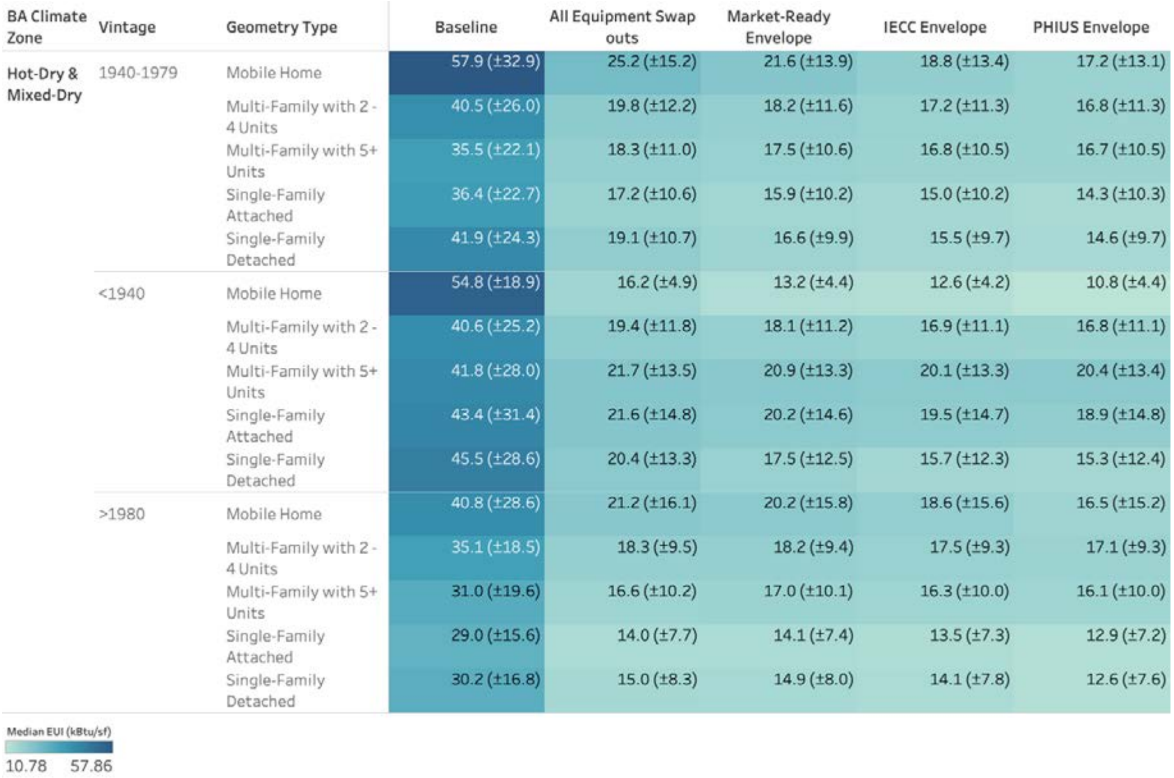
Figure 4. Median (± standard deviation) of site EUI (kBtu/sf) across the United States

Site EUI considering vintage and type of dwelling unit for each climate zone is presented in Figure 5–Figure 9. Among the dwelling units, mobile homes showed the largest reduction in site EUI across all climate zones in the United States.



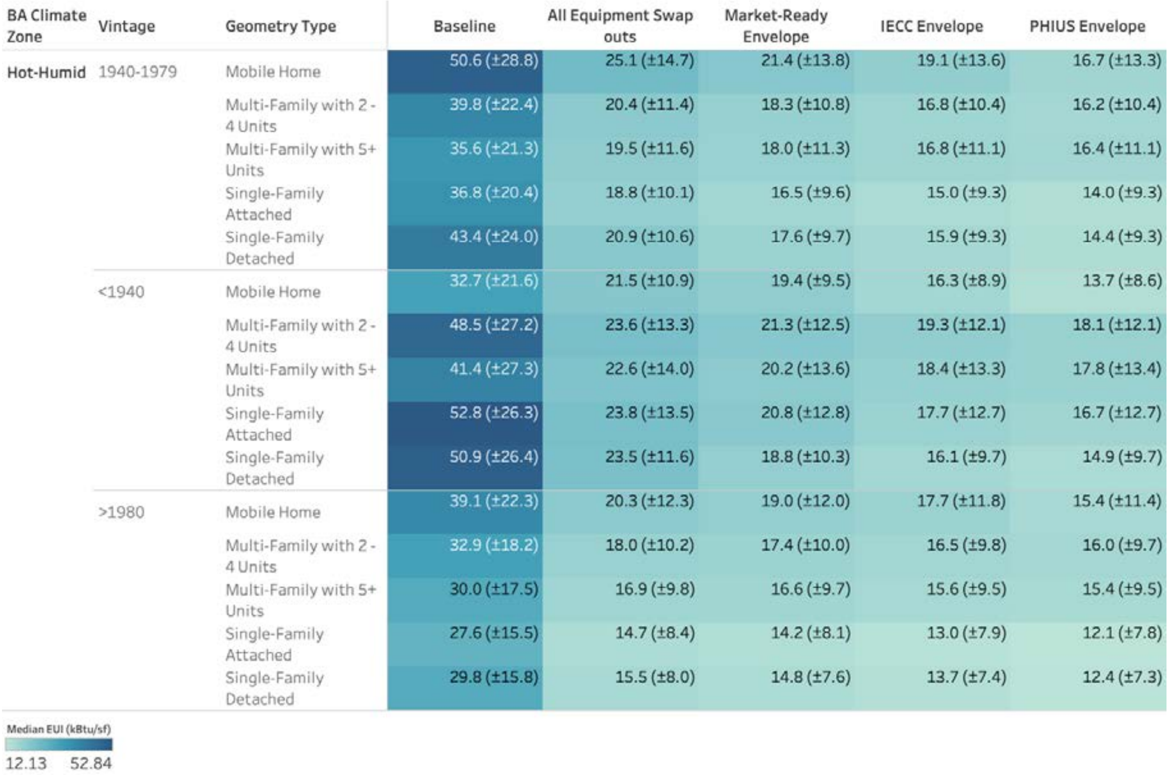
BA Climate Zone	Vintage	Geometry Type	Baseline	All Equipment Swap outs	Market-Ready Envelope	IECC Envelope	PHIUS Envelope
Cold & Very Cold	1940-1979	Mobile Home	112.0 (±46.8)	41.0 (±18.9)	34.0 (±15.9)	23.8 (±13.0)	18.1 (±11.9)
		Multi-Family with 2 - 4 Units	84.7 (±38.9)	33.1 (±15.8)	27.2 (±13.7)	21.8 (±12.4)	19.2 (±11.9)
		Multi-Family with 5+ Units	65.2 (±37.1)	28.6 (±14.9)	24.7 (±13.0)	20.1 (±11.5)	18.3 (±11.1)
		Single-Family Attached	68.3 (±36.7)	27.0 (±13.5)	22.3 (±11.0)	17.4 (±9.0)	15.9 (±8.9)
		Single-Family Detached	83.3 (±37.1)	30.3 (±13.8)	23.7 (±11.1)	18.2 (±9.4)	15.8 (±9.0)
	<1940	Mobile Home	109.5 (±37.0)	33.9 (±14.2)	26.0 (±9.6)	17.2 (±6.1)	10.8 (±5.3)
		Multi-Family with 2 - 4 Units	93.1 (±40.9)	34.1 (±16.2)	26.9 (±13.8)	20.4 (±12.6)	18.1 (±12.1)
		Multi-Family with 5+ Units	81.1 (±45.7)	32.5 (±18.0)	26.6 (±15.3)	20.6 (±13.6)	18.4 (±13.0)
		Single-Family Attached	78.4 (±45.9)	28.3 (±17.3)	21.9 (±14.4)	16.4 (±12.6)	14.3 (±12.2)
		Single-Family Detached	97.3 (±39.9)	33.8 (±14.6)	24.9 (±11.4)	17.9 (±9.2)	15.6 (±8.9)
	>1980	Mobile Home	74.5 (±36.0)	29.8 (±15.3)	27.8 (±14.1)	22.5 (±12.1)	16.6 (±11.3)
		Multi-Family with 2 - 4 Units	56.2 (±28.5)	24.2 (±12.9)	23.1 (±12.2)	19.5 (±11.2)	17.9 (±11.1)
		Multi-Family with 5+ Units	46.0 (±28.5)	22.0 (±12.9)	21.6 (±12.1)	18.4 (±11.1)	17.0 (±10.9)
		Single-Family Attached	47.5 (±25.5)	20.0 (±10.6)	19.0 (±9.6)	15.7 (±8.0)	13.7 (±7.9)
		Single-Family Detached	48.2 (±23.9)	19.6 (±9.9)	18.5 (±9.0)	15.5 (±7.7)	13.1 (±7.3)

Figure 5. Median (± standard deviation) of site EUI (kBtu/sf) in the Cold & Very Cold climate zone



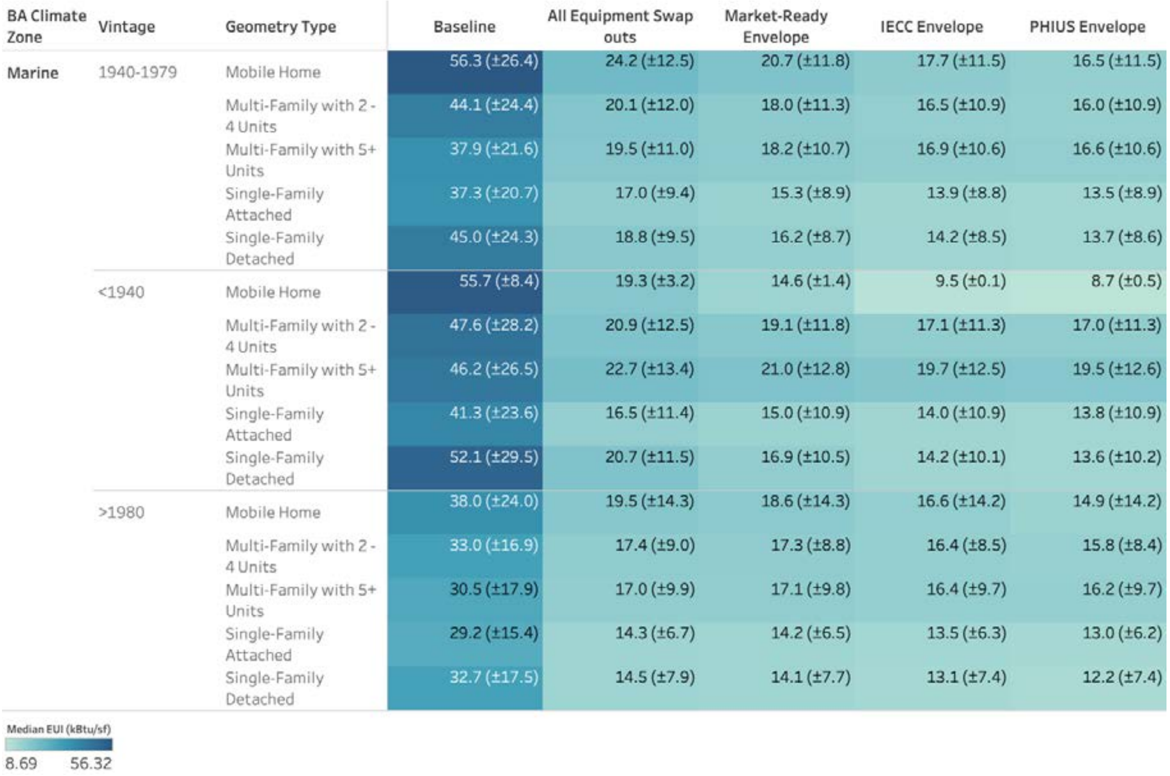
BA Climate Zone	Vintage	Geometry Type	Baseline	All Equipment Swap outs	Market-Ready Envelope	IECC Envelope	PHIUS Envelope
Hot-Dry & Mixed-Dry	1940-1979	Mobile Home	57.9 (±32.9)	25.2 (±15.2)	21.6 (±13.9)	18.8 (±13.4)	17.2 (±13.1)
		Multi-Family with 2 - 4 Units	40.5 (±26.0)	19.8 (±12.2)	18.2 (±11.6)	17.2 (±11.3)	16.8 (±11.3)
		Multi-Family with 5+ Units	35.5 (±22.1)	18.3 (±11.0)	17.5 (±10.6)	16.8 (±10.5)	16.7 (±10.5)
		Single-Family Attached	36.4 (±22.7)	17.2 (±10.6)	15.9 (±10.2)	15.0 (±10.2)	14.3 (±10.3)
		Single-Family Detached	41.9 (±24.3)	19.1 (±10.7)	16.6 (±9.9)	15.5 (±9.7)	14.6 (±9.7)
	<1940	Mobile Home	54.8 (±18.9)	16.2 (±4.9)	13.2 (±4.4)	12.6 (±4.2)	10.8 (±4.4)
		Multi-Family with 2 - 4 Units	40.6 (±25.2)	19.4 (±11.8)	18.1 (±11.2)	16.9 (±11.1)	16.8 (±11.1)
		Multi-Family with 5+ Units	41.8 (±28.0)	21.7 (±13.5)	20.9 (±13.3)	20.1 (±13.3)	20.4 (±13.4)
		Single-Family Attached	43.4 (±31.4)	21.6 (±14.8)	20.2 (±14.6)	19.5 (±14.7)	18.9 (±14.8)
		Single-Family Detached	45.5 (±28.6)	20.4 (±13.3)	17.5 (±12.5)	15.7 (±12.3)	15.3 (±12.4)
	>1980	Mobile Home	40.8 (±28.6)	21.2 (±16.1)	20.2 (±15.8)	18.6 (±15.6)	16.5 (±15.2)
		Multi-Family with 2 - 4 Units	35.1 (±18.5)	18.3 (±9.5)	18.2 (±9.4)	17.5 (±9.3)	17.1 (±9.3)
		Multi-Family with 5+ Units	31.0 (±19.6)	16.6 (±10.2)	17.0 (±10.1)	16.3 (±10.0)	16.1 (±10.0)
		Single-Family Attached	29.0 (±15.6)	14.0 (±7.7)	14.1 (±7.4)	13.5 (±7.3)	12.9 (±7.2)
		Single-Family Detached	30.2 (±16.8)	15.0 (±8.3)	14.9 (±8.0)	14.1 (±7.8)	12.6 (±7.6)

Figure 6. Median (± standard deviation) of site EUI (kBtu/sf) in the Hot-Dry & Mixed-Dry climate zone



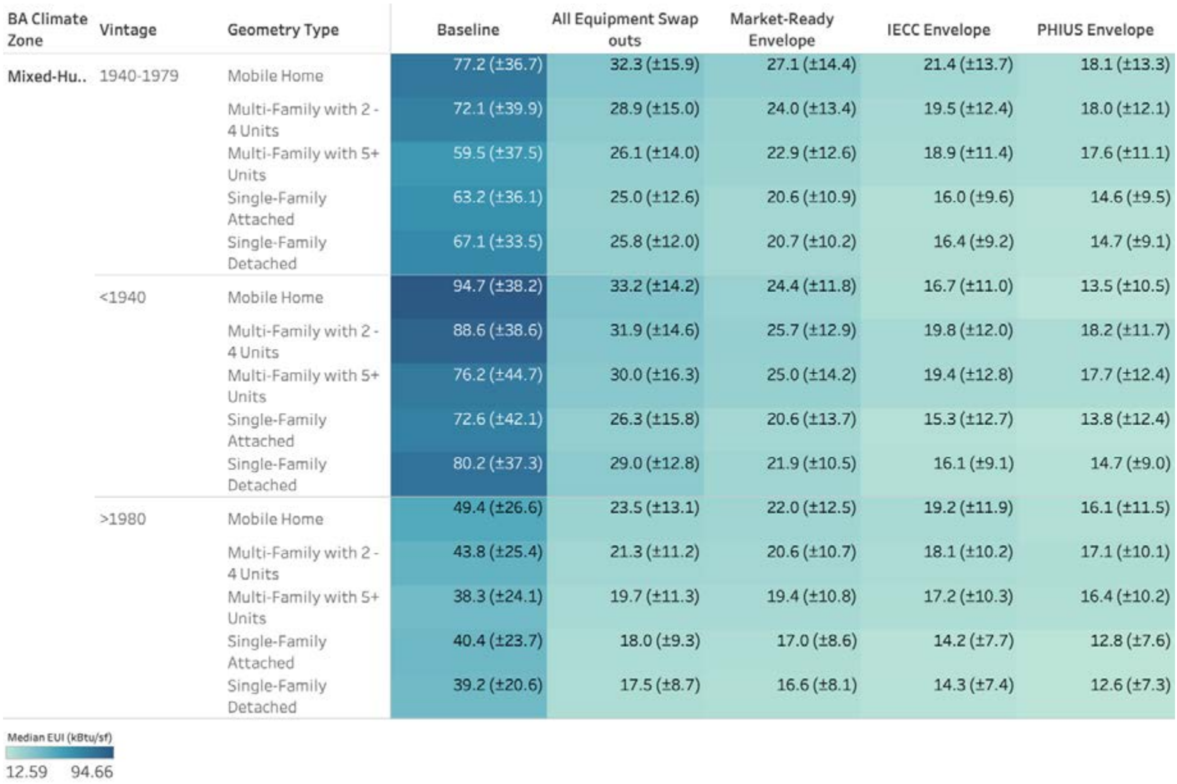
BA Climate Zone	Vintage	Geometry Type	Baseline	All Equipment Swap outs	Market-Ready Envelope	IECC Envelope	PHIUS Envelope
Hot-Humid	1940-1979	Mobile Home	50.6 (±28.8)	25.1 (±14.7)	21.4 (±13.8)	19.1 (±13.6)	16.7 (±13.3)
		Multi-Family with 2 - 4 Units	39.8 (±22.4)	20.4 (±11.4)	18.3 (±10.8)	16.8 (±10.4)	16.2 (±10.4)
		Multi-Family with 5+ Units	35.6 (±21.3)	19.5 (±11.6)	18.0 (±11.3)	16.8 (±11.1)	16.4 (±11.1)
		Single-Family Attached	36.8 (±20.4)	18.8 (±10.1)	16.5 (±9.6)	15.0 (±9.3)	14.0 (±9.3)
		Single-Family Detached	43.4 (±24.0)	20.9 (±10.6)	17.6 (±9.7)	15.9 (±9.3)	14.4 (±9.3)
	<1940	Mobile Home	32.7 (±21.6)	21.5 (±10.9)	19.4 (±9.5)	16.3 (±8.9)	13.7 (±8.6)
		Multi-Family with 2 - 4 Units	48.5 (±27.2)	23.6 (±13.3)	21.3 (±12.5)	19.3 (±12.1)	18.1 (±12.1)
		Multi-Family with 5+ Units	41.4 (±27.3)	22.6 (±14.0)	20.2 (±13.6)	18.4 (±13.3)	17.8 (±13.4)
		Single-Family Attached	52.8 (±26.3)	23.8 (±13.5)	20.8 (±12.8)	17.7 (±12.7)	16.7 (±12.7)
		Single-Family Detached	50.9 (±26.4)	23.5 (±11.6)	18.8 (±10.3)	16.1 (±9.7)	14.9 (±9.7)
	>1980	Mobile Home	39.1 (±22.3)	20.3 (±12.3)	19.0 (±12.0)	17.7 (±11.8)	15.4 (±11.4)
		Multi-Family with 2 - 4 Units	32.9 (±18.2)	18.0 (±10.2)	17.4 (±10.0)	16.5 (±9.8)	16.0 (±9.7)
		Multi-Family with 5+ Units	30.0 (±17.5)	16.9 (±9.8)	16.6 (±9.7)	15.6 (±9.5)	15.4 (±9.5)
		Single-Family Attached	27.6 (±15.5)	14.7 (±8.4)	14.2 (±8.1)	13.0 (±7.9)	12.1 (±7.8)
		Single-Family Detached	29.8 (±15.8)	15.5 (±8.0)	14.8 (±7.6)	13.7 (±7.4)	12.4 (±7.3)

Figure 7. Median (± standard deviation) of site EUI (kBtu/sf) in the Hot-Humid climate zone



BA Climate Zone	Vintage	Geometry Type	Baseline	All Equipment Swap outs	Market-Ready Envelope	IECC Envelope	PHIUS Envelope
Marine	1940-1979	Mobile Home	56.3 (±26.4)	24.2 (±12.5)	20.7 (±11.8)	17.7 (±11.5)	16.5 (±11.5)
		Multi-Family with 2 - 4 Units	44.1 (±24.4)	20.1 (±12.0)	18.0 (±11.3)	16.5 (±10.9)	16.0 (±10.9)
		Multi-Family with 5+ Units	37.9 (±21.6)	19.5 (±11.0)	18.2 (±10.7)	16.9 (±10.6)	16.6 (±10.6)
		Single-Family Attached	37.3 (±20.7)	17.0 (±9.4)	15.3 (±8.9)	13.9 (±8.8)	13.5 (±8.9)
		Single-Family Detached	45.0 (±24.3)	18.8 (±9.5)	16.2 (±8.7)	14.2 (±8.5)	13.7 (±8.6)
	<1940	Mobile Home	55.7 (±8.4)	19.3 (±3.2)	14.6 (±1.4)	9.5 (±0.1)	8.7 (±0.5)
		Multi-Family with 2 - 4 Units	47.6 (±28.2)	20.9 (±12.5)	19.1 (±11.8)	17.1 (±11.3)	17.0 (±11.3)
		Multi-Family with 5+ Units	46.2 (±26.5)	22.7 (±13.4)	21.0 (±12.8)	19.7 (±12.5)	19.5 (±12.6)
		Single-Family Attached	41.3 (±23.6)	16.5 (±11.4)	15.0 (±10.9)	14.0 (±10.9)	13.8 (±10.9)
		Single-Family Detached	52.1 (±29.5)	20.7 (±11.5)	16.9 (±10.5)	14.2 (±10.1)	13.6 (±10.2)
	>1980	Mobile Home	38.0 (±24.0)	19.5 (±14.3)	18.6 (±14.3)	16.6 (±14.2)	14.9 (±14.2)
		Multi-Family with 2 - 4 Units	33.0 (±16.9)	17.4 (±9.0)	17.3 (±8.8)	16.4 (±8.5)	15.8 (±8.4)
		Multi-Family with 5+ Units	30.5 (±17.9)	17.0 (±9.9)	17.1 (±9.8)	16.4 (±9.7)	16.2 (±9.7)
		Single-Family Attached	29.2 (±15.4)	14.3 (±6.7)	14.2 (±6.5)	13.5 (±6.3)	13.0 (±6.2)
		Single-Family Detached	32.7 (±17.5)	14.5 (±7.9)	14.1 (±7.7)	13.1 (±7.4)	12.2 (±7.4)

Figure 8. Median (± standard deviation) of site EUI (kBtu/sf) in the Marine climate zone



BA Climate Zone	Vintage	Geometry Type	Baseline	All Equipment Swap outs	Market-Ready Envelope	IECC Envelope	PHIUS Envelope
Mixed-Hu..	1940-1979	Mobile Home	77.2 (±36.7)	32.3 (±15.9)	27.1 (±14.4)	21.4 (±13.7)	18.1 (±13.3)
		Multi-Family with 2 - 4 Units	72.1 (±39.9)	28.9 (±15.0)	24.0 (±13.4)	19.5 (±12.4)	18.0 (±12.1)
		Multi-Family with 5+ Units	59.5 (±37.5)	26.1 (±14.0)	22.9 (±12.6)	18.9 (±11.4)	17.6 (±11.1)
		Single-Family Attached	63.2 (±36.1)	25.0 (±12.6)	20.6 (±10.9)	16.0 (±9.6)	14.6 (±9.5)
		Single-Family Detached	67.1 (±33.5)	25.8 (±12.0)	20.7 (±10.2)	16.4 (±9.2)	14.7 (±9.1)
	<1940	Mobile Home	94.7 (±38.2)	33.2 (±14.2)	24.4 (±11.8)	16.7 (±11.0)	13.5 (±10.5)
		Multi-Family with 2 - 4 Units	88.6 (±38.6)	31.9 (±14.6)	25.7 (±12.9)	19.8 (±12.0)	18.2 (±11.7)
		Multi-Family with 5+ Units	76.2 (±44.7)	30.0 (±16.3)	25.0 (±14.2)	19.4 (±12.8)	17.7 (±12.4)
		Single-Family Attached	72.6 (±42.1)	26.3 (±15.8)	20.6 (±13.7)	15.3 (±12.7)	13.8 (±12.4)
		Single-Family Detached	80.2 (±37.3)	29.0 (±12.8)	21.9 (±10.5)	16.1 (±9.1)	14.7 (±9.0)
	>1980	Mobile Home	49.4 (±26.6)	23.5 (±13.1)	22.0 (±12.5)	19.2 (±11.9)	16.1 (±11.5)
		Multi-Family with 2 - 4 Units	43.8 (±25.4)	21.3 (±11.2)	20.6 (±10.7)	18.1 (±10.2)	17.1 (±10.1)
		Multi-Family with 5+ Units	38.3 (±24.1)	19.7 (±11.3)	19.4 (±10.8)	17.2 (±10.3)	16.4 (±10.2)
		Single-Family Attached	40.4 (±23.7)	18.0 (±9.3)	17.0 (±8.6)	14.2 (±7.7)	12.8 (±7.6)
		Single-Family Detached	39.2 (±20.6)	17.5 (±8.7)	16.6 (±8.1)	14.3 (±7.4)	12.6 (±7.3)

Figure 9. Median (± standard deviation) of site EUI (kBtu/sf) in the Mixed-Humid climate zone

Utility Bill Savings

The utility bills for all the dwelling units in the baseline and upgrade package scenarios were calculated as described in the Methodology for Utility Bill Calculation section. The utility bills of each dwelling unit and package upgrade scenario were compared against the reference case to compute the bill savings due to package upgrades. The distribution of the bill savings across different upgrade packages is shown in Figure 10.

One of the main research objectives for this analysis was to better understand when it does and does not make sense to upgrade thermal envelopes when replacing fossil heating equipment with heat pumps. One aspect of this decision is how the switch affects household utility bills. For the *All Equipment Swap-Outs* package, we observed that there is a subset of dwelling units, especially in the Cold & Very Cold climate zone, that have negative utility bill savings—i.e., an increase in annual utility bills. This can be primarily attributed to replacement of gas space and water heating with electric heat pumps. In some states, using natural gas for heating is cheaper due to the relation of electricity to gas prices; the improved efficiency of the heat pump systems does not always overcome this cost differential. Additionally, many homes that do not currently have air conditioning see an increase in annual electricity bills because we model them as using their heat pumps for air conditioning in the summer months. Figure 11 shows that the *All Equipment Swap-Outs* median bill savings is negative for homes that had natural gas space heating and no prior cooling system; the median savings is positive in all other cohorts, although standard deviations are large.

With improvements in the building thermal envelope, the HVAC energy needed to maintain the same comfort level decreases. Thus, the remaining three packages have higher utility bill savings compared to the *All Equipment Swap-Outs* package, as indicated by Figure 10 and Figure 11.

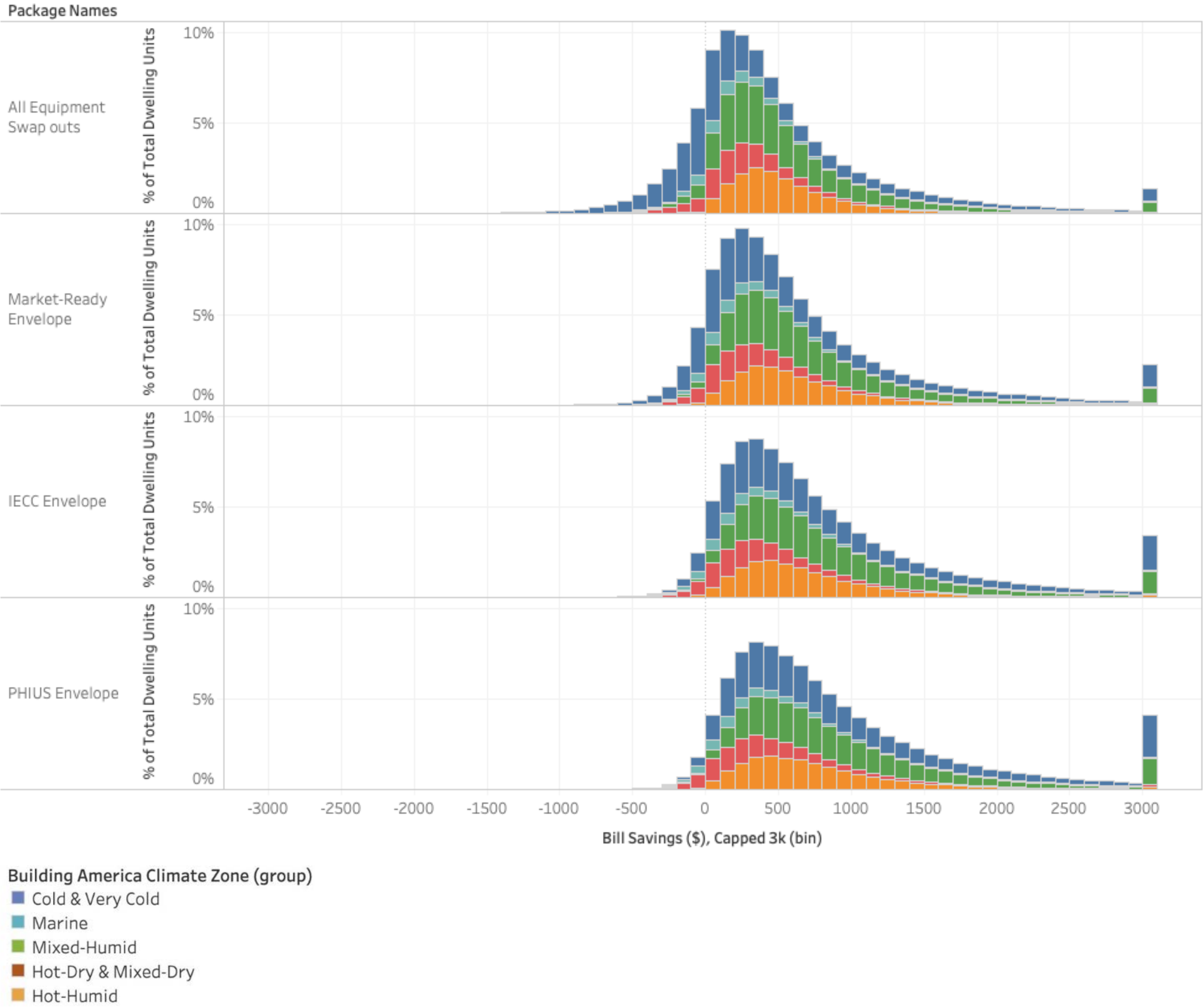
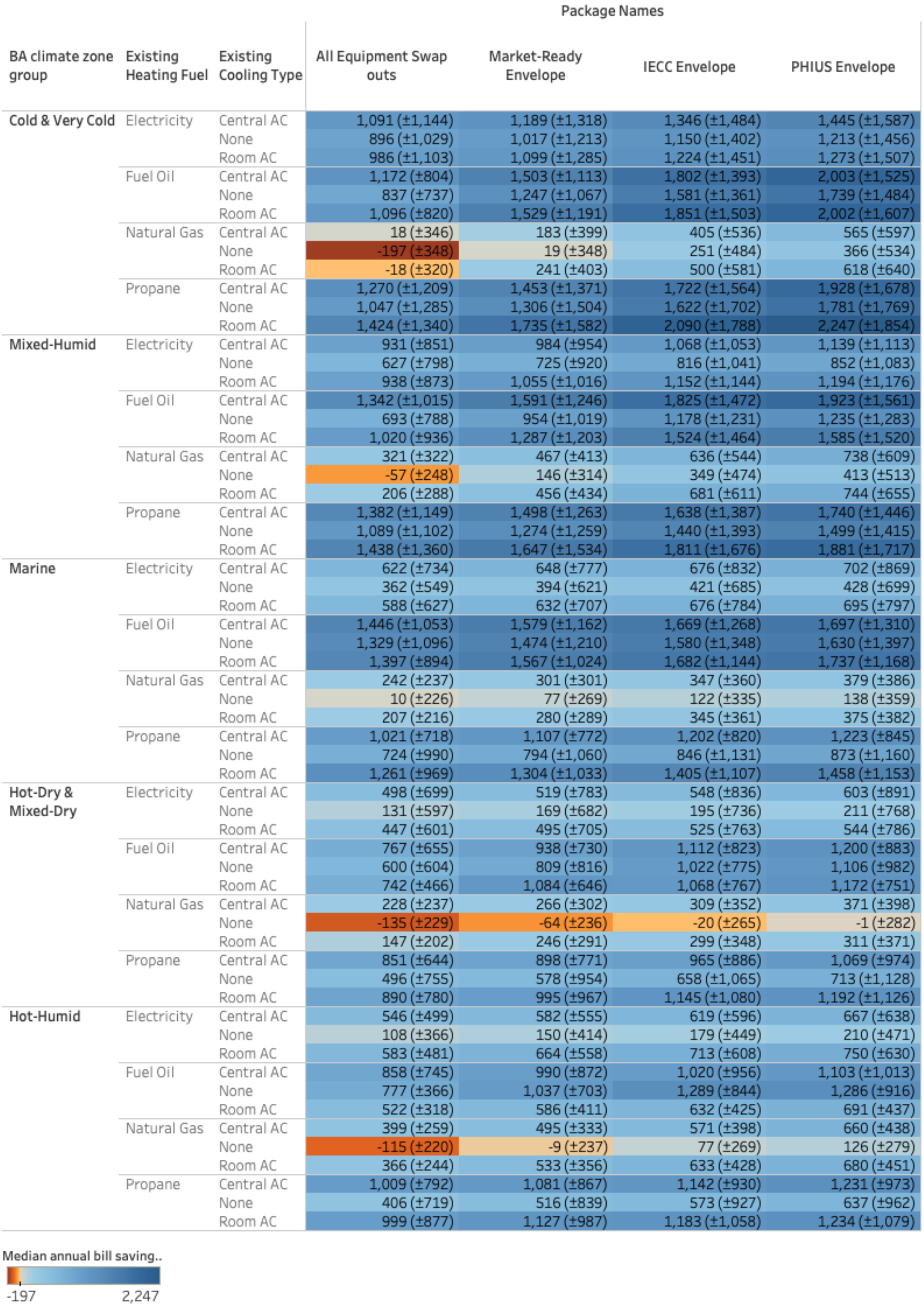


Figure 10. Distribution of utility bill savings



			Package Names			
BA climate zone group	Existing Heating Fuel	Existing Cooling Type	All Equipment Swap outs	Market-Ready Envelope	IECC Envelope	PHIUS Envelope
Cold & Very Cold	Electricity	Central AC	1,091 (±1,144)	1,189 (±1,318)	1,346 (±1,484)	1,445 (±1,587)
		None	896 (±1,029)	1,017 (±1,213)	1,150 (±1,402)	1,213 (±1,456)
		Room AC	986 (±1,103)	1,099 (±1,285)	1,224 (±1,451)	1,273 (±1,507)
	Fuel Oil	Central AC	1,172 (±804)	1,503 (±1,113)	1,802 (±1,393)	2,003 (±1,525)
		None	837 (±737)	1,247 (±1,067)	1,581 (±1,361)	1,739 (±1,484)
		Room AC	1,096 (±820)	1,529 (±1,191)	1,851 (±1,503)	2,002 (±1,607)
	Natural Gas	Central AC	18 (±346)	183 (±399)	405 (±536)	565 (±597)
		None	-197 (±348)	19 (±348)	251 (±484)	366 (±534)
		Room AC	-18 (±320)	241 (±403)	500 (±581)	618 (±640)
	Propane	Central AC	1,270 (±1,209)	1,453 (±1,371)	1,722 (±1,564)	1,928 (±1,678)
		None	1,047 (±1,285)	1,306 (±1,504)	1,622 (±1,702)	1,781 (±1,769)
		Room AC	1,424 (±1,340)	1,735 (±1,582)	2,090 (±1,788)	2,247 (±1,854)
Mixed-Humid	Electricity	Central AC	931 (±851)	984 (±954)	1,068 (±1,053)	1,139 (±1,113)
		None	627 (±798)	725 (±920)	816 (±1,041)	852 (±1,083)
		Room AC	938 (±873)	1,055 (±1,016)	1,152 (±1,144)	1,194 (±1,176)
	Fuel Oil	Central AC	1,342 (±1,015)	1,591 (±1,246)	1,825 (±1,472)	1,923 (±1,561)
		None	693 (±788)	954 (±1,019)	1,178 (±1,231)	1,235 (±1,283)
		Room AC	1,020 (±936)	1,287 (±1,203)	1,524 (±1,464)	1,585 (±1,520)
	Natural Gas	Central AC	321 (±322)	467 (±413)	636 (±544)	738 (±609)
		None	-57 (±248)	146 (±314)	349 (±474)	413 (±513)
		Room AC	206 (±288)	456 (±434)	681 (±611)	744 (±655)
	Propane	Central AC	1,382 (±1,149)	1,498 (±1,263)	1,638 (±1,387)	1,740 (±1,446)
		None	1,089 (±1,102)	1,274 (±1,259)	1,440 (±1,393)	1,499 (±1,415)
		Room AC	1,438 (±1,360)	1,647 (±1,534)	1,811 (±1,676)	1,881 (±1,717)
Marine	Electricity	Central AC	622 (±734)	648 (±777)	676 (±832)	702 (±869)
		None	362 (±549)	394 (±621)	421 (±685)	428 (±699)
		Room AC	588 (±627)	632 (±707)	676 (±784)	695 (±797)
	Fuel Oil	Central AC	1,446 (±1,053)	1,579 (±1,162)	1,669 (±1,268)	1,697 (±1,310)
		None	1,329 (±1,096)	1,474 (±1,210)	1,580 (±1,348)	1,630 (±1,397)
		Room AC	1,397 (±894)	1,567 (±1,024)	1,682 (±1,144)	1,737 (±1,168)
	Natural Gas	Central AC	242 (±237)	301 (±301)	347 (±360)	379 (±386)
		None	10 (±226)	77 (±269)	122 (±335)	138 (±359)
		Room AC	207 (±216)	280 (±289)	345 (±361)	375 (±382)
	Propane	Central AC	1,021 (±718)	1,107 (±772)	1,202 (±820)	1,223 (±845)
		None	724 (±990)	794 (±1,060)	846 (±1,131)	873 (±1,160)
		Room AC	1,261 (±969)	1,304 (±1,033)	1,405 (±1,107)	1,458 (±1,153)
Hot-Dry & Mixed-Dry	Electricity	Central AC	498 (±699)	519 (±783)	548 (±836)	603 (±891)
		None	131 (±597)	169 (±682)	195 (±736)	211 (±768)
		Room AC	447 (±601)	495 (±705)	525 (±763)	544 (±786)
	Fuel Oil	Central AC	767 (±655)	938 (±730)	1,112 (±823)	1,200 (±883)
		None	600 (±604)	809 (±816)	1,022 (±775)	1,106 (±982)
		Room AC	742 (±466)	1,084 (±646)	1,068 (±767)	1,172 (±751)
	Natural Gas	Central AC	228 (±237)	266 (±302)	309 (±352)	371 (±398)
		None	-135 (±229)	-64 (±236)	-20 (±265)	-1 (±282)
		Room AC	147 (±202)	246 (±291)	299 (±348)	311 (±371)
	Propane	Central AC	851 (±644)	898 (±771)	965 (±886)	1,069 (±974)
		None	496 (±755)	578 (±954)	658 (±1,065)	713 (±1,128)
		Room AC	890 (±780)	995 (±967)	1,145 (±1,080)	1,192 (±1,126)
Hot-Humid	Electricity	Central AC	546 (±499)	582 (±555)	619 (±596)	667 (±638)
		None	108 (±366)	150 (±414)	179 (±449)	210 (±471)
		Room AC	583 (±481)	664 (±558)	713 (±608)	750 (±630)
	Fuel Oil	Central AC	858 (±745)	990 (±872)	1,020 (±956)	1,103 (±1,013)
		None	777 (±366)	1,037 (±703)	1,289 (±844)	1,286 (±916)
		Room AC	522 (±318)	586 (±411)	632 (±425)	691 (±437)
	Natural Gas	Central AC	399 (±259)	495 (±333)	571 (±398)	660 (±438)
		None	-115 (±220)	-9 (±237)	77 (±269)	126 (±279)
		Room AC	366 (±244)	533 (±356)	633 (±428)	680 (±451)
	Propane	Central AC	1,009 (±792)	1,081 (±867)	1,142 (±930)	1,231 (±973)
		None	406 (±719)	516 (±839)	573 (±927)	637 (±962)
		Room AC	999 (±877)	1,127 (±987)	1,183 (±1,058)	1,234 (±1,079)

Figure 11. Median and standard deviation annual bill savings by climate zone, heating fuel, and cooling type. Median annual bill savings is negative mainly for the *All Equipment Swap-Outs* package in homes that had natural gas space heating and no prior cooling system; the median savings is positive in all other cohorts, although standard deviations are large, indicating large variation in bill savings within each cohort.

Relationship Between Bill Savings and Energy Prices

To understand the variation in utility bill savings within each climate zone, one can look at the median bill savings by state for each heating fuel type, as shown in Figure 12. The size of the circle represents the number of homes receiving the package with each heating fuel type and in each state. The color of the circle in each state signifies the median annual bill savings. As seen in Figure 11, it is clear that the utility bill savings are dependent on the existing fuel type.

One major factor for the bill impacts in the *All Equipment Swap-Outs* scenario is the average residential electricity and gas prices in each state, shown in Figure 13. The left graph of Figure 13 shows the marginal electricity price against the marginal gas price in each state, colored by median bill savings for the *All Equipment Swap-Outs* package. The negative bill savings occurs in states with low gas prices, such as North Dakota and Minnesota. States with higher natural gas prices also tend to have higher electricity prices (e.g., New England states), though Florida, Georgia, and Alabama are exceptions to this. The right graph shows the median *All Equipment Swap-Outs* package bill savings against the ratio of electricity to gas price, by state. One can see a clear trend between this ratio and bill savings, although the ratio is correlated with climate.

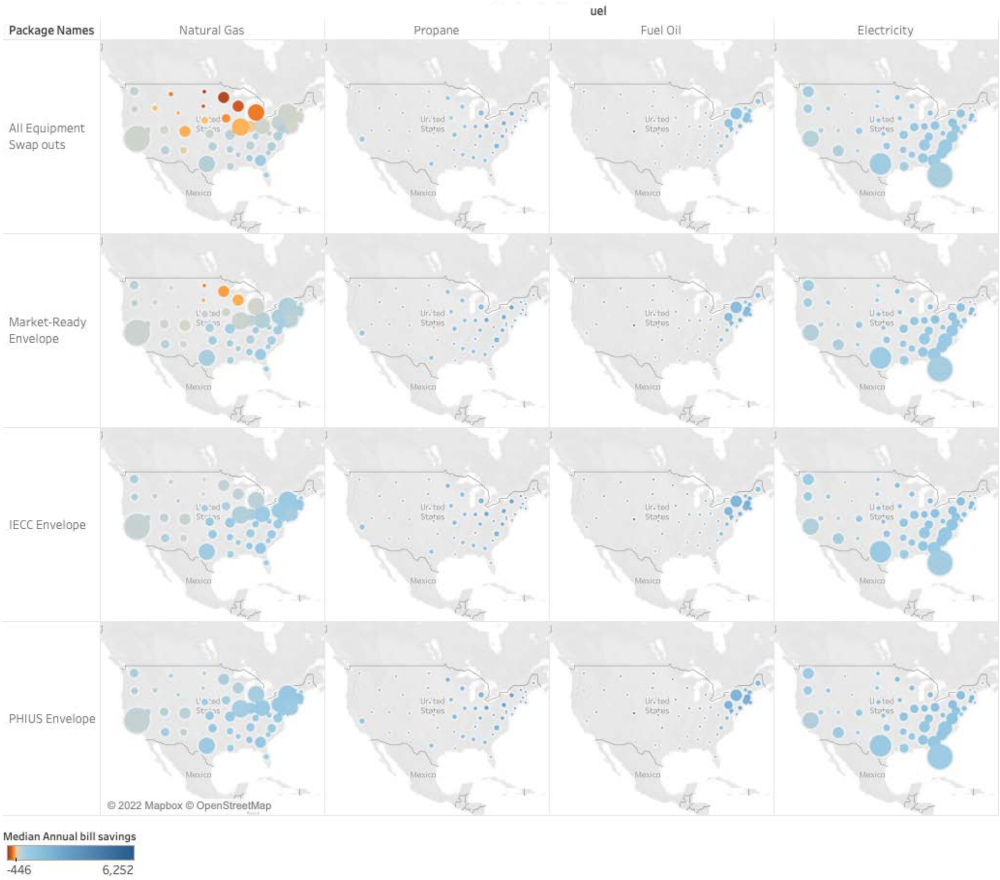


Figure 12. Distribution of median utility bill savings for each heating fuel type

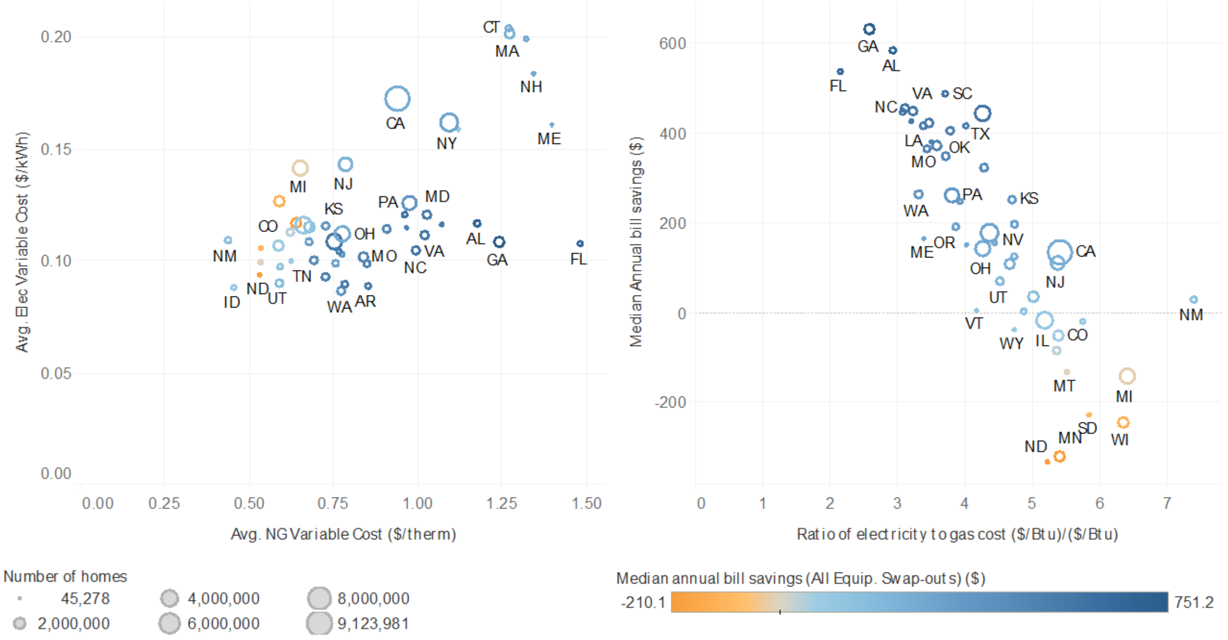


Figure 13. (Left) Marginal electricity price plotted against marginal gas price in each state, colored by median bill savings for the *All Equipment Swap-Outs* package. (Right) Median *All Equipment Swap-Outs* package bill savings plotted against the ratio of electricity to gas price, by state.

Importance of Distributions

Figure 14 shows the maps of 5th, 50th (median), and 95th percentile savings by county for each package upgrade. Though the median annual bill savings were observed to be positive for most of the counties and states, there were more counties in the lower 5th percentile with negative bill savings for the *All Equipment Swap-Outs* package. The 5th percentile map raises concerns about energy affordability: what if the households in this 5th percentile are already struggling to pay their bills? Additionally, because heat pump performance is more sensitive to outdoor temperature than fossil equipment, the annual bill increases are likely to be concentrated in winter months. Even if bill impacts are neutral on an annual basis, the unpredictable increase in winter bills could be more challenging for households already struggling to pay utility bills.

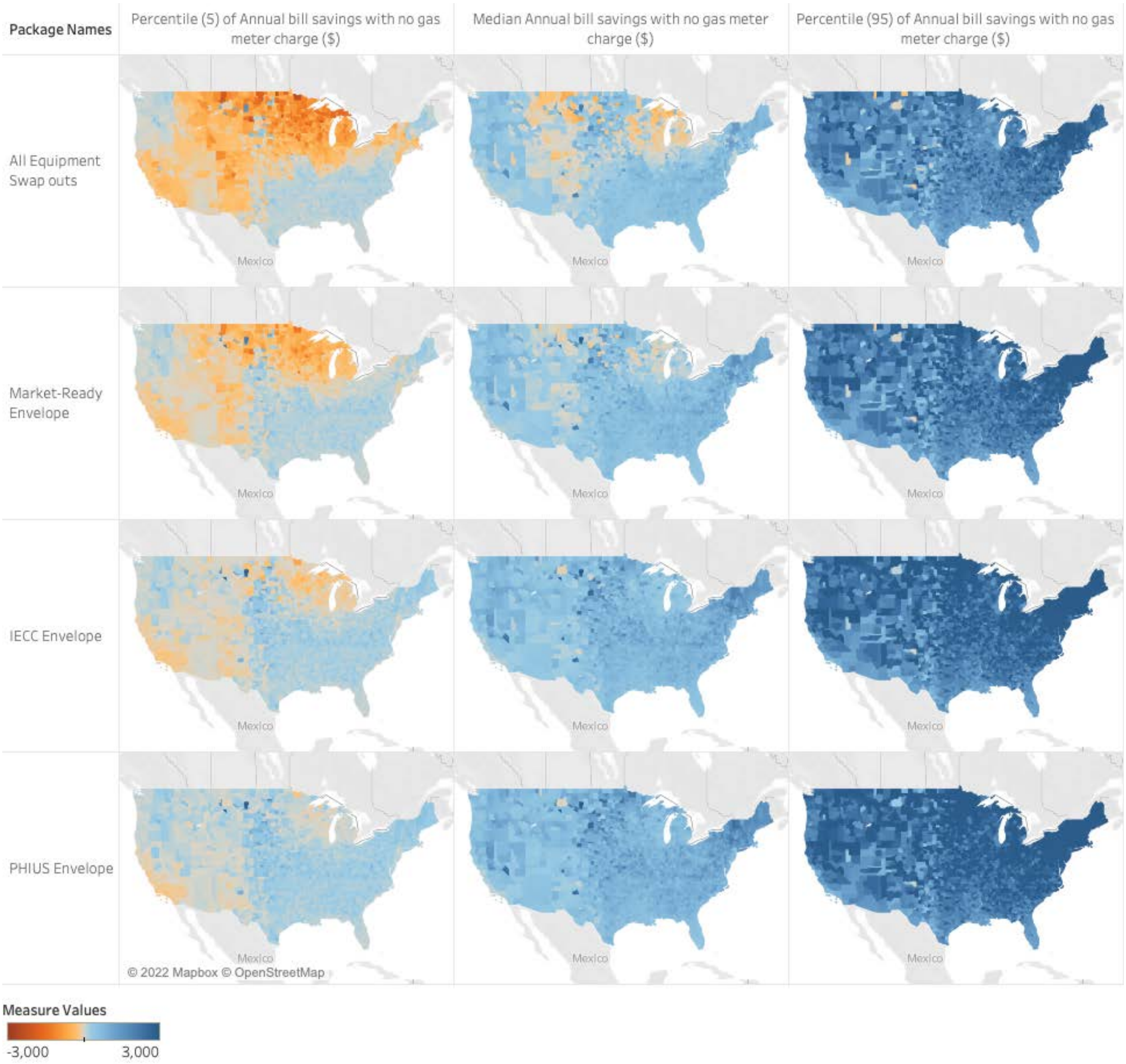


Figure 14. Maps of 5th, 50th, and 95th percentile savings by county for each package upgrade

HVAC Capacity

The HVAC capacity of each residential dwelling unit is calculated using methods consistent with Air Conditioning Contractors of America Manual J and S procedures [21, 22] in ResStock. As described in Table 1, the heat pumps were sized for the larger of the design heating load or cooling load. This is an optimistic assumption; in some cases, the existing ductwork may not be able to accommodate the airflows required for larger (e.g., 4- and 5-ton) heat pumps, which would require replacing the ductwork. Alternatively, the heating load could be met with a smaller 2- or 3-ton ducted heat pump supplemented with additional ductless units or additional electric resistance heating capacity.

The ducted unit that was modeled is a higher-efficiency (SEER1 22, HSPF1 10) variable speed unit, but it does not meet the cold climate criteria from ENERGY STAR, which requires 70%

capacity retention and coefficient of performance (COP) > 1.75 at 5ºF [23]. The ductless unit we modeled does meet those criteria. When sizing to meet the heating load, the capacity retention of the ducted unit (50% at 5ºF and 25% at −15ºF) leads to larger nominal heating capacities than would be required with air-source heat pumps that do meet the cold climate criteria. The Northeast Energy Efficiency Partnerships (NEEP) cold climate ASHP list includes over 25,000 products (combinations of indoor and outdoor units) that have a coefficient of performance of 2 or greater while running at maximum capacity at 5ºF. Modeling these ASHPs with improved cold climate performance is an area of ongoing capability development (e.g., [24]).

The heat pumps are modeled with supplementary electric resistance heat that operates during hours when the heat pump alone as sized cannot meet the set point. In the case of the ducted unit, the compressor was also assumed to not operate below 0ºF.

We analyzed how heating and cooling loads—and thus the rated heat pump capacities—change with application of the package upgrades. The overall distributions of rated HVAC capacities for the package upgrades are shown in Figure 15. The height of each bar represents the number of buildings for the HVAC capacity bin. The largest bin in the figure includes all dwelling units above 96 kBtu/h.

The median and standard deviation of capacities in each climate zone are shown in Figure 16. The HVAC capacity requirement to meet the occupant comfort is highest in *All Equipment Swap-Outs* and lowest in *PHIUS Envelope* among the upgrade packages. With the increase in building envelope efficiency, the HVAC capacity decreases, as depicted by the trend of decreasing HVAC capacity from *All Equipment Swap-Outs* to the *PHIUS Envelope* package.

While the envelope packages would likely have high upfront costs, they have the potential to both significantly reduce the upfront cost of heat pump equipment and potentially reduce the need for expensive electrical upgrades (e.g., for high-amperage electric resistance heat) and ductwork upgrades. In case of ducted ASHPs, the typical cost of high-efficiency SEER1 21/HSPF1 10 ASHPs is $140/kBtu/h of rated cooling capacity and a fixed cost around $6,000 (root-mean-square error = $2,259 based on [25]; implicitly includes electrical upgrades). Residential heat pumps and air conditioners typically cannot be found in sizes larger than 60 kBtu/h (5 tons). When the HVAC capacity exceeds 60 kBtu/h (5 tons), two pieces of equipment would be required to meet the load, so the fixed cost part of the equipment cost equation would increase significantly as well. In homes that have only one existing duct system, installing a second ducted unit would require installation of a second duct system, which would be expensive and very disruptive, or alternatively, ductless units could supplement the main ducted unit.

Similarly, the typical cost of high-efficiency SEER1 29.3/HSPF1 14 ductless MSHPs is $300/kBtu/h, and each unit (indoor-outdoor pair) costs around $2,300 (root-mean-square error = $3,626 based on [25]; implicitly includes electrical upgrades). Thus, there is even greater potential for cost savings with lower HVAC capacity in the case of ductless MSHPs.

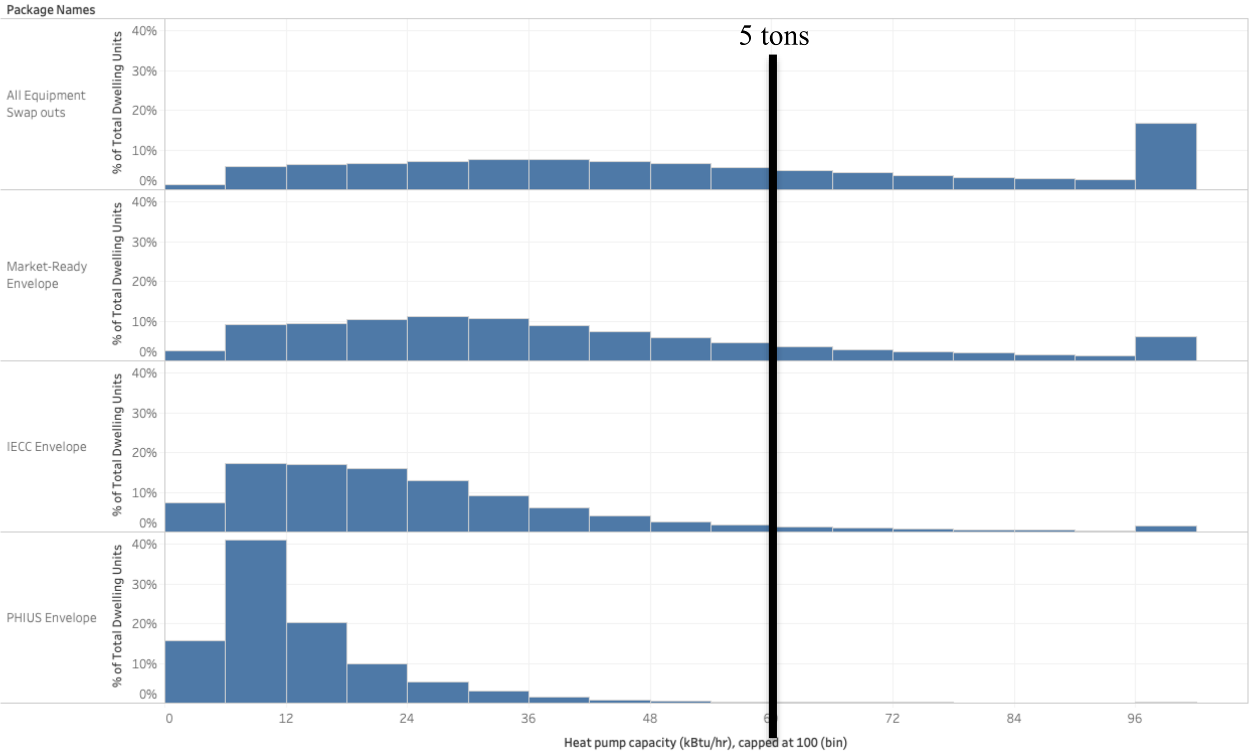
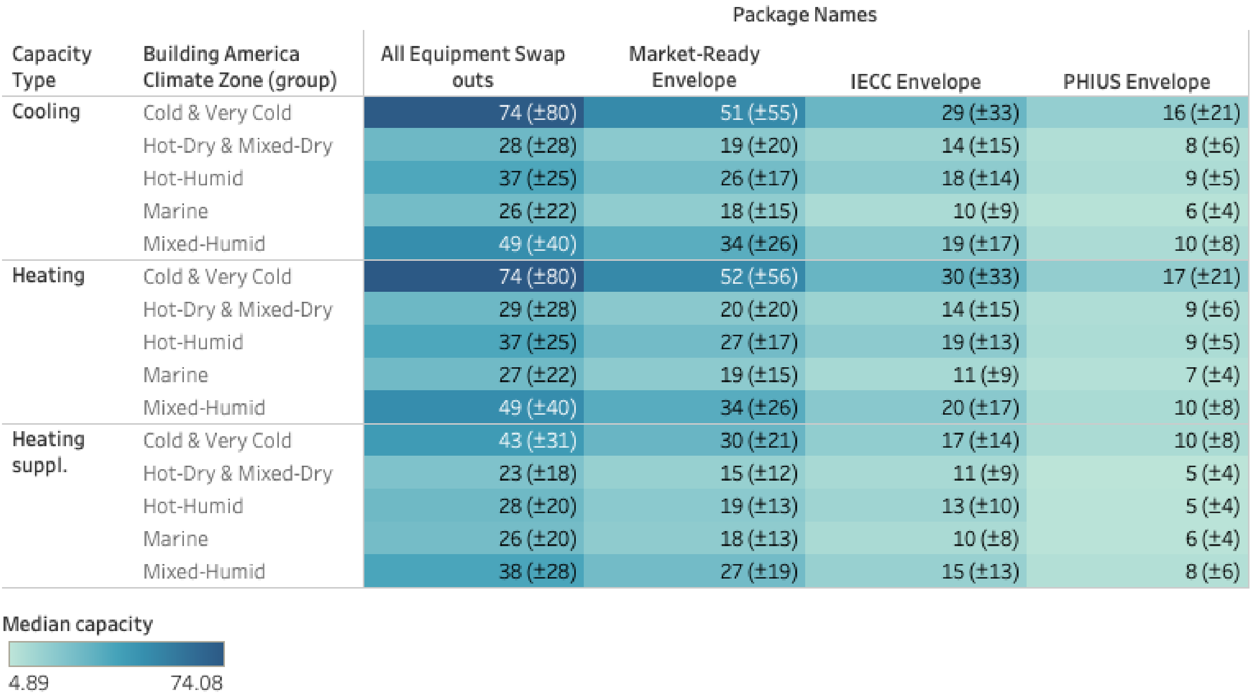


Figure 15. Distributions of nominal heat pump capacity (kBtu/h) for the package performance levels



Capacity Type	Building America Climate Zone (group)	All Equipment Swap outs	Market-Ready Envelope	IECC Envelope	PHIUS Envelope
Cooling	Cold & Very Cold	74 (±80)	51 (±55)	29 (±33)	16 (±21)
	Hot-Dry & Mixed-Dry	28 (±28)	19 (±20)	14 (±15)	8 (±6)
	Hot-Humid	37 (±25)	26 (±17)	18 (±14)	9 (±5)
	Marine	26 (±22)	18 (±15)	10 (±9)	6 (±4)
	Mixed-Humid	49 (±40)	34 (±26)	19 (±17)	10 (±8)
Heating	Cold & Very Cold	74 (±80)	52 (±56)	30 (±33)	17 (±21)
	Hot-Dry & Mixed-Dry	29 (±28)	20 (±20)	14 (±15)	9 (±6)
	Hot-Humid	37 (±25)	27 (±17)	19 (±13)	9 (±5)
	Marine	27 (±22)	19 (±15)	11 (±9)	7 (±4)
	Mixed-Humid	49 (±40)	34 (±26)	20 (±17)	10 (±8)
Heating suppl.	Cold & Very Cold	43 (±31)	30 (±21)	17 (±14)	10 (±8)
	Hot-Dry & Mixed-Dry	23 (±18)	15 (±12)	11 (±9)	5 (±4)
	Hot-Humid	28 (±20)	19 (±13)	13 (±10)	5 (±4)
	Marine	26 (±20)	18 (±13)	10 (±8)	6 (±4)
	Mixed-Humid	38 (±28)	27 (±19)	15 (±13)	8 (±6)

Figure 16. Median (± standard deviation) of nominal heat pump capacity (kBtu/h) across U.S. climate zones and package performance levels

Carbon Emission Impacts

While not the primary objective of this analysis, we calculated ranges of carbon emissions impacts that could be expected from ABC innovations aligned with the simulated packages.

For changes in fossil fuel use, we used emissions factors from Table 7.1.2(1) of the draft *ANSI/RESNET/ICCC 301 Standard for the Calculation and Labeling of the Energy Performance of Dwelling and Sleeping Units using an Energy Rating Index* [26]. The factors include both combustion and upstream precombustion emissions, including the global warming potential of carbon dioxide, methane, and nitrous oxide.

For changes in electricity use, we used emissions factors from Cambium 2021 data [27] from the National Renewable Energy Laboratory's 2021 Standard Scenarios [28]. As is appropriate for long-lasting changes in electrical load, we used long-run marginal emission rates (LRMER) from Cambium [29]. We levelized the rates over 16 years (2022–2038), which corresponds to the typical lifetime of ASHP equipment. Using longer lifetimes (e.g., for the envelope components) would result in lower emissions intensities, so using 16 years is a conservative estimate for the electrification measures. We compared emissions impacts for five different future grid scenarios, ranging from one where the cost of renewable electricity generation is higher than baseline forecasts to one aligned with achieving a 95% clean electricity system by 2035. We used annual long-run marginal emission rate factors for simplicity of calculation; using hourly factors was out of scope but was done for subsequent analysis [24]. The factors were applied with geographic resolution of 20 Generation and Emission Assessment (GEA) regions, which are based on the U.S. Environmental Protection Agency's Emissions & Generation Resource Integrated Database (eGRID) regions [30]. Increases in CO_2e from refrigerant leakage were not accounted for, but these are expected to be relatively minor and not change the direction of these findings [31].

The results of the emissions impact analysis are presented in Figure 17. Regardless of future grid scenario, all packages are expected to reduce average CO_2e emissions in every state.

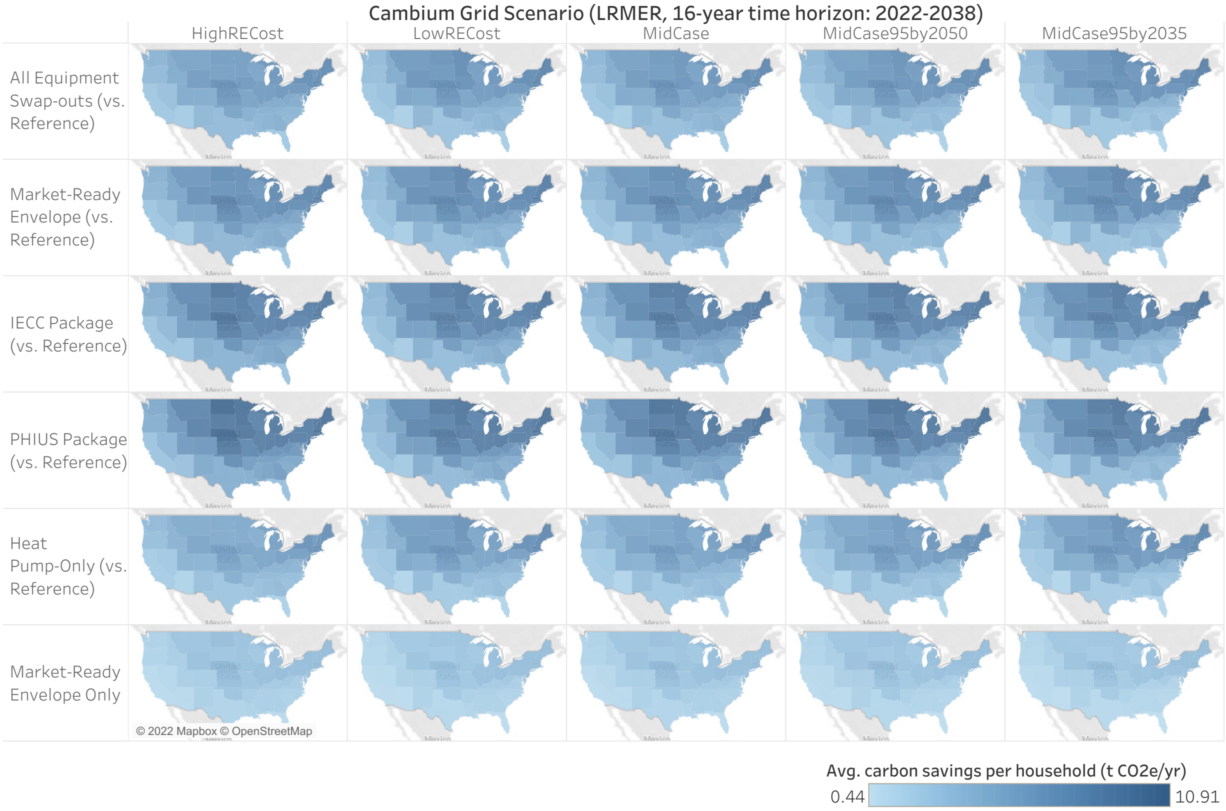


Figure 17. Maps of average carbon emissions equivalent reductions by state for different package performance levels and for five different future grid scenarios

Informing Cost Targets

An important use case for the segment-specific utility bill savings potentials described previously is the development of cost targets for packages that will likely require further technology cost compression to be viable in the retrofit market. These are primarily the packages with higher-performance envelope upgrades (*IECC Envelope* and *PHIUS Envelope*), but the methodology used to develop cost targets could be applied to the other packages as well.

Translating annual utility bill savings into installed cost targets for the packages can be done by calculating the discounted lifetime utility bill savings for the packages using a standard net present value (NPV) calculation:

$$NPV = \sum_{t=0}^{n} \frac{Rt}{(1+i)^t} - C \tag{6}$$

where Rt is the net cash flow during a specific time period, i is the discount rate, t is the number of time periods, and C is the initial cash investment. Given that the objective in this case is using the NPV calculation to determine a cost target for the initial investment, C, one can use the equation and an assumed lifetime and discount rate for the project to determine a cost target under the assumption that the packages should be available at no additional lifetime cost to the consumer.

There are various consumer cost thresholds that could be used to define the lifetime over which to calculate the package NPV. Several that are commonly used by homebuyers and builders to make investment decisions include thresholds based on the average life of a home mortgage (i.e., 30 years) or the typical length of time a homeowner stays in a home (i.e., 12 years) [].

Similarly, the assumed discount rate will have an impact on the project NPV and its cost target, so several discount rates could be used to estimate low- and high-cost targets for the package. These cost target ranges can then be used in combination with data on the current costs of these projects to determine the necessary levels of cost compression.

It is important to note that cost targets developed through this approach would be defined at the package level, but stakeholders will likely be interested in how these package-level targets translate into targets for individual measures that are part of the package and, further, how the costs for each of those measures are broken out by cost categories, including soft costs. Deriving more granular cost targets and understanding the drivers of those are important areas for future research.

Conclusion

Using ResStock, we defined and simulated four different retrofit packages: *All Equipment Swap-Outs*, *Market-Ready Envelope*, *IECC Envelope*, and *PHIUS Envelope*. We analyzed and organized the results by typology segments to understand the variation of energy and utility bill savings by climate zone, building type, and other parameters. The key takeaways from the analysis are listed below:

- Equipment-only heat pump upgrades (the *All Equipment Swap-Outs* package) are estimated to lead to increased utility bills in about 10% of dwelling units (using 2019 prices). However, we only assessed one model of ducted variable-speed heat pump with SEER1 22 and HSPF1 10, which does not meet typical "cold climate" heat pump specifications. This finding will be very sensitive to the details of the heat pump efficiency level and installation configuration being modeled. The addition of heat pumps also increases the cooling bill for homes without existing air conditioning.
- Equipment-only bill increases are related to price of electricity relative to natural gas, heating oil, and propane prices. The results presented here use 2019 prices, and results will change with fluctuations in the prices of these fuels.
- Building envelope upgrades can significantly mitigate these bill increases, with negative bills occurring in 4%, 2%, and 1% of homes for the *Market-Ready Envelope*, *IECC Envelope*, and *PHIUS Envelope* packages, respectively.
- If implemented prior to installing the heat pumps, these envelope packages can significantly reduce required heat pump capacities an\d potentially avoid electrical and ductwork upgrades, saving on upfront investment costs.
- The NPV of utility bill savings from this analysis can be used to inform cost compression targets for the ABC Initiative.

- All package performance levels are expected to reduce carbon equivalent emissions in every state, regardless of future grid scenario.

Future work on this subject could include:

- Understanding the sensitivity of these results to the heat pump efficiency level and installation configuration being modeled.
- Understanding impacts of these packages on energy burden in disadvantaged communities.
- Consideration of electrical panel upgrades and associated costs for the package upgrades.
- Consideration of the full set of co-benefits associated with upgrade packages.

CRediT Author Statement

Prateek Munankarmi: Methodology, simulation, formal analysis, visualization, validation, writing-original draft; **Eric Wilson**: Conceptualization, methodology, formal analysis, validation, supervision, writing-original draft; **Janet Reyna**: Conceptualization, writing – review & editing, supervision, project administration; **Elaina Present**: Software, writing – review & editing; **Stacey Rothgeb**: Conceptualization, writing – review & editing, supervision, project administration, funding acquisition; **Aven Satre-Meloy**: Conceptualization, writing – review & editing

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