How Deep is Your Retrofit? A Novel Data Platform to Determine Recommended Retrofit Upgrade Packages and Associated Cost Targets for U.S. Residential Buildings

Aven Satre-Meloy, Lawrence Berkeley National Laboratory
Brett Webster and Lucas Toffoli, RMI

ABSTRACT

Scaling whole-building energy efficient retrofits has been a persistent challenge driven by the high upfront costs and installation complexity of such upgrades. Accelerating deployment requires innovations across the value chain to reduce costs, simplify installation, and better capture the numerous benefits retrofits provide. An essential component of delivering these innovations is providing targeted information about the building stock, recommended retrofit interventions, and project costs to both demand- and supply-side actors in the retrofit market.

In this paper, we review results of an analysis to determine priority retrofit market segments, recommended performance levels, and retrofit package cost targets for residential buildings in the northeastern U.S. These results are available in a publicly accessible and interactive data platform. Our analysis combines detailed building energy upgrade simulations with energy cost modeling for a representative sample of 550,000 single-family and multifamily housing units. We present installed cost targets for the recommended retrofit packages applied to housing units in northeastern states and use these to determine promising market entry points for retrofit developers and program designers in that region.

To highlight the role of envelope measures in the recommended packages, we extend our analysis in a case study of the electricity system cost savings that envelope interventions can deliver in New York State. The results underscore the importance of whole-building retrofit solutions (not just electrification) that are needed to accelerate decarbonization across both the buildings and electricity sectors.

Introduction

Energy use in residential buildings is a substantial driver of carbon dioxide (CO_2) emissions in the U.S., accounting for around 20% of total energy-related CO_2 emissions in 2020 (EIA 2021). Achieving a decarbonized residential building stock in line with U.S. national goals for a net-zero economy will require rapidly accelerating progress on energy efficiency and electrification. Of particular concern is the existing stock of more than 130 million housing units (including manufactured homes), most of which will still be in use in 2050.

A common theme among previous studies of residential building decarbonization is extensive deployment of retrofits in existing buildings, including both thermal envelope improvements and electrification of building end uses, especially heating and water heating (Berrill et al. 2022; Langevin et al. 2023). In the most aggressive building decarbonization pathway Langevin et al. (2023) model, they project that 109 million existing homes will need to undergo an envelope retrofit at or above current code levels by 2050, implying an envelope retrofit rate of 3% (this is in addition to a 4- and 12-fold increase in deployment rates for residential air source heat pumps (ASHPs) and heat pump water heaters (HPWHs) compared to reference case projections). Such unprecedented change will require increased ambition in the public sector via new regulatory and policy actions (going beyond the recently passed Inflation

Reduction Act (IRA) and Bipartisan Infrastructure Law), and it will also require elevated and sustained investment from both the public sector and private industry.

A number of deployment barriers can account for the fact that rates of whole-building, deep retrofits are currently well below 1% in the U.S. (Laski and Burrows 2017). The most prominent of these is the high upfront installed costs of whole-building retrofits (Goldstein et al. 2018; Less et al. 2021). While these projects nearly always generate utility bill savings for building owners and occupants given the magnitude of energy savings they deliver, they are most often not cost-effective for building owners over their lifetime using typical metrics given their high installed costs, even when accounting for various incentives that may reduce these (Wilson et al. 2024). Accelerating deployment thus requires innovations across the value chain from manufacturers and developers to installers to reduce the costs of whole-building retrofits. But achieving ambitious rates of deployment for whole-building retrofits also necessitates having access to more detailed information on the types of retrofit projects that are appropriate for different segments of the market as well as the costs that these projects could support given estimates of their lifetime value. Such information will prove invaluable in supporting early market actors while the costs of such projects remain high.

In this paper, we build upon previous work to identify these high-priority residential market segments and provide specific recommendations for the retrofit measures and target performance levels aligned with sectoral decarbonization objectives. We undertake detailed cost modeling to determine what these whole-building retrofit upgrades should cost so that they are at least lifetime cost-neutral (with any further reductions in installed costs ensuring the projects are cost-negative or generate positive cash flows). These results signal to a range of stakeholders what costs they should target for various retrofit packages in order to accelerate their adoption. Importantly, we do not collect or estimate the actual installed costs for the various modeled upgrade packages but rather use the package assignments and savings data to estimate what the packages should cost in order to have broad market uptake.

Our methodology is based on a recent report that provided recommended performance levels and estimated cost targets for the entire residential building stock and made these available in a publicly accessible, interactive data platform[1] (Webster et al. 2024). Here, we extend this analysis in two key ways: 1) we analyze how estimated cost targets for whole-building retrofits in northeastern states vary across key building characteristics, such as building and heating fuel types to identify the segments of the market that can support higher-cost projects in the near-term, and 2) we present a case study of the electricity system cost savings that such projects can generate, focusing on New York State. Our results from these novel analyses can provide further guidance to supply- and demand-side actors on which buildings to prioritize for early retrofit deployment efforts and also provide a more holistic assessment of the benefits of scaling whole-building retrofits.

Methods and Data

The analysis presented in this paper follows several methodological steps, including: 1) the development of a synthetic, calibrated data set of baseline building characteristics for a representative sample of 550,000 existing single-family and multifamily housing units in the U.S.; 2) creation of multiple modeled performance upgrade packages and application of these to

---

[1] Available at: https://public.tableau.com/app/profile/nrel.buildingstock/viz/ABCMarketGuidanceforZero-carbonAlignedResidentialBuildings_16759824008870/Introduction

all baseline samples; 3) determination of recommended upgrade performance levels for all samples based on prescriptive criteria related to achieving a "zero-carbon-aligned" residential building stock; 4) estimation of upgrade package cost targets required to achieve cost-neutrality for a given package over its lifetime; 5) modeling of avoided electricity system power generation/capacity as well as transmission and distribution costs attributable to energy savings that would be delivered with full deployment of the prescriptive upgrade packages.

Methodology relevant to these steps is covered in some detail in a recent report (Webster et al. 2024). Here, we provide a brief overview of each of these steps to aid the reader in interpreting our results for retrofit package recommendations, modeled cost targets, and estimated supply-side electricity system benefits. Additional methodological details can be found in Appendix C of Webster et al. (2024).

Residential Baseline Building Stock Modeling and Upgrade Analysis

Our analysis begins with a synthetic dataset of 550,000 samples of single-family and multifamily housing units produced by the ResStock modeling tool developed by the National Renewable Energy Laboratory (NREL 2020). ResStock models the existing residential building stock with high granularity, combining detailed data on the U.S. housing market with physics-based simulations and high-performance computing to produce simulated datasets of the entire U.S. housing stock with hundreds of parameters related to building characteristics and high-resolution end-use load data, including for baseline conditions as well as for sets of prescriptive performance upgrade packages. These data have been extensively validated in a previous research project to calibrate data against metered utility records (Wilson et al. 2022), and they are publicly available for download (NREL 2022a). Additional methodological details on ResStock relevant to the present analysis are available in Reyna et al. (2022).

Next, we assess the energy, utility bill, and CO_2 emissions impacts of a range of prescriptive upgrade measure packages that are defined with specific performance levels and application criteria. A team of researchers involved in the Advanced Building Construction (ABC) Initiative worked collaboratively to define these prescriptive packages, which focused on pairing building equipment electrification and appliance efficiency upgrades with various levels of envelope performance, thus developing a suite of "whole-building" retrofit packages that vary in terms of performance level, potential savings, and feasibility or practicality of delivery (including packages that are more "market-ready" as well as those with a less mature market.).

The research team decided upon four performance upgrade retrofit packages to model across the full 550,000 sample of residential housing units. Descriptions of the four packages are:

1. <u>All equipment swap-out:</u> Electrification of building mechanical equipment to high-performance heat pumps plus replacement of major appliances with ENERGY STAR options and lighting upgrades to 100% LED (83 lumens/watt) plus duct sealing and insulation.
2. <u>Equipment + conventional envelope:</u> Includes all equipment upgrades in Package 1 plus building envelope upgrades with continuous exterior insulation (at the time of re-siding) and window replacements with low-emissivity storm windows.
3. <u>Equipment + IECC envelope:</u> Includes all equipment upgrades in Package 1 plus insulation, air leakage, and mechanical ventilation upgrades to levels consistent with 2021 IECC residential prescriptive path building envelope requirements (ICC 2021).

4. Equipment + Phius envelope: Includes all equipment upgrades in Package 1 plus insulation, air leakage, and mechanical ventilation upgrades to levels consistent with the 2018 Phius standard (Phius 2021).

Details for these packages are presented in Table 1, and additional specifications are available in a companion report (Munankarmi et al. 2023).

Table 1. Prescriptive upgrade packages, performance levels, and eligibility criteria

Building component	Modeled performance upgrade packages			
	All equipment swap-out	Equipment + conventional envelope	Equipment + IECC envelope	Equipment + Phius envelope
Water heater	Heat pump water heater; 80 gallons; UEF 2.4			
Heating and cooling	● Air-source heat pump (homes with ducts): SEER 22; 10 HSPF (not cold-climate) ● Mini-split heat pump (homes without ducts): SEER 29.3; 14 HSPF (cold-climate)			
Duct Sealing/ Insulation	All ducts in unconditioned spaces sealed to 10% and insulated to R-8			Ducts entirely within thermal envelope, no losses
Lighting	100% LED, 83 lumens/W			
Appliances	● ENERGY STAR (refrigerator and dishwasher) ● ENERGY STAR Most Efficient (heat pump dryer and clothes washer) ● Induction cooktop and electric resistance oven			
Window U-Value, Solar Heat Gain Coefficient (SHGC)	No upgrade	Low-e storm windows, U-value 0.29–0.69; SHGC 0.42–0.59	U-value 0.3–0.4; SHGC 0.25–0.4, by climate	U-value 0.12–0.5; SHGC 0.25–0.4, by climate
Wall/floor R-Value		R-6.5 continuous if existing <R-19 and home older than 1990	R-13 to R-30, by climate	R-22 to R-51, by climate
Roof/attic R-Value		R-29 to R-51, by climate	R-30 to R-60, by climate	R-51 to R-82, by climate
Foundation wall R-Value		No upgrade	R-0 to R-15, by climate	R-7 to R-30, by climate
Slab edge R-Value			No upgrade	2 ft, R-7 to R-30, by climate
Air leakage		7%–62% reduction	3 ACH50	1 ACH50
Mechanical ventilation		ERV/HRV if post-retrofit infiltration <7 ACH50	ERV/HRV	ERV/HRV

Note: The ducted air-source heat pump retains about 25% of its rated capacity at −15°F so is not considered a cold-climate heat pump, while the ductless mini-split heat pump retains about 80% at −15°F so is considered a cold-climate heat pump. Both were autosized to have nominal capacity based on the larger of heating or cooling design loads, while considering the heat pump's reduced capacity at the design temperature.

To assess the energy, utility bill, and CO_2 savings for these packages across the 550,000 housing unit sample, we construct a reference case upgrade that assumes like-for-like equipment and appliance upgrades (to federal minimum efficiency levels as of 2021) and then simulate the impact of these four prescriptive packages against the reference case. Utility bill calculations use 2019 average fixed and variable charges by state for electricity and non-electric fuels, and CO_2 emissions calculations use long-run marginal emissions rates (LRMER) from NREL's Cambium dataset (Gagnon et al. 2021) for grid electricity (assuming the Cambium 2021 “MidCase” scenario) and fossil fuel emissions factors from RESNET (RESNET 2021). Munankarmi et al. (2023) provide additional methodological details for these calculations as well as further exploration of package energy, utility bill, and CO_2 savings, a detailed review of which is beyond the scope of this paper.

Upgrade Package Assignment Logic

After simulating the impacts of the prescriptive packages on baseline building operations for our sample of residential housing units, we next develop a set of heuristics and criteria by which we assign packages for all the samples included in our analysis. Scaling these samples to all 133 million housing units in ResStock yields retrofit performance recommendations for the entire residential housing stock. This section describes the criteria used to determine package recommendations, which are also covered in more detail in Webster et al. (2024) in Appendix C1.

We design a set of package assignment criteria that have the primary objective of achieving a “zero-carbon-aligned” residential building stock. As introduced in Webster et al. (2024), the concept of “zero-carbon alignment” includes a set of conditions that are agnostic to technologies or standards but generally indicate compatibility with a decarbonized building stock. The concept includes the following primary conditions applicable to “zero-carbon-aligned” buildings:

- Have no on-site fossil fuel consumption and/or are fully electrified;
- Have site energy and thermal end-use consumption totals that are low enough to facilitate electrification without substantial mechanical and/or electrical upgrades;
- Currently source or can “readily” source (e.g., under a reasonable targeted scenario) all energy from a carbon-neutral grid and/or on-site carbon-neutral resources (such as rooftop PV);
- Facilitate electricity system decarbonization by minimizing peak and general power demand, including through grid interactivity or off-grid operation

Our analysis elaborates further upon these conditions by determining specific thresholds and requirements that can be used to assign packages to specific housing units. Criteria for assignment are shown in Table 2. Criteria are separated for two categories: 1) single-family and small multifamily (MF) building types; and 2) large MF building types. The former use site energy usage thresholds that are based on estimates of available on-site generation from rooftop PV, whereas the latter thresholds are based on energy-use intensity (EUI) targets specific to multifamily buildings from ASHRAE’s *Advanced Energy Design Guide (AEDG) for Multifamily Buildings* (ASHRAE 2022).

Table 2. Package assignment determination criteria

Metric	Criteria for assignment		Upgrade package assignment
	Single-family & Small MF (2-4 units)	Large MF	
Baseline site energy usage	Less than estimated solar generation from rooftop PV	Less than AEDG* MF target site EUI based on climate region	If all three conditions met, no upgrade assigned
Space & water heating	Electric space/water heating (either ASHP/ HWHP or other electric)		
Insulation	Insulated if in cold climate (i.e., walls are insulated and no single-pane windows)		
Upgrade site energy usage	Select lowest-performance package that reduces energy use below estimated solar generation from rooftop PV	Select lowest-performance package that reduces energy use below AEDG MF target site EUI based on climate region	"All equipment swap-out" vs. equipment + envelope assigned
Upgrade HVAC capacity	Select lowest-performance package that keeps heat pump capacity < 3 tons (criteria not applied to housing units with existing AC > 3 tons)		Equipment + "conventional" vs. "IECC" vs. "Phius" envelope assigned
Upgrade supplemental heating capacity	Select lowest-performance package that keeps supplemental electric resistance capacity < 2.7-ton limit (criteria only applied to housing units in counties with heating design temp <0˚F; criteria not applied to housing units that heat with electricity)		

Advanced Energy Design Guide for Multifamily Buildings: Achieving Zero Energy (ASHRAE 2022).

Developing Retrofit Package Cost Targets

After assigning packages to housing units based on the criteria above, we develop upgrade package cost targets that are intended to inform both supply- and demand-side actors on the installed cost ranges that should be targeted to achieve accelerated market uptake. Providing industry and policymakers with modeled cost targets can serve as a benchmark for on-going efforts to reduce the costs of whole-building retrofits.

The cost targets presented in this analysis represent how much each installed package would need to cost such that it could be considered "cost-neutral" over its lifetime when accounting for the package's value. This "value" estimate is based on several components, outlined below and further described in Webster et al. (2024). This work intends to provide a holistic view of project cost targets such that they incorporate both projected utility bill savings as well as other components, including the avoided costs of other (e.g., "reference case") replacements and renovations in addition to non-energy impacts, which can often be large in terms of perceived value to occupants. For each package assignment, we calculate the following cost target components:

- Equipment utility bill savings, calculated based on the energy savings attributable to the building mechanical equipment and appliances portion of the upgrade package. These savings are calculated over the lifetime of the equipment (assumed to be 15 years) and discounted to the present using a 3.4% discount rate.[2]
- Envelope utility bill savings, which are calculated on the energy savings attributable to the envelope upgrades included in the package. We use a 30-year lifetime to calculate the lifetime present value of these savings.
- Avoided costs of equipment considering avoided costs of like-for-like equipment or appliance replacements that the home would have otherwise purchased in lieu of the upgrades included in the package.
- Avoided costs of re-siding/roofing, similarly representing the assumption that the building would likely undergo a re-siding job or roof replacement in its lifetime that would be unnecessary when considering the package upgrades.
- Non-energy impacts (NEIs) that are included as a multiplier on the utility bill savings for the package (with the specific multiplier taken from a meta-analysis of NEIs and their values (Skumatz et al. 2014)).

We consider versions of the cost targets that both exclude and include the NEIs, thus yielding a range of conservative to more optimistic estimates of cost targets. For the IECC/Phius-level upgrades in particular, upgrade package costs may well exceed the pertinent cost targets in many cases, thus indicating the need for cost compression to achieve the cost targets.

Electricity System Cost Analysis

Using the package assignment results for New York State, we analyze the impacts on statewide load profiles in future-looking scenarios where the buildings, transportation, and industrial sectors electrify, and the electricity system decarbonizes to achieve New York State's 2040 zero-emission electricity target. New York State was selected for our case study because much of the state is in a cold climate, the state has progressive decarbonization targets, and utility distribution system data were readily available. The purpose of this analysis is to quantify the system-wide value that envelope measures in the assigned packages could deliver in the context of economy-wide decarbonization. As described above, the cost targets for the packages were derived using estimates of current utility bill savings. However, in the context of rapid electrification across sectors and electricity system decarbonization, building envelope interventions may deliver outsized benefits that could justify greater investments today (or support higher cost targets). We examined two residential load growth scenarios based on the retrofit interventions defined in Table 1:

1. Equipment electrification only ("Equipment Only"): All existing residential buildings including mobile homes, single-family homes, and multifamily homes receive the "All-equipment swap-out" package by 2050, with half of homes receiving it by 2035.
2. Recommended retrofit package ("Recommended Retrofit"): All existing residential buildings receive the retrofit packages recommended (below and in Webster et al. (2024)) by 2050, with half of homes receiving their recommended retrofit by 2035.

---

[2] Additional methodological details related to utility bill calculations are available in Munankarmi et al. (2023).

Both scenarios assume a linear building retrofit rate to their target year retrofit percentages (50% by 2035 and 100% by 2050). We evaluate the energy, generation, and distribution capacity avoided, as well as the savings from reduced HVAC system capacity in the "Recommended Retrofit" scenario versus the "Equipment Only" scenario. For wholesale energy and generation capacity costs, we use the NREL Cambium dataset (Gagnon et al. 2021). For distribution system savings, we utilize distribution system cost data from National Grid's 2018 Marginal Cost of Service (MCOS) study (National Grid 2018) to calculate the Locational System Relief Value (LSRV) and Demand Reduction Value (DRV) values for our analysis. We make two core assumptions in our calculations for the distribution system: 1) we assume that all new load is spread evenly across the distribution system; and 2) we assume that the National Grid distribution system upgrade needs and costs are representative of the other utilities in New York State, and we scale the numbers to the state level.

To evaluate the system-wide peak load impacts of the two scenarios, we generated hourly load profiles for each scenario using a combination of annual energy results and the profile shapes from NREL's End Use Savings Shapes (NREL 2022b). Hourly load profiles from non-residential sectors were taken from NREL's Electrification Futures Study under its "high electrification" and "rapid adoption" scenario (Mai et al. 2018).

Results and Discussion

This section presents results of our analysis with a specific focus on the upgrade package assignments and estimated cost targets for different segments of the residential building stock. First, we examine how upgrade package assignments vary by building type and state in the northeast. Second, we assess how cost targets vary within states at the county level for the upgrade packages that are relevant to whole-building retrofits (i.e., include both equipment and envelope upgrades). Third, we investigate how cost targets vary across building characteristics in order to identify priority market segments in the northeast for early deployment of whole-building retrofits. Fourth, we present results from our case study on the electricity system cost savings that assigned upgrade packages can deliver in New York State.

Regional Retrofit Package Assignments

Figure 1 shows bar plots of the number of housing units that are assigned each upgrade package in our analysis with results broken out by state in the northeast and by residential building type. For the approximately 26 million housing units in the northeastern states, the most commonly assigned upgrade package is the "Equip. + conventional envelope" package (45% of housing units) followed by the "Equip. + IECC envelope" package (23%), the "All equipment swap-out" package (19%) and the "Equip. + Phius envelope" package (11%), with the remaining housing units assigned no package (per Table 2, if certain criteria are already met by the baseline housing unit, then no upgrade is assigned). These results make the case that, irrespective of state or building type, there is a substantial need for whole-building retrofits to achieve a decarbonized residential building stock in the northeast.

Differences across the region are primarily seen in terms of the size of the existing housing stock, with NY, PA, NJ, and MA having the largest number of residential housing units, but there are also notable regional differences in frequency of package assignment — more northern states, such as CT, MA, ME, NH, and VT, tend to be assigned a higher share of envelope upgrade–inclusive packages whereas mid-Atlantic states such as DE and MD have a higher share of the equipment-only package (likely due to colder temperatures and higher thermal demands in northerly states).

In terms of building types, the single-family and small multifamily building types tend to have a higher share of each of the envelope-inclusive packages assigned than do multifamily housing units in the large multifamily building types (5+ units). This is likely due to the lower baseline energy consumption per housing unit in multifamily buildings compared to single-family buildings. The highest share of the more aggressive performance envelope packages ("Equipment + IECC envelope" and "Equipment + Phius envelope" level) is in single-family detached buildings, signaling the whole-building retrofit need for this market segment, in particular.

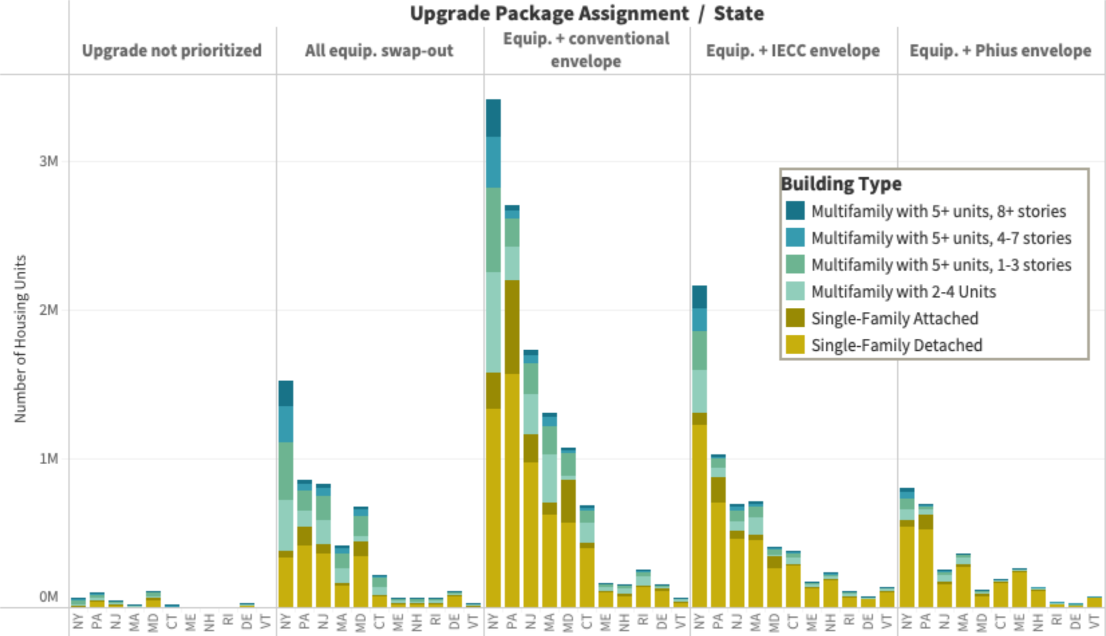

Figure 1. Package assignments by number of housing units for single-family and multifamily buildings in northeastern U.S. states.

Retrofit Package Cost Targets

For each housing unit and upgrade package assignment shown in Figure 1, we develop estimates of cost targets using the steps described in the Methods section. Figure 2 shows how these cost targets vary by county for the northeastern states in our analysis. Given that cost targets vary depending on the package that is assigned, we present sub-figures for each upgrade package, and the shading is based on the median cost target for all housing units that are assigned that upgrade package in a given county.

Figure 2 demonstrates that the "Equipment + conventional envelope" package supports or requires a lower (i.e., "more aggressive") cost target than do the "Equipment + IECC envelope" or "Equipment + Phius envelope" packages. This result is due to the fact that the energy and utility bill savings for this package tend to be lower than for the higher-performance packages, but the latter are also likely to cost substantially more than the former given the technical and practical difficulties associated with such high-performance package installations in a retrofit context.

Figure 2 shows some variability regionally but also shows that, even within states, there is a range of estimated cost targets, which highlights the diversity of the residential building stock. Differences are less pronounced between states, which is somewhat surprising given that the bill savings calculations included in our targets utilize state-level electricity and gas rates, but county-level differences within states are likely more influenced by underlying building characteristics, such as building type, heating fuel, and vintage, and these are the factors that we turn to in Figures 3 and 4.

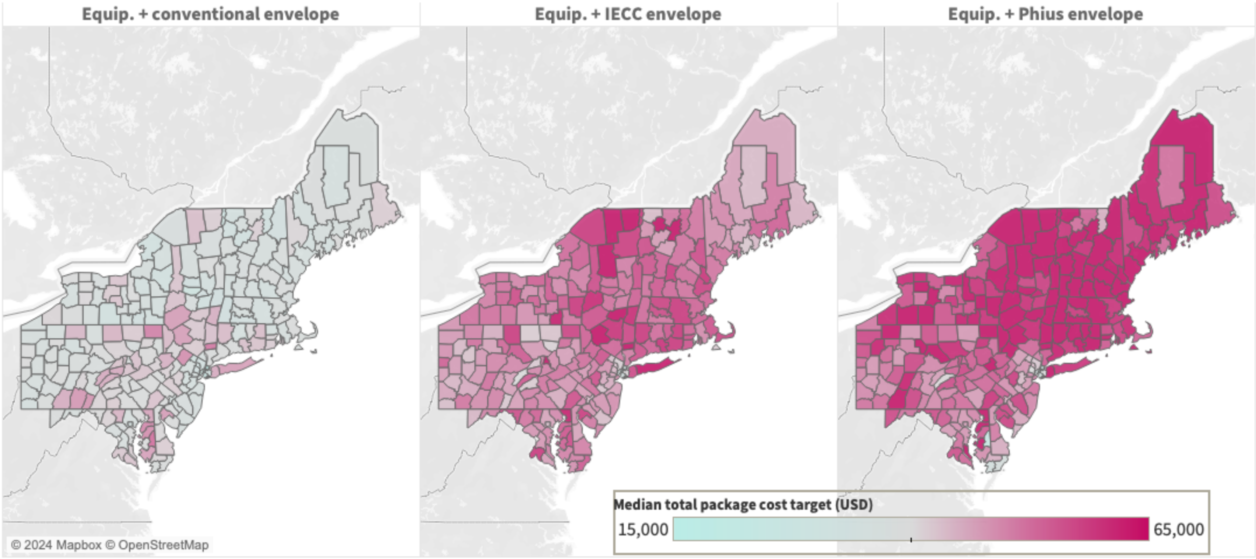

Figure 2. Median package cost targets by county for the northeastern region.

Figure 3 shows the median package cost target for all housing units in northeastern states that are assigned a whole-building retrofit and breaks these results out further by building type and baseline fuel. This figure provides more insight into how our estimated cost targets vary by key building characteristics and can help identify where higher cost targets are likely to be supported (offering a more tractable market-entry point for retrofit project providers while costs of new technologies for delivering whole-building retrofits are still prohibitively high).

In terms of variation across building types, Figure 3 shows that detached single-family dwellings tend to support the highest median cost targets for each upgrade package type, with attached single-family and small multifamily (2-4 units) supporting slightly lower median cost targets. Single-family detached homes in the northeast have high baseline thermal energy demands due to the age of the housing stock and low presence of insulation or existing envelope efficiency. Over two-thirds of the single-family housing stock in the northeastern states included in our analysis were built before 1980; further, nearly 50% do not have exterior wall insulation, and 71% do not have foundation wall insulation. The median baseline annual site energy use for our sample of single-family housing units is around three times that of housing units in large multifamily buildings, which can likely be attributed to the larger typical size of single-family homes (with a median floor area around two times the median floor area of housing units in large multifamily buildings) and proportionately greater exterior envelope area.

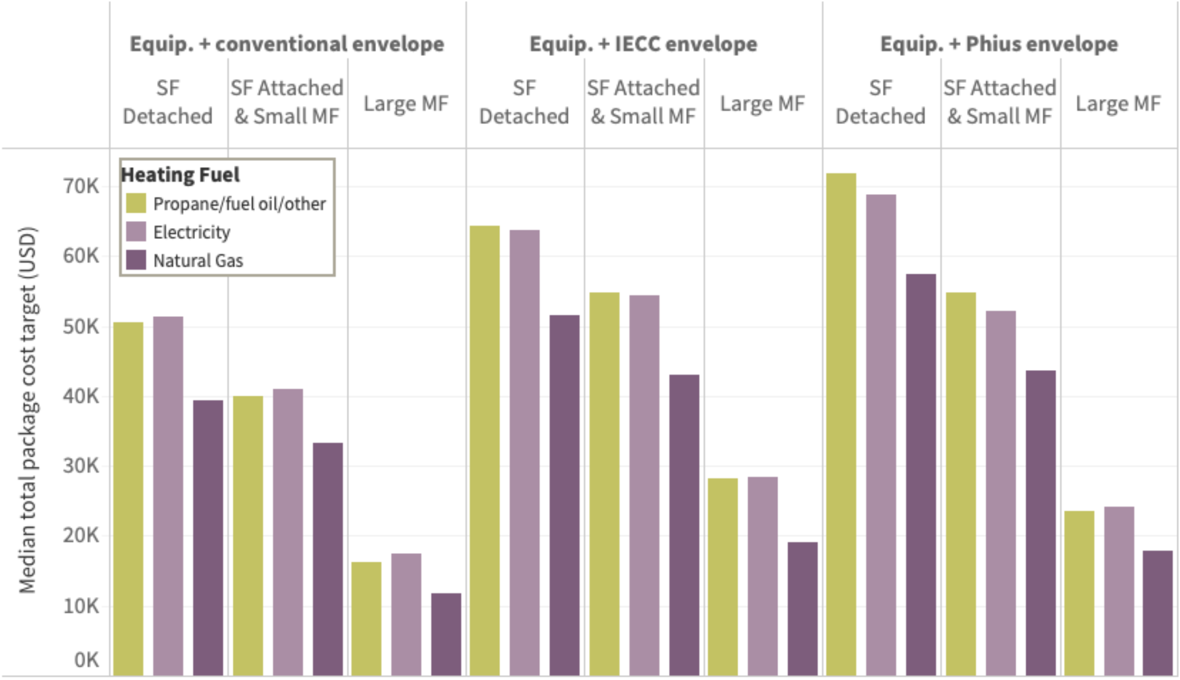

Figure 3. Median package cost target by package assignment, building type, and fuel type for northeastern states. Note, targets are per dwelling unit for small and large multifamily buildings.

The other trend shown in Figure 3 is the difference in the median cost target across heating fuel types. These findings are mostly consistent across package assignments and building types, with dwellings heated by natural gas supporting the lowest median cost targets across upgrade assignments and building types. These findings are driven by the economics of heating with natural gas compared to electricity or other non-electric fuels (e.g., delivered fuels like propane or fuel oil) under current typical utility tariffs and fuel costs. Given the low relative bill savings attainable from saving natural gas (given its lower relative price), the package bill savings for those housing units are consistently lower over the lifetime of the project and thus support a lower cost target for the upgrade. While electricity and delivered fuel-heated housing units have fairly similar cost targets across building types and assigned upgrade packages, the differences in bill savings attributable to equipment replacements versus envelope upgrades are notable, with the former being larger in electricity-heated dwellings (which, in many cases, are replacing costly electric resistance technologies with efficient heat pumps), while the latter are typically larger in dwellings heated with delivered fuels, which is due to the envelope upgrades having a larger impact on energy and utility bill savings in these dwellings.

While these results can shed some light on the building and heating fuel types that should be targeted in efforts to accelerate the deployment of whole-building retrofits given their more favorable economics, we can look further into additional building characteristics for those housing units that support the highest cost targets in our sample. For this part of the analysis, we filter our results for those housing units that have cost targets in the top 10% of all units, regardless of which upgrade package is assigned (though only the whole-building retrofits that include envelope upgrades are considered).

This filtering provides a market-sizing and prioritization for market actors that are looking for entry points to scaling whole-building retrofits. The results are shown in Figure 4, which presents a treemap visualization to highlight priority market segments and the number of housing units corresponding to various aggregations of state, heating type, and building vintage. Given the predominance of single-family homes in the region, the figure focuses on the market for single-family homes, but an interactive visualization that shows proportional priority markets for single-family and multifamily separately is available for interested readers.[3]

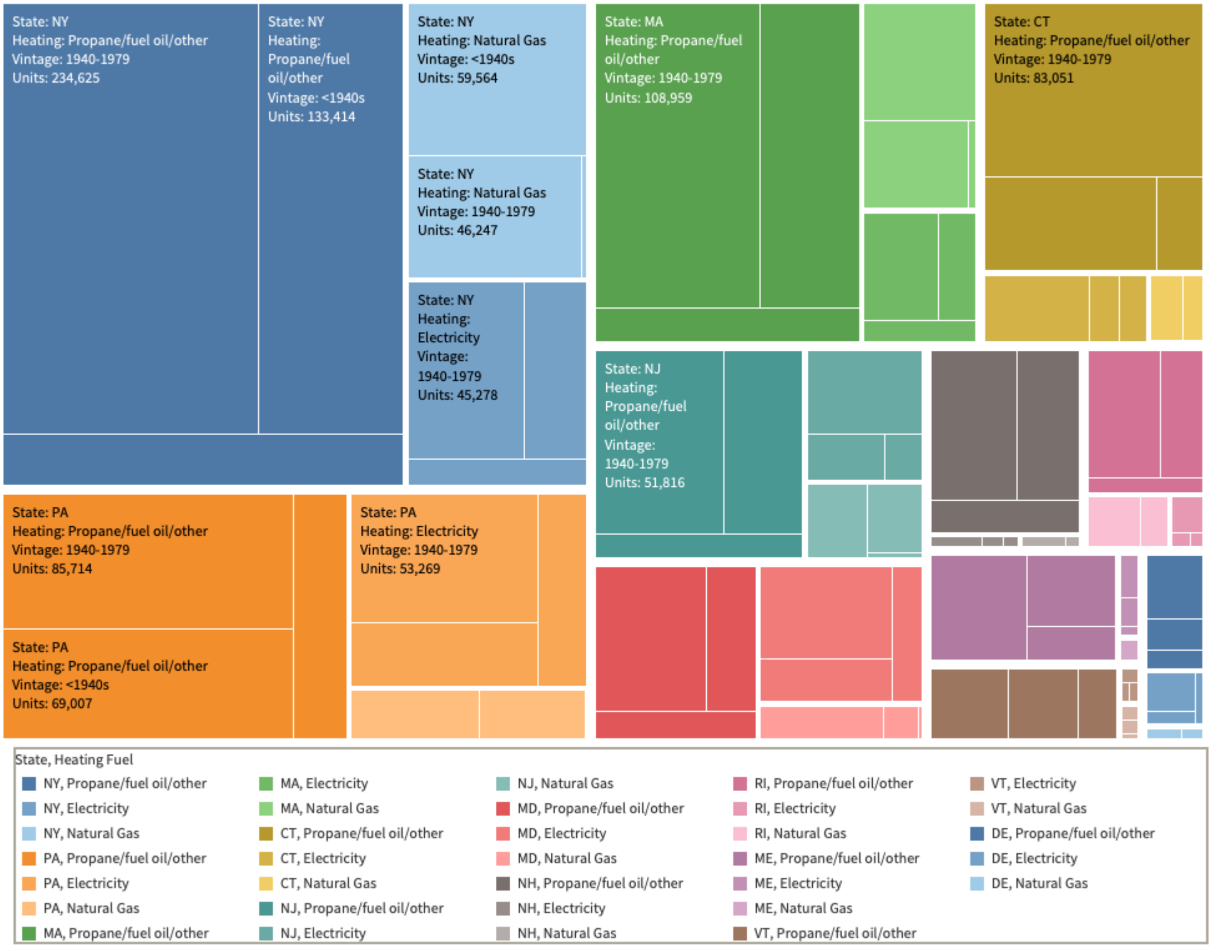

Figure 4. Housing unit characteristics for all housing units with top 10% of cost targets for each retrofit upgrade package. Boxes are sized to represent the number of housing units for a given market segment, and distinct colors represent different states while hues represent heating types within a given state. Labels are shown for select segments and note the vintage and number of units corresponding to that segment.

Figure 4 presents findings that can be used by both supply- and demand-side actors to inform the design and delivery of whole-building retrofits based on key market segment parameters. For example, a solution developer that wants to target the market for whole-building retrofits in the northeast could use these results to determine that the most favorable market-entry point in terms of potential to aggregate demand for high-value projects is in New York mid-century single-family homes that heat with delivered fuels; this represents an estimated market size of approximately 235k homes. Targeting the same market but for older homes (built before 1940) would add another approximately 133k homes. Recognizing that limiting activity to a

---

[3] Interactive dashboard of results available at: https://public.tableau.com/app/profile/aven.satre.meloy/viz/NortheastUSRetrofitPackageAssignmentandCostTargetDashboard/Figure_4_MF?publish=yes

single state may not be beneficial for market scaling, the same building typology is also common among high-value projects across multiple states (e.g., MA, PA, NJ, CT). The homogeneity of the characteristics of these typologies suggests that there is some potential for solution replicability and application to a large market of homes in need of whole-building retrofits (though building type, heating type, and vintage are only a limited subset of characteristics that are relevant to the design and delivery of these solutions).

Though not shown in Figure 4, the predominance of certain typologies throughout the northeastern housing stock is a finding that remains even when adding further segmentation variables, such as wall structure (e.g., wood frame vs. brick), HVAC system type (e.g., ducted vs. ductless), presence of window or wall insulation, and other factors that are relevant to the design of whole-building retrofit solutions. In other words, the results presented here suggest substantial opportunity for market actors to take advantage of high need based on meeting the objectives of a decarbonized building stock, high value in terms of the costs that could be supported over a project's lifetime, and high replicability potential in terms of the market size of segments that would require similar types of solutions.

Electricity System Impacts

In NY State, the distribution of recommended retrofit packages is as follows: 3.4M units receive "Equip + conventional envelope", 2.1M units receive "Equipment + IECC Envelope", 1.5M units receive "All-equipment swap-out", 0.8M units receive "Equipment + Phius Envelope", and 0.07M units require no upgrade. Results from the electricity system analysis show that adopting these upgrade packages ("Recommenced Retrofit" scenario) instead of all homes receiving the "All-equipment swap-out" package (i.e., the "Electrify Only" scenario) would decrease peak load by 11.4 GW by the year 2050 in New York. This represents more than a 25% peak load reduction through building envelope investments alongside building electrification measures. Our analysis shows that electrification across all sectors will drive considerable load growth in New York: 41.7 GW under the "Electrify Only" scenario (2.25x New York's current peak) and 30.3 GW under the "Recommended Retrofit" scenario (1.95x current peak).

We find that over 65% of peak load in 2050 is driven by the residential sector under the "Electrify Only" scenario, while this number shrinks to 50% under the "Recommended Retrofit" scenario (the residential sector contributes 43.8% of peak load in New York today), highlighting the importance of residential buildings in managing peak loads, especially as the regional electricity grid changes to winter peaking.

We find that the reduction in peak load in the "Recommended Retrofit" scenario versus the "Electrify Only" scenario adds up to a cumulative value of over $103B statewide by 2050, representing a lifetime total system value of $15,844 per dwelling unit. As shown below in Figure 5, almost 40% of this value comes from the ability to downsize HVAC systems, which would be a value stream attributed most likely to building owners (absent any emerging utility-owned HVAC programs). The remaining 60% would be savings to utilities. The primary driver of utility savings is from generation capacity; as the electricity system decarbonizes, investments in clean firm generation will be required to reach New York's zero emissions by 2040 target. As many of these technologies (including advanced nuclear, hydrogen, and natural gas with carbon capture and sequestration) are still uncertain and relatively high cost, the "Recommended Retrofit" scenario can potentially deliver increasing capacity savings over time.

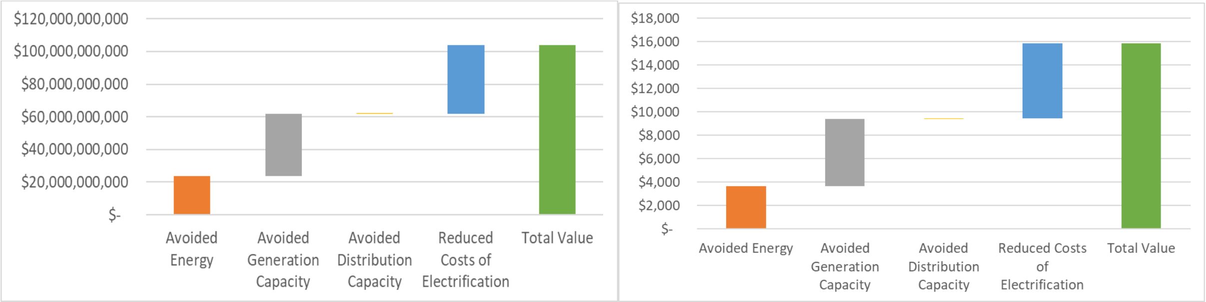

Figure 5: Cumulative value of "Recommended Retrofit" scenario over "Electrify Only" by 2050 statewide (left) and per dwelling unit (right)

It should be noted that these system-wide value results cannot be directly added to the cost targets presented above, especially as they are in relation to a scenario where all buildings electrify vs. electrifying with the recommended packages (whereas the utility bill savings that make up a portion of the cost targets are in relation to a reference case where in-kind equipment replacements occur). Rather, what it shows is that there is incremental value to be captured, including at the larger system level, as buildings electrify from accompanying the electrification measures with the recommended envelope packages. This value may not be sufficient to justify the costs of building envelope retrofits entirely without cost compression, but these value streams could help provide justification for utility programs to provide incentives specifically for building envelope retrofits to accompany building electrification.

Conclusions

This paper presented results on recommended building retrofit packages and estimated cost targets for the northeastern single-family and multifamily housing stock. It identifies both the levels of retrofit performance that are needed on a housing unit basis to align with residential building decarbonization goals and estimates the cost targets that need to be met for these retrofit projects to be financially viable (on the basis of lifetime cost-neutrality). It also highlights how retrofit recommendations and cost targets in the northeastern housing stock vary across a range of key building characteristics, such as building type, vintage, and heating fuel. The paper's results are made available via a publicly accessible, interactive data platform, which can be used by stakeholders across the residential retrofit market to inform both supply- and demand-side actors in scaling the uptake of whole-building retrofits.

We find that there is a large potential in the northeast housing market with nearly 80% of the 26 million housing units in the region needing a retrofit that includes both high-performance heat pump and envelope upgrades. Cost targets for these upgrades vary geographically within states and also across building and heating fuel types. Solutions developers that target mid-century, single-family homes that heat with electricity or delivered fuels will find a large potential market for deploying retrofit projects that have more favorable economics than do other segments of the building stock. Targeting these for early efforts to scale whole-building retrofits can provide a more promising market entry point while the costs of such projects remain high. Additionally, we find that as buildings electrify there is further incremental value to be captured at the system level for envelope-inclusive retrofits.

Our analysis did not present data on the actual costs of whole-building retrofits at the various performance levels recommended (and for the IECC/Phius-level packages this would be difficult to do given the rarity of such projects), but future work in this area is needed to understand how much the costs of these projects must be compressed in order to meet the costs that we suggest are supported by the projects' savings. In addition, while our cost targets do include estimates of the value of non-energy impacts attributable to energy efficiency retrofits, future work should attempt to better measure and quantify these. More accurate accounting could notably change the cost targets presented in this paper and make a stronger case for the consumer benefits of scaling these projects in addition to the electricity system benefits we quantify here.

References

ASHRAE. 2022. "Advanced Energy Design Guide for Multifamily Buildings." American Society of Heating, Refrigeration, and Air-Conditioning Engineers. www.ashrae.org/technical-resources/aedgs/zero-energy-aedg-free-download.

Berrill, P., E.J.H. Wilson, J.L. Reyna, A.D. Fontanini, and E.G. Hertwich. 2022. "Decarbonization Pathways for the Residential Sector in the United States." *Nature Climate Change* 12 (8): 712–18. doi.org/10.1038/s41558-022-01429-y.

EIA. 2021. "In 2020, the United States Produced the Least CO2 Emissions from Energy in Nearly 40 Years." U.S. Energy Information Administration (EIA). 2021. www.eia.gov/todayinenergy/detail.php?id=50626.

Gagnon, P., W. Frazier, W. Cole, and E. Hale. 2021. "Cambium Documentation: Version 2021." *Renewable Energy*.

Goldstein, D.B., P. Turnbull, and C. Higgins. 2018. "A National Retrofit Challenge to Meet the Paris Goal of 1.5 Degrees." In *American Council for an Energy Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*, 13. Asilomar, CA: ACEEE.

ICC. 2021. "2021 International Energy Conservation Code (IECC)." Washington, DC: International Code Council. codes.iccsafe.org/content/IECC2021P1.

Kerry, J., and G. McCarthy. 2021. "The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050." Washington, DC: U.S. Department of State and U.S. Executive Office of the President.

Langevin, J., A. Satre-Meloy, A.J. Satchwell, R. Hledik, J. Olszewski, K. Peters, and H. Chandra-Putra. 2023. "Demand-Side Solutions in the US Building Sector Could Achieve Deep Emissions Reductions and Avoid over $100 Billion in Power Sector Costs." *One Earth* 6 (8): 1005–31. doi.org/10.1016/j.oneear.2023.07.008.

Laski, J., and V. Burrows. 2017. "From Thousands to Billions: Coordinated Action towards 100% Net Zero Carbon Buildings By 2050." London: World Green Building Council. https://worldgbc.org/wp-content/uploads/2022/03/From-Thousands-To-Billions-WorldGBC-report_FINAL-issue-310517.compressed.pdf.

Less, B., I. Walker, N. Casquero-Modrego, and L. Rainer. 2021. "The Cost of Decarbonization and Energy Upgrade Retrofits for US Homes." Berkeley, CA: Lawrence Berkeley National Laboratory. escholarship.org/uc/item/0818n68p.

Mai, T.T., P. Jadun, J.S. Logan, C.A. McMillan, M. Muratori, D.C. Steinberg, L.J. Vimmerstedt, B. Haley, R. Jones, and B. Nelson. 2018. "Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States." NREL/TP--6A20-71500, 1459351. doi.org/10.2172/1459351.

Munankarmi, P., E. Wilson, J. Reyna, E. Present, S. Rothgeb, and A. Satre-Meloy. 2023. "Modeled Results of Four Residential Energy Efficiency Measure Packages for Deriving Advanced Building Construction Research Targets." NREL/TP--5500-81441, 1988149, MainId:82214. doi.org/10.2172/1988149.

National Grid. 2018. "Enhanced Marginal Cost of Service Study of Niagara Mohawk Power Corporation d/b/a National Grid to Determine Locational Value of Distributed Energy Resources." Case 15-E-0751. Syracuse, NY: Niagara Mohawk Power Corporation d/b/a National Grid.

NREL. 2020. "ResStock Analysis Tool." Golden, CO. www.nrel.gov/buildings/resstock.html.

———. 2022a. "End-Use Savings Shapes Residential Round 1 Technical Documentation and Measure Applicability Logic." ResStock. 2022. https://tinyurl.com/29pz3wmu.

———. 2022b. "ResStock." Public Datasets. 2022. resstock.nrel.gov/datasets.

Phius. 2021. "Phius CORE Prescriptive 2021 Checklist." Phius. March 1, 2021. www.phius.org/phius-core-prescriptive-2021-checklist.

RESNET. 2021. "Draft PDS-01, BSR/RESNET/ICC 301-2022 Addendum B, CO2 Index." Residential Energy Services Network (RESNET). 2021. https://tinyurl.com/mf477vp2.

Reyna, J., E. Wilson, A. Satre-Meloy, A. Egerter, C. Bianchi, M. Praprost, A. Speake, et al. 2022. "U.S. Building Stock Characterization Study: A National Typology for Decarbonizing U.S. Buildings." NREL/TP-5500-83063. Golden, CO: National Renewable Energy Laboratory. www.nrel.gov/docs/fy22osti/83063.pdf.

Skumatz, L.A. 2014. "Non-Energy Benefits / Non-Energy Impacts (NEBs/NEIs) And Their Role & Values In Cost-Effectiveness Tests: State Of Maryland Final Report." Superior, CO: Skumatz Economic Research Associates, Inc. (SERA).

Webster, B., A. Satre-Meloy, L. Badger, A. Donovan, D. Lane, K. McGrath, E. Wilson, et al. 2024. "Accelerating Residential Building Decarbonization: Market Guidance to Scale Zero-Carbon-Aligned Buildings." Advanced Building Construction Collaborative.

Wilson, E., A. Parker, A. Fontanini, E. Present, J. Reyna, R. Adhikari, C. Bianchi, et al. 2022. "End-Use Load Profiles for the U.S. Building Stock: Methodology and Results of Model Calibration, Validation, and Uncertainty Quantification." NREL/TP-5500-80889, 1854582, MainId:78667. doi.org/10.2172/1854582.

Wilson, E.J.H., P. Munankarmi, B.D. Less, J.L. Reyna, and S. Rothgeb. 2024. "Heat Pumps for All? Distributions of the Costs and Benefits of Residential Air-Source Heat Pumps in the United States." *Joule* 0 (0). doi.org/10.1016/j.joule.2024.01.022.