Target-Setting Methodology for the Affordable Home Energy Shot

January 2025

DOE/EE-2971

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Acknowledgments

The authors would like to acknowledge the other members of the Affordable Home Energy Shot working group who contributed to this analysis and offered important feedback and suggestions, including: John Agan, Kelly Crawford, Adam Hasz, Dale Hoffmeyer, Devinn Lambert, Ramachandran Narayanamurthy, Michael Pechan, Rachel Pierson, Tony Reames, Michael Reiner, Roland Risser, and Kelly Visconti.

The authors would like to acknowledge those who reviewed this report throughout its development, including: John Agan, Ashley Armstrong, Colin Cunliff, Susan Hamm, Terrence Mosley, Michael Pechan, Rachel Pierson, Michael Reiner, Elisah VandenBussche, Lupe Villatoro, and Brian Walker.

The authors would like to acknowledge the ResStock team for generating the underlying data forming the core of this analysis. The authors would also like to thank Janet Reyna and Gretchen Maia for providing descriptions of efforts to incorporate Alaska and Hawaii into future ResStock datasets.

The authors would like to thank and acknowledge Rachel Pierson for her tireless leadership of the Affordable Home Energy Shot team during her tenure in the Office of the Under Secretary for Science and Innovation.

List of Acronyms

AC	air-conditioning
ACS	American Community Survey
AMI	area median income
ASHP	air-source heat pump
BAU	business-as-usual
DHW	domestic hot water
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
HEAR	Home Electrification and Appliance Rebates
HOMES	Home Efficiency Rebates
GHG	greenhouse gas
HSPF	heating seasonal performance factor
HVAC	heating, ventilation, and air-conditioning
IEA	International Energy Agency
IIJA	Infrastructure Investment and Jobs Act
IRA	Inflation Reduction Act
LIHEAP	Low Income Home Energy Assistance Program
LMI	low- and moderate-income; ≤80% of AMI
NEEP	Northeast Energy Efficiency Partnerships Inc.
NPV	net present value
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research and Development Authority
PG&E	Pacific Gas & Electric Company
PSE&G	Public Service Enterprise Group Incorporated
PUMA	Public Use Microdata Area
PUMS	Public Use Microdata Sample
RECS	Residential Energy Consumption Survey
SEER	seasonal energy efficiency ratio
SIR	savings-to-investment ratio
U.S.	United States
WAP	Weatherization Assistance Program

Executive Summary

In October 2023, the United States (U.S.) Department of Energy (DOE) announced the launch of the Affordable Home Energy Shot™, a new initiative focused on the research, development, and demonstration of clean energy solutions to decarbonize and deliver energy and cost savings for affordable homes. The Affordable Home Energy Shot™ aims to reduce the cost of decarbonizing affordable homes by at least 50% and decrease residents' energy costs by at least 20% within a decade.

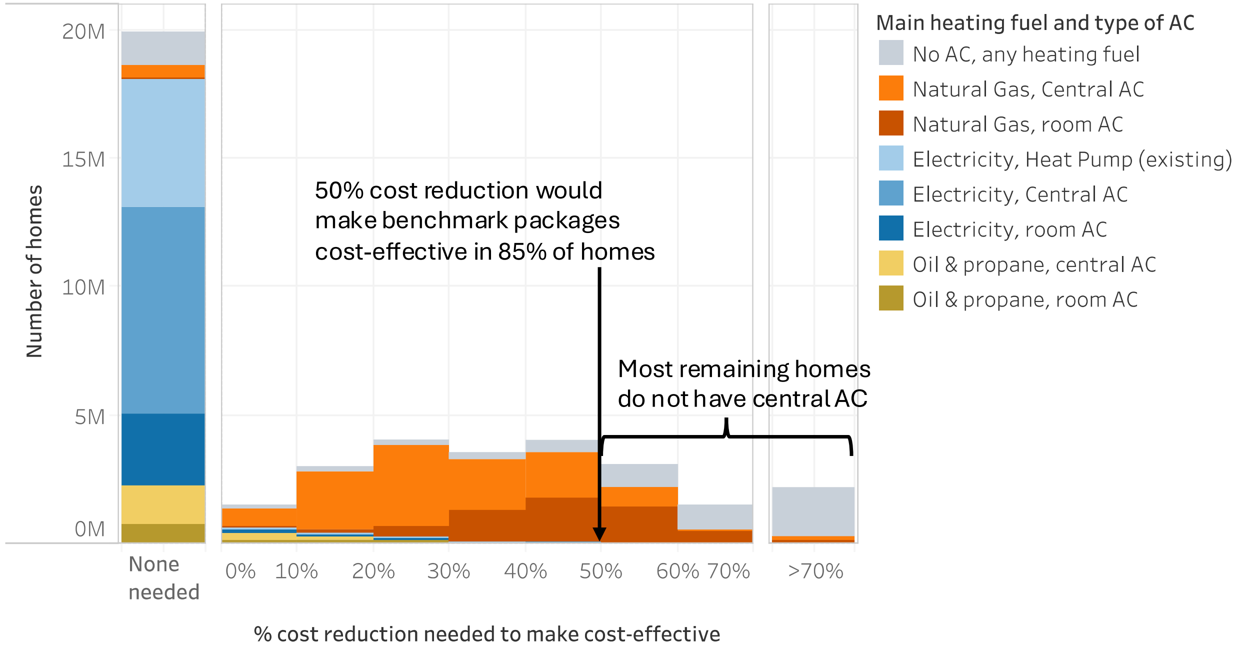
The Affordable Home Energy Shot aims to advance both building decarbonization and energy justice by directing DOE research and development resources toward retrofit technologies designed to be accessible for households with low incomes, historically underserved communities and populations with protected characteristics. This report documents the process used to set numeric targets for the Affordable Home Energy Shot, while also providing an innovative case study for incorporating distributional equity considerations into analysis of residential building technologies for a federal research and development initiative.

Figure ES-1 summarizes how the target of 50% cost reduction was selected. Currently available technology is already cost-effective for at least 45% of households that make less than or equal to 80% of the area median income (AMI).[i] This demonstrates the large opportunity for today's existing deployment programs, including the $8.8 billion Home Energy Rebates Program that is part of the Inflation Reduction Act of 2022.

At the same time, there is a large fraction of these households where such decarbonization packages are not currently cost-effective, even with incentives. As a result, these already-disadvantaged households are likely to miss out on the significant benefits associated with home energy upgrades. These benefits include increased resilience to extreme cold and heat, increased passive survivability during extreme weather events coupled with utility outages, and other health benefits associated with reduced exposures to indoor and outdoor pollutants. The Affordable Home Energy Shot™ aims to make sure these households can also benefit from home energy solutions that will save them money while improving their wellbeing.

With a 50% reduction in up-front costs, 85% of households making less than or equal to 80% of the AMI can cost-effectively realize the benefits of a high-performance home. Nearly all of the remaining 15% of households live in homes that currently lack whole-home air conditioning, and many lack air conditioning of any kind. Retrofit packages with heat pumps would extend air conditioning access to this segment of homes. While not directly quantified in the traditional cost-effectiveness test used in this analysis, access to air conditioning is a key benefit that provides protection from the serious health risks associated with excess heat exposure. Continued assistance through federal, state, and local programs, together with research and development efforts like the Affordable Home Energy Shot™, is needed to deploy energy-saving and life-improving technology to the households that need it most.

[i] We use consumer net present value as a metric for cost-effectiveness, which excludes societal benefits and costs. The use of net present value is not intended to represent likely adoption of technologies. Rather, net present value is used to indicate the level of economic potential adoption that could be achieved with sufficient effort—in the form of financing, incentive programs, and other market transformation work—to reduce the economic and non-economic barriers to adoption.



ES-1. Distribution of the cost reduction needed to make at least one of the six modeled benchmark home upgrade packages cost-effective across all households making less than or equal to 80% of the area median income (AMI)

See section 3.4 for details. Homes in gray are those that currently lack any air conditioning; the benchmark packages add air conditioning services to these homes, which add energy usage but also unquantified co-benefits, complicating the use of net present value (NPV) alone to communicate their value. As explained in section 3.2, the NPV includes a pessimistic assumption of $10,000 in electrical upgrades per dwelling unit for all homes not currently using electricity for heating, as well as duct upgrades for homes in Cold and Very Cold climate zones, so this figure is likely an underestimate of current cost-effectiveness.

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1. Introduction

In October 2023, the United States (U.S.) Department of Energy (DOE) announced the launch of the Affordable Home Energy Shot™, a new initiative focused on the research, development, and demonstration of clean energy solutions to decarbonize and deliver energy and cost savings for affordable homes. The Affordable Home Energy Shot™ aims to reduce the cost of decarbonizing affordable homes by at least 50% and decrease residents' energy costs by at least 20% within a decade. This report documents the process used to set these targets, while also serving as a case study for evaluating the distributional impacts of new technologies.

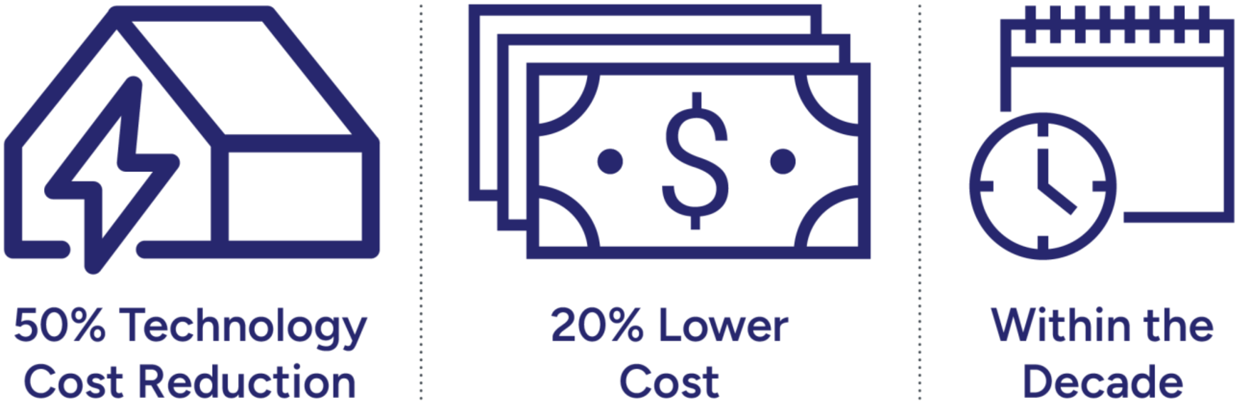

Figure 1. Overview of the Affordable Home Energy Shot™ target

1.1. Motivation

The intent of the Affordable Home Energy Shot is to address the persistent burdens faced by low-income households and communities of color. More than one in four (27%) U.S. households had trouble meeting their energy needs in 2020, including 20% that were forced to spend less on food, medical, or other basic necessities to pay their energy bills.[1] In 2023, one in five American adults lived in a household that was behind on energy bill payments by at least one month.[2] These trends disproportionately impact renters and homeowners with low incomes—who often live in older homes that lack adequate insulation and energy-efficient appliances.

These households not only suffer economic insecurity but are also less likely to benefit from the significant health and resilience benefits that building energy upgrades would bring. For example, building envelope improvements make a home more resilient to extreme weather.[3, 4] In the United States, approximately 2,000 heat-related or cold-related mortalities are observed annually in cause-of-death medical records (2006–2010 average), and approximately 100,000 U.S. mortalities are linked to non-optimal temperatures each year via epidemiological analysis.[5, 6, 7] Upgrades can also result in improved indoor and outdoor air quality, resulting in fewer asthma attacks and other adverse health impacts. Decarbonization of the U.S. building stock was estimated to avoid $17 billion in annual healthcare expenditures via improved outdoor air quality.[8] These benefits are in addition to the energy savings benefits accounted for in the cost-effectiveness measure.

Additionally, one-third of U.S. greenhouse gas (GHG) emissions are attributable to America's 130 million homes and commercial buildings. The buildings sector uses 40% of the nation's energy and 74% of its electricity for power, heating, and cooling.[9]

To address the critical challenges of decarbonizing the buildings sector and improving the energy affordability of our nation's housing, DOE launched the eighth Energy Earthshot™—the Affordable Home Energy Shot™—which seeks to accelerate innovative strategies that will reduce the cost of decarbonizing our nation's residential buildings.

1.2. Focus on Existing Affordable Homes

While increasing the supply of new housing can help improve overall housing affordability, an estimated 75% of today's homes will still exist in 2050.[10] The Affordable Home Energy Shot directs DOE's research and development (R&D) resources and strategy towards ensuring that decarbonization solutions benefit those households in the greatest need—specifically, the 50 million single-family, multifamily, and manufactured existing homes rented or owned by households earning less than or equal to 80% of the area median income (AMI). For the Affordable Home Energy Shot, we define "affordable homes" as this set of 50 million homes, which includes both subsidized and unsubsidized (naturally occurring) affordable housing, as well as homes considered unaffordable because of high rent or mortgage payments.

By targeting the design barriers most prevalent in this set of homes, this Energy Earthshot will advance retrofit solutions that lead to more efficient, healthy, and resilient homes in low-income communities, as well as across the residential building stock more broadly.

1.3. Three Innovation Areas

DOE is focused on three innovation areas to address the design barriers most prevalent in affordable homes: **building envelope**, **efficient electrification**, and **smart controls**. Across the three areas, the approach strives to advance technologies and installation solutions that are scalable and provide the opportunity for creating wealth and investment in communities through the growth of small businesses and entrepreneurs.

Table 1. Innovation Areas

Building envelope	**Efficient electrification**	**Smart controls**
Innovations in insulation, air sealing, and windows improve livability and make homes more resilient.	Innovations improve the affordability, comfort, and performance of electric equipment.	Flexible energy loads transform homes into energy resources.
Example innovations: • Advanced leakage detection • Low-impact retrofit techniques • Panelized exterior insulation	Example innovations: • Lower-voltage equipment • Compact heat pump units • Integrated ventilation packages	Example innovations: • Smart electric panels and load management • Grid-interactive technologies • Shared circuit control between loads

1.4. Relationship to Existing Energy Efficiency Efforts

The potential for cost-effective energy efficiency measures in low-income households is large.[11] Some portion of that potential is achieved through existing state, utility, and federal programs. For example, utility energy efficiency programs spent an estimated $936 million on low-income programs in 2019,[12] and DOE's Weatherization Assistance Program (WAP) allocated grantees approximately $329 million in funding in 2024[13] and received an infusion of $3.5 billion in funding in the Infrastructure Investment and Jobs Act (IIJA).[14] The Low Income Home Energy Assistance Program (LIHEAP), which received $4.1 billion in funding in federal Fiscal Year 2024 (including approximately $100 million from IIJA),[15] also allows grantees to allocate up to 15% of their LIHEAP funding for weatherization or 25% with an approved federal waiver from the U.S. Department of Health and Human Services (HHS). LIHEAP is administered by the Administration for Children and Families within HHS. In federal Fiscal Year 2024, grantees' LIHEAP allocations for weatherization, according to estimates provided in their state plans,[ii] totaled approximately $500 million.[16, 17]

A number of provisions in the Inflation Reduction Act (IRA) aim to facilitate energy- efficiency retrofits for low-income households. For instance, point-of-sale rebates through the $4.5 billion Home Electrification and Appliance Rebates (HEAR) programs make it more affordable for households to carry out efficiency upgrades and install high-efficiency home appliances and equipment.[18] HEAR rebates are only available to low- and moderate-income (LMI) households, with $225 million in funding specifically allocated for Tribes. IRA also increases and extends through 2032 energy-efficient home improvement tax credits that subsidize expenditures for qualifying improvements to existing residences that satisfy certain efficiency standards and other requirements, including upgraded building envelope components, heating and cooling systems, and electrical panels.[19]

Nevertheless, much of the potential for cost-effective energy efficiency upgrades for low-income households is ultimately not captured by existing programs because of limited program budgets and various other economic and non-economic barriers. For example, while about one in four U.S. households is low-income, low-income households receive only about 13% of utility energy-efficiency spending.[20] WAP has provided building envelope upgrades to over 7 million low-income households since its inception in 1976, and its funding levels are able to support upgrades for approximately 35,000 homes per year.[21] However, as of 2023 more than 38.6 million households were eligible for WAP assistance, three orders of magnitude above the program's annual assistance rate.[22] Some of these households live in dwellings that require rehabilitation and repairs beyond the scope of WAP and would therefore require pre-weatherization investments to qualify for assistance. LIHEAP funding levels for weatherization efforts are similar in magnitude to WAP funding levels. Grantees are only allowed to allocate a maximum of 15% of their LIHEAP funding for weatherization (or 25% with an approved federal waiver)—LIHEAP funds are primarily distributed in the form of direct financial assistance to help low-income households pay their energy bills.

Achieving the Affordable Home Energy Shot target could increase such programs' ability to decarbonize the affordable housing stock and deliver energy cost savings and other co-benefits to low-income households. Technologies' up-front cost and energy savings are major determinants of whether they can be deployed through energy efficiency programs. WAP prioritizes decarbonization measures based on their cost-effectiveness, and measures are only eligible if their

[ii] This figure is derived from estimates provided in grant recipient state plans for federal Fiscal Year 2024 and is therefore not representative of the total amount transferred. Final reporting on total transfers within federal Fiscal Year 2024 has not yet been yet been submitted to HHS.

savings-to-investment ratio (SIR) meets or exceeds 1.0, meaning resulting energy cost savings over their lifetime (discounted to present value) equal or exceed their up-front cost.[23, 24] States maintain this SIR requirement in their LIHEAP weatherization plans, though some offer exceptions.[25] Many utility low-income energy efficiency programs have similar cost-effectiveness criteria—requirements vary broadly by state.[26]

1.5. Background on Distributional Equity Analysis

A large body of research focuses on modeling potential pathways toward decarbonization of the U.S. economy. These modeling efforts typically project decarbonization pathways that reduce GHG emissions while minimizing cost and typically have a national-scale focus that aggregates the U.S. population across sociodemographic characteristics. These pathways focused on optimizing economic efficiency are unlikely to address the long-standing inequities in the energy system's impacts on different sub-populations. Households with low incomes, for instance, typically spend a much larger share of their incomes on electricity, heating, and transportation fuels, bearing much higher housing energy and transport energy burdens.[27] These households are also more likely to limit their energy use out of economic necessity, making them more vulnerable to heat- and cold-related health impacts. One of the root causes of these challenges is that low-income households are more likely to live in older, less energy-efficient homes with less efficient appliances.[28] A review of energy-efficiency retrofits—mostly retrofits of low-income households—observed that subjective reports of thermal comfort/discomfort, non-asthma respiratory symptoms, general health, and mental health nearly always improve after retrofit implementation.[29]

Modeling efforts that evaluate the distributional impacts of decarbonization and technology deployment pathways—that is, how their impacts differ across geographic and demographic communities—can help identify decarbonization strategies that advance energy equity. Spurlock et al. (2022) developed a framework mapping the practice of large-scale decarbonization pathways modeling to the tenets of energy justice: recognition, procedural, distributional, and restorative justice.[30] This framework positions restorative justice, which calls for repairing historical harms done to communities, as the central criterion that should inform all steps of modeling study development. Recognition justice calls for historical context to motivate which target populations (e.g., low-income households) are explicitly recognized and disaggregated within the study. Procedural justice calls for engaging with the recognized communities to define the outcome metrics that matter to people in those communities. Distributional justice calls for the modeling to estimate outcome metrics at a high enough level of spatial resolution, with models that are responsive to the underlying heterogeneity such that non-linear correlations between population characteristics and outcome metrics can be sufficiently captured.

A number of recent national-scale studies have analyzed the distributional impacts of decarbonization across income levels in the context of federal climate policy, both hypothetical and recently adopted (i.e., IRA).[31, 32, 33] These high-level studies use a range of power sector and energy system models in combination with national survey data on consumer expenditures and sociodemographic characteristics. Their results provide insights on supply-side and climate policy strategies for reducing energy burden in low-income households. Complementary analysis efforts are necessary to evaluate approaches for equitably decarbonizing our nation's homes, businesses, and community buildings. Recent national-scale and place-based analyses, for example, have disaggregated households by income and other relevant factors (e.g., renter status, housing characteristics) to explore the cost-effectiveness and economic and environmental impacts of specific retrofit measures.[34,35] Other recent examples of distributional equity analysis evaluated the influence of behavioral factors on retrofit decisions[36] and the potential impacts of IRA Home Energy Rebates (i.e., HOMES and HEAR programs).[37]

The Affordable Home Energy Shot aims to advance both building decarbonization and energy justice by directing DOE R&D resources toward retrofit technologies designed to be accessible for households with low incomes, underserved communities and populations with protected characteristics. Its target-setting analysis leverages ResStock, which statistically models the diversity of the U.S. housing stock to provide a detailed assessment of how upgrade costs and energy savings would be expected to vary based on over 100 building characteristics, including location, building type, insulation, appliance efficiency, floor area, and heating fuel.[38] The underlying ResStock dataset assesses the cost and benefits of a range of benchmark upgrade packages, providing cost-effectiveness distributions with high geospatial and building characteristic granularity.[39] To compare the cost-effectiveness of these retrofit packages for lower- versus higher-income households across different locations and building types, the target-setting analysis uses household income probability distributions developed from national survey data, along with the non-linear correlations between housing characteristics, household income, and renter status.

This analysis provides an innovative case study for incorporating distributional equity considerations into analysis of residential building technology for a federal R&D initiative. By explicitly modeling the characteristics of the housing stock occupied by low-income households facing long-standing inequities, the analysis incorporates recognition justice centered around restorative justice, as called for in the Spurlock et al. (2022) framework. The high resolution of the ResStock modeling enables the analysis to address distributional justice by evaluating the cost-effectiveness of benchmark energy-efficiency retrofits for these target households versus the rest of the U.S. population. This approach also aligns with the distributional equity analysis framework recently developed by Woolf et al. (2024) for DOE's Building Technologies Office, a guide for incorporating equity consideration into utilities' decisions about investments in distributed energy resources.[40] Taking a narrower focus on such investment decisions, Woolf et al. (2024) likewise discuss identification of priority populations, development of equity-focused metrics, and use of data and analysis to estimate these metrics for the priority population and the rest of the utility customers.

As emphasized by both Spurlock et al. (2022) and Woolf et al. (2024), procedural justice—meaningfully engaging recognized communities and stakeholders for input to guide analysis development—is the bedrock of distributional equity analysis. Target setting for the Affordable Home Energy Shot sought first to establish a level of ambition consistent with broader decarbonization and affordability goals, based on internal analysis. Now that the Energy Earthshot has been launched publicly, DOE is eager to engage stakeholders, including occupants of the affordable housing stock targeted by this initiative, and incorporate their feedback into implementation through both future analyses and technology R&D and demonstration. To kickstart this dialogue, DOE hosted the inaugural Affordable Home Energy Shot Summit in June 2024, a virtual event that was open to the public and convened stakeholders ranging from federal and state government officials to advocates and community leaders focused on affordable housing. Moving forward, engaging with communities and integrating their perspectives will be vital to achieving the ambitious targets developed in this analysis.

2. Survey of Cost Compression Opportunities

Historical installed costs for building decarbonization technologies have not been formally tracked over time. Going forward, such costs—and their possible future cost trajectories—will be tracked in the Buildings Annual Technology Baseline, a new cost assessment dataset supported by DOE, with the initial release expected in 2025.

For this target-setting exercise, we surveyed the costs and cost-compression opportunities for established and emerging residential decarbonization technologies across the United States and

Europe. Less et al. (2021) collected residential decarbonization project costs from programs around the United States.[41] They found that upgrade costs varied by project size and scale but were typically on the scale of tens of thousands of dollars for deep energy retrofits with energy savings of 30–50%. To study the costs of specific decarbonization measures, a convenience sample of ~1,700 home energy upgrade projects collected cost data for ~10,000 individual measures.[42] Approximately two thirds of these projects reported some type of rebate or incentive, with about half of the projects reporting monthly cost savings when financed without rebates. The lowest-cost approaches to achieve high energy savings and emissions reductions combined equipment electrification alongside on-site solar and moderate weatherization measures such as air sealing, attic insulation, or cavity-fill insulation.[43] The authors observe that home energy upgrades are moving beyond superinsulation strategies due to their current high costs.[44]

A recent report estimated cost targets for residential decarbonization packages that would make the packages economically viable, defined as having positive net present value.[45] While the report did not attempt to estimate current costs, it found to achieve economically viable decarbonization of every home across all studied states and housing types, package costs would need to be reduced significantly, to as low as $20,000 for some homes. Economically viable decarbonization of the median home would require target package costs varying between roughly $40,000 and $80,000 based on state, housing type, and envelope upgrade package.

2.1. Cost Compression Studies

A 2021 literature review reported typical costs (collected between 2016 and 2021) for ductless air-source heat pumps (1-ton, single-zone: $4,000–$5,500) and heat pump water heaters ($2,600–$4,700), with additional premiums for higher efficiency, including in cold climates, and extra interior zones.[46] Pathways have been proposed for potential cost reductions of ductless air-source heat pumps (ASHPs) by 29% and heat pump water heaters by 41% as driven by 120V equipment that avoids electrical upgrades, a 5% bulk-volume discount, and several soft-cost-reduction strategies.[47]

A business's "gross margin" is the fraction of revenue that remains after subtracting the direct costs associated with goods sold; the remainder is largely composed of business operations, overhead costs, and profit. Substantial savings opportunities related to decarbonization-measure soft costs were identified by comparing gross margins in the home performance subsector (~48%) against the residential remodeling (30-35%) and general contracting and renewable energy (10–25%) subsectors.[48, 49] Many soft costs are associated with professional services and project management. Some soft costs may be unique to the home performance industry and remain necessary, such as measurements of airflow or duct leakage, while others might reasonably be eliminated, such as a combustion check in a home with all-electric equipment. Improvements to both scale and business processes are suggested to bring gross margins of the home performance industry in line with other construction industries, with potential cost reductions of ~20% if alignment is achieved.

New York's Carbon Neutral Buildings Roadmap (2022) reviewed potential cost reductions through 2040 for several decarbonization technologies.[50] Moderate-to-large potential price reductions were reported for ASHPs (16%), geothermal heat pumps (28%), heat pump water heaters (35%), high-performance windows (24%), and prefabricated panels for envelopes (40%), with maximum cost reduction estimates being an additional 10% greater in magnitude for most technologies. Reported innovation thresholds, defined as literature cost reduction estimates yielding widespread adoption or as "moonshot" targets, were higher than the Roadmap's maximum cost reduction estimates for ASHPs (40%), geothermal heat pumps (50%), heat pump water heaters (50%), high-performance windows (45%), and prefabricated panels for envelopes (55%).

2.1.1. Learning Curves and Cost Projections

Costs are expected to fall with increasing production scale. Cost reductions can be modeled via learning curves derived from historical cost and production data.[51, 52, 53] While more complex models exist, a learning rate of 10% indicates that a doubling of production volume would yield a 10% reduction in cost as indicated by historical precedent. When the central tendency of ASHP learning rates observed in the literature (9.8%) was applied to a European “electrify everything” scenario, costs were projected to fall 29% (range: 11–44%) between 2016 and 2050.[54] A more recent study identified a similar learning rate of 11.1% in the Dutch market.[55]

Future ASHP costs were also studied under the International Energy Agency’s (IEA’s) Sustainable Development Scenario, a future projection of the energy sector that would achieve key emissions-reduction targets such as the Paris Agreement.[56] The study estimated future cost decreases of ~7% between 2019 and 2030 and 23% over the full 2019–2070 study window, assuming that spillover technology developments from the larger air conditioning (AC) sector would benefit heat pumps. As the study had a global scope, it is not clear if spillover from air-conditioning (AC) deployment would apply in the United States, where AC is already commonplace. In a restricted analysis without spillover benefits, heat pump costs decreased by ~1% by 2030 and by 11% by 2070. Cost projections were limited to the heat pump equipment cost and excluded both geothermal applications and additional components needed for the final operational system.

2.2. HVAC Producer Price Index

In recent years, heating, ventilation, and air-conditioning (HVAC) equipment price increases have outpaced overall inflation by almost a factor of two: the HVAC producer price index has increased 43% (63%) in the last 5 (10) years, while the consumer price index has increased by only 23% (32%).[57, 58] This feature is expected to be in part attributable to trailing supply-chain pressures from the COVID-19 pandemic. Future transitions to low-global-warming-potential refrigerants may also slow potential heat pump cost reductions. One manufacturer expects air conditioner and heat pump equipment prices to increase 15–20% over the next 2 years (2024–2026).[59]

2.3. Survey of Electrical Upgrade Costs

Switching a fossil-fired furnace, boiler, and/or water heater to an electric heat pump and/or heat pump water heater may require expensive upgrades to a building’s electrical infrastructure and service in order to accommodate the new electric load(s). To characterize the potential costs of these electrical upgrades and ensure that they are considered in our analysis, we conducted a review of upgrade cost estimates in both existing literature and online references. Table 2 shows the cost estimates that were retrieved for key customer- and utility-owned electrical infrastructure components. The largest costs come from the need to replace utility-owned transformers and poles, and these costs may be incurred by customers in certain cases—for example, if their home is the only one on the transformer.[60] Customers may also incur significant costs for upgrading utility service wires and breaker panels. The cost range for the latter set of upgrades varies widely, with higher-end estimates near $5,000 a piece, though service upgrade fees could be more expensive still depending on the situation.

Table 2. Survey of Electrical Upgrade Costs Associated With Residential Electrification Upgrades (excludes new circuit wiring, which is included in measure costs)

Item	Min	Max	Source	Notes
Service breaker panel upgrade	$1,300	$5,000	NV5 report for Pacific Gas & Electric Company (PG&E)[61]	
	$750	$2,000	HomeAdvisor.com[62]	upgrade to 200 amp
	$1,300	$2,500	HomeGuide.com[63]	upgrade to 200 amp
	$1,200	$2,000	Angi.com[64]	upgrade to 200 amp
	$1,800	$4,500	Fixr.com[65]	upgrade to 200 amp
	$2,744	$4,256	E3 Report[66]	min = low-rise multifamily max = single-family
	$750	$2,000	New York State Energy Research and Development Authority (NYSERDA) Report (not public)	N = 18, LMI homes
Service wire, meter box, and other upgrades	$1,300	$5,000	NV5 report for PG&E[67]	homeowner equipment service upgrade fee
	$100	$4,650	Angi.com[68]	min = meter box max = meter box plus relocation of panel
	$200	$8,300	HomeAdvisor.com[69]	min = meter box max = entrance cable plus relocation of panel plus meter replacement
	$200	$4,800	Fixr.com[70]	min = meter box max = meter box plus relocate panel
		$5,000	Public Service Enterprise Group Incorporated (PSE&G) Incentives Website[71]	Under this program, residential customers can receive up to $1,500 for a behind-the-meter Level 2 charger installation and up to $5,000 for pole-to-meter service upgrades.
Transformer	$6,000	$8,000	NV5 report for PG&E[72]	
Pole replacement	$9,000	$11,000	NV5 report for PG&E[73]	

The frequencies with which upgrades will be necessary are not well understood, but are generally expected to be higher in older buildings, older neighborhoods, lower-income neighborhoods, and buildings without central air conditioning.

3. Target Setting Procedure

Building on the literature review described in the previous section, the procedure for setting targets for the Affordable Home Energy Shot took the following steps:

1. Characterize the U.S. affordable housing stock using a ResStock dataset.

2. **Develop an *up-front cost benchmark*** for benchmark packages of representative technologies currently on the market, including building envelope upgrades, ASHPs, and heat pump water heaters.[iii] Assess how these benchmark costs vary across diverse climates, building types, and other characteristics of the U.S. affordable housing stock.
3. **Develop a *cost-effectiveness benchmark***. Evaluate the energy cost savings of the benchmark upgrades across the diversity of the U.S. affordable housing stock to understand in which situations the benchmark upgrades are cost-effective (i.e., the present value of the energy cost savings over the useful life of the upgrades is greater than the up-front cost).
4. **Select an up-front cost reduction target** that, if applied to the benchmark packages, would result in upgrades being cost-effective in most affordable housing units, including the application of modest incentives necessary in some situations.
5. **Determine an energy cost savings target** that corresponds to the approximate level of energy cost savings resulting from the benchmark package.

The remainder of this section is organized around these five steps. See section 3.6 for limitations of the analysis.

3.1. Characterize the U.S. Housing Stock

The up-front cost benchmark, energy savings, and cost-effectiveness benchmark at the core of this target-setting analysis were developed using ResStock. ResStock is a DOE model of the U.S. housing stock with datasets of results that are publicly released. Using 550,000 representative dwelling unit samples—one for every 242 real homes—ResStock provides a detailed picture of how upgrade costs and energy cost savings would be expected to vary across the diversity of the U.S. housing stock with very high resolution (see Figure 2). This high-resolution representation of housing stock diversity makes ResStock an ideal tool for evaluating the distributional impacts of residential energy technology adoption, programs, and policies on different groups of households.

ResStock uses large public and private data sources, statistical sampling, detailed sub-hourly building simulations, and high-performance computing to evaluate what-if technology scenarios for 550,000 statistically representative households. For a more detailed description of the methodology, data sources, calibration, and validation, see Wilson et al. (2022).[74] For a detailed description of the simulation results dataset used for this analysis, see Wilson et al. (2024).[75] In brief, the ResStock methodology used for this analysis involved the following components.

Stock Characterization

The model first describes the U.S. housing stock with over 100 building characteristics that impact energy consumption. These include geographic, building, and sociodemographic characteristics such as climate zone, appliance ownership and efficiency levels, insulation amount, building type (e.g., single-family detached, multi-family with 2-4 units), floor area, heating fuel, income, tenure (renter vs. owner), and many others.

These characteristics are derived from public data sources, such as the U.S. Energy Information Administration's (EIA's) Residential Energy Consumption Survey (RECS) and U.S. Census Bureau's American Community Survey (ACS). For a full list of data sources, see Table 1 in Wilson

[iii] As explained in the introduction, the scope of the Affordable Home Energy Shot potentially includes a wide range of technologies across the three pillar areas (building envelope, efficient electrification, and smart controls). The technology package used for this analysis was for the purpose of setting the cost benchmark and does not imply that these are the only technologies within the scope of the initiative.

et al. (2022).[76] These sources have been queried for conditional probability distributions for building stock characteristics and demographics.

Development of Income Probability Distributions

The ResStock dataset[77] used for this target-setting analysis was generated before household income characteristics were added to ResStock.[iv] Input files containing sets of probability distributions for two income-related characteristics (absolute household income and percentage of AMI) and tenure (owner-occupied or renter-occupied) were developed for ResStock in 2022.

Probability distributions for household income and tenure were queried from the ACS Public Use Microdata Sample (PUMS), 2019 (5-yr sample).[78] Probabilities for three tenure categories (owner, renter, and not available) were queried for each combination of five building types (the ACS “Units in structure” field was collapsed to the five types from EIA RECS field TYPEHUQ), 2,351 public use microdata areas (PUMAs), and two vacancy statuses (occupied or vacant), for a total of 23,510 combinations.[79] Probabilities for 19 discrete bins of gross household income were queried for each combination of five building types, 2,351 PUMAs, three tenure categories (owner, renter, or not available), and six vintage categories representing when the home was built, for a total of 211,590 combinations.[80] The probability distributions for eight bins of AMI percentages were developed for each combination of 19 household income bins, 11 bins for number of household members, and 2,351 PUMAs, for a total of 517,220 combinations. As stated in the notes for the AMI input file, the percentages of AMI were “calculated using annual household income in 2019 U.S. dollars (continuous, not binned) from 2019-5yrs PUMS data and 2019 Income Limits from the U.S. Department of Housing and Urban Development. These limits adjust for household size and local housing costs (AKA Fair Market Rents).”[81]

Post-Processing Income Characteristics

To facilitate this target-setting analysis, the input files were used to develop AMI weighting factors for each of the 550,000 sampled dwelling units. These AMI weighting factors were used to allocate each sample’s weight (1 sample = 242 dwelling units) to one of two different AMI bins: 0–80% AMI and >80% AMI. Figure 2 shows the geographic distribution of households with less than or equal to 80% of AMI in each of four housing types, as simulated in this analysis.

[iv] The 2022.1 ResStock dataset release was the first to include household income bin and owner/renter status assigned to each sample. The 2024.1 ResStock dataset release was the first to include income as a binned percentage of area medium income (AMI).

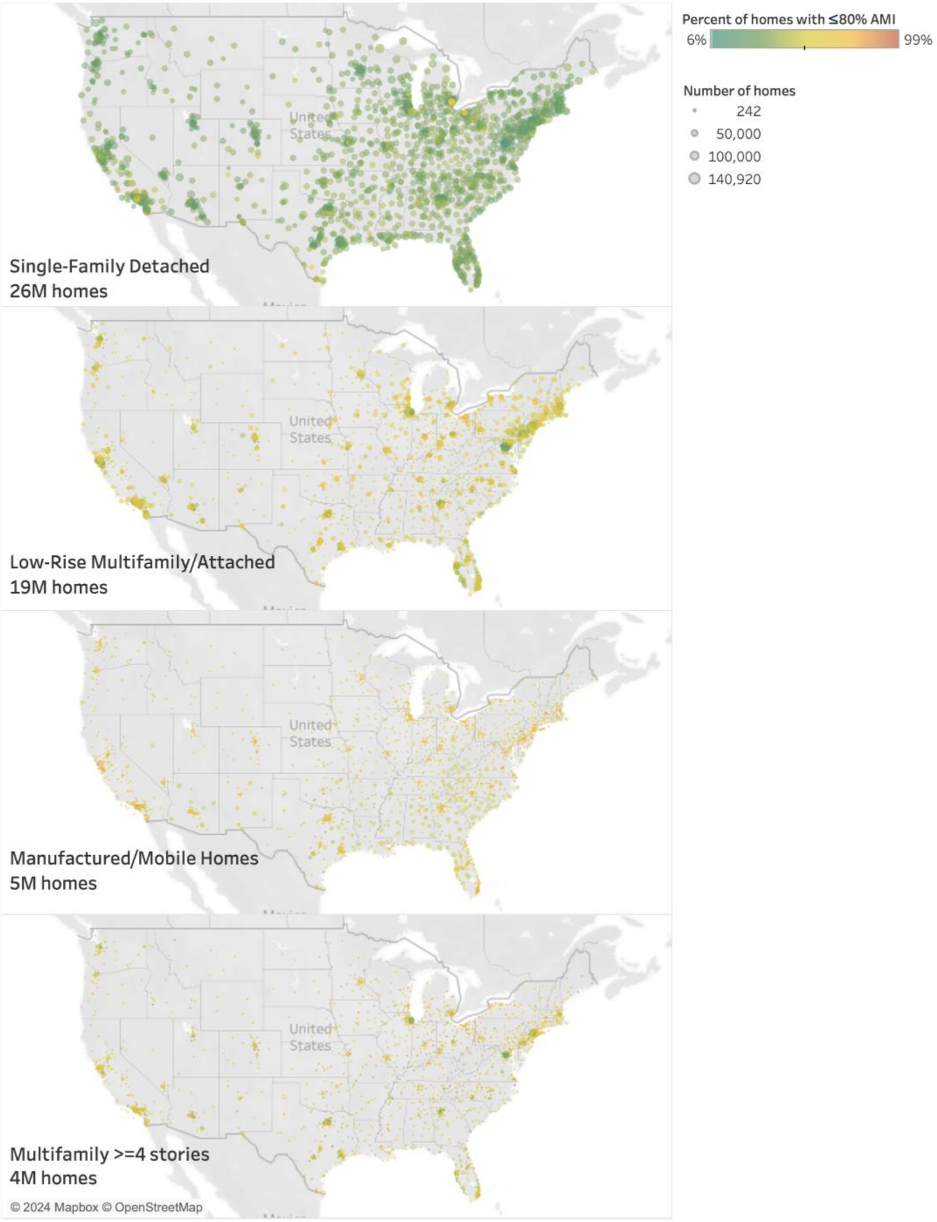

Figure 2. Map of the U.S. housing stock as represented in ResStock, showing location of households with less than or equal to 80% AMI in each of four housing types

Data for Alaska and Hawaii were not available at the time of analysis. After state-level microdata became available via RECS 2020 in 2023, these data have been integrated into ResStock, and future ResStock analyses starting in 2025 will include results for Alaska and Hawaii. See sections 3.4.2 and 3.6 for additional information.

Each circle represents one of 2,351 U.S. Census public use microdata areas (PUMAs; minimum population of 100,000 people, maximum typically 200,000), with the size of the circle representing the number of households in each area with ≤80% AMI. The color of each circle represents the percentage of all homes of each type that have ≤80% AMI. Of the four housing types, single-family detached homes are most prevalent for households with ≤80% AMI (26 million), but the other three types are more likely to be occupied by a household with ≤80% AMI. Inset figure demonstrates the granularity of the U.S. Census PUMAs for a region including the D.C., Baltimore, Philadelphia, and New York City metropolitan areas.

Sampling
The characteristic database was then sampled. ResStock uses quota-based sampling with random assignment of non-correlated parameters. A typical run of ResStock contains 550,000 statistically representative residential dwelling unit models, generating a ratio of approximately 1:242 compared to the dwelling units that exist across the United States.

The finest geographic granularity of the national version of ResStock is the intersection of county and PUMA. PUMAs are a collection of census tracts with a minimum population of 100,000 and a typical maximum population of 200,000.

Through this approach, ResStock statistically models the diversity in the U.S. housing stock and the distributional impacts of building technologies in different communities.

Physics Simulation
These representative dwelling unit models were then simulated using physics-based building energy modeling capabilities. Each sample's characteristics were translated into building energy simulation input files using the OpenStudio-HPXML workflow,[82] which is built upon the OpenStudio modeling platform. OpenStudio input files were them simulated using the EnergyPlus simulation engine with sub-hourly timesteps for determining heat flows through building materials and empirically derived algorithms for the energy use of heating, AC, and water-heating equipment along with appliances, lighting, and other devices.

Model Outputs
ResStock produces annual and hourly or sub-hourly time-series energy use outputs for each end use (e.g., electricity and on-site natural gas, propane, and fuel oil for heating, cooling, refrigeration, cooking) for each representative dwelling unit. The time-series output can be used to calculate time-varying carbon emission impacts and utility bills during or after the building simulations.

Upgrades
The model can answer questions in "what-if" scenarios. For example: What if homes with no wall insulation were retrofitted with dense-packed cellulose? How can energy efficiency improvements be targeted for specific customer segments to improve cost-effectiveness? Outputs include annual and hourly or sub-hourly energy use for the baseline home and the hypothetical upgraded home.

Validation
ResStock was calibrated and validated using EIA, utility meter, and submetering data through the End-Use Load Profiles work.[83] This effort helped understand how and when energy is used in homes today across the United States, enabling cities, states, and utilities to understand the time-sensitive value of energy efficiency, demand response, and distributed energy resources. Large-scale validation of the underlying OpenStudio-HPXML workflow and residential modeling capabilities of the EnergyPlus engine is discussed in Park et al. (2022).[84]

3.2. Develop an Up-Front Cost Benchmark

This step involved establishing a benchmark for the up-front cost (also known as first cost or capital expense) of installing affordable home energy upgrade packages, including how these costs vary across the diverse climates, building types, and other characteristics of the U.S. housing stock. To do this, we identified six benchmark upgrade packages of representative technologies currently on the market—including building envelope upgrades, ASHPs, and heat pump water heaters—that result in 95% reduction of on-site fossil fuel combustion through decarbonization of space heating and domestic water heating.[v]

The benchmark package analysis leveraged a dataset of existing simulation and analysis results to which the authors had access. That dataset and analysis have subsequently been published by Wilson et al. (2024).[85] The main cost equations for ASHPs in that analysis were developed from a database of cost data from 1,739 projects, collected and analyzed by Lawrence Berkeley National Laboratory.[86] Additional sources for cost data are listed in Table 6 of Wilson et al. (2024).[87]

Three changes were made to the packages in that analysis:

1. A heat pump water heater was added at an assumed cost of $4,000 per dwelling unit.
2. For homes currently heating with a non-electric fuel, $10,000 per dwelling unit was added to represent a worst-case scenario of electrical upgrades that might be necessary to accommodate the space-heating and water-heating electrification. This value was based on the survey of electrical upgrade costs presented in section 2.3.[vi] This is a conservative assumption, and many homes may not need such electrical upgrades.
3. For homes that currently heat with a non-electric fuel, are located in Building America Cold or Very Cold climate zones,[88] and have centrally ducted heating or cooling, it was assumed that part or all of the duct systems in these homes would need to be upgraded to accommodate the higher airflow required when fuel-fired furnaces are replaced with heat pumps, with the costs of these upgrades presented in Table 3. This is a conservative assumption, and many homes may not need such duct upgrades.

Table 3. Assumed Cost of Duct Upgrades for Homes Currently Heating With a Non-electric Fuel

Building Type/Height	Cold & Very Cold	All other climates
Single-Family Detached	$ 4,999	$ 0
Manufactured/Mobile Homes	$ 3,670	$ 0
Low-Rise Multifamily/Attached	$ 1,454	$ 0
Multifamily ≥ 4 Stories	$ 85	$ 0

Costs are based on $9.30 per square foot times the mean duct surface area per dwelling unit for the four building types, as reported in ResStock.

The Wilson et al. (2024) results included six benchmark packages of measures, shown in Table 4. The results also included a reference scenario in which existing equipment is replaced with federal minimum efficiency equipment (or like-for-like if existing equipment exceeds minimum efficiency). This reference scenario was used to calculate the incremental costs of upgrading equipment at time of wear-out when evaluating consumer NPV for the cost-effectiveness benchmark discussed in the next section. The reference-case water heater was assumed to cost $2,000 per dwelling

[v] As explained in the introduction, the scope of the Affordable Home Energy Shot potentially includes a wide range of technologies across the three pillar areas. The technology package used for this analysis was for the purpose of setting the cost benchmark and does not imply that these are the only technologies within the scope of the initiative.

[vi] As mentioned, there is a wide range in values for each item, and the frequencies with which upgrades will be necessary are not well understood but are generally expected to be more common in older buildings, older neighborhoods, lower-income neighborhoods, and buildings without central AC. We assume values near the high end of the ranges—$5,000 for panel upgrade and $5,000 for service upgrade per dwelling unit.

unit. Figure 3 shows the average up-front costs in each state for the least expensive and most expensive of the six modeled packages. These six sets of up-front costs form the basis of the up-front cost benchmark.

Table 4. Definitions of the Six Upgrade Scenarios

Scenario name	Upgrade details			Applicability criteria:	Capacity retention @ 5 °F (-15 °C)	Minimum temp. for heat pump operation	Sizing method
	Heat pump type	Cooling efficiency (seasonal energy efficiency ratio [SEER])	Heating efficiency (heating seasonal performance factor [HSPF])				
Min. eff. ASHP	central single speed	15	9	with ducts (79%)	47%	0°F (-18 °C)	Cooling priority
	ductless var. speed	14.5	8.2	w/o ducts (21%)		None	
Med. eff. ASHP	central var. speed	22	10	with ducts (79%)	49%	0°F (-18 °C)	Max. of heating/cooling load
	ductless var. speed	17	9.5	w/o ducts (21%)		None	
High eff. cold-climate ASHP	central var. speed	24	13	with ducts (79%)	85%	None	
	ductless var. speed	29.3	14	w/o ducts (21%)			
Min. eff. ASHP + envelope	Same as min. eff. ASHP plus envelope upgrades described in Table 5						
Med. eff. ASHP + envelope	Same as med. eff. ASHP plus envelope upgrades described in Table 5						
High eff. cold-climate ASHP + envelope	Same as high eff. cold-climate ASHP plus envelope upgrades described in Table 5						
Reference scenario	All heating and cooling equipment replaced with equipment meeting federal minimum efficiency standards or like-for-like efficiency (whichever efficiency is higher); see Table 6 in Wilson et al. (2024).						

All six scenarios also included sealing and insulating all ducts located in unconditioned space down to 10% leakage and R-8 (RSI-1.4) insulation. The capacity retention of the heat pumps is assumed to be linear between the listed percentage and temperature and 100% of the rated output capacity at 47°F (8.3°C). All capacity retention curves and input values were originally developed for the BEopt software and were derived from a combination of laboratory test data (central ASHPs) and manufacturer reported data collected by Northeast Energy Efficiency Partnerships Inc. (NEEP) (central cold-climate ASHPs and ductless ASHPs).[89, 90] See section S4 of Wilson et al. (2024) for performance simulation details.

Note: Seasonal energy efficiency ratio (SEER) and heating seasonal performance factor (HSPF) cannot be expressed in SI units; they are regulated metrics in the United States that describe the result of evaluating regulated products under a specific test procedure at specific standard rating conditions. As determined in accordance with 10 CFR part 430 Subpart B, Appendix M, SEER is the total heat removed from the conditioned space during the annual cooling season, expressed in Btu, divided by the total electrical energy consumed by the air conditioner or heat pump during the same season, expressed in watt-hours; HSPF is the total space heating required in region IV during the space heating season, expressed in Btu, divided by the total electrical energy consumed by the heat pump system during the same season, expressed in watt-hours.[91]

Table 5. Details of the Envelope Upgrades in the Six Upgrade Scenarios

Envelope upgrades	Upgrade details	Applicability criteria
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 (RSI-1.1) wall insulation with re-siding	R-6.5 (RSI-1.1) of continuous wall insulation, e.g., 1" of rigid polyisocyanurate board installed under new siding	Homes older than 1990 with less than R-19 (RSI-3.3) wall insulation
Low-e storm windows	Exterior low-e storm windows	Homes with single- and double-pane windows

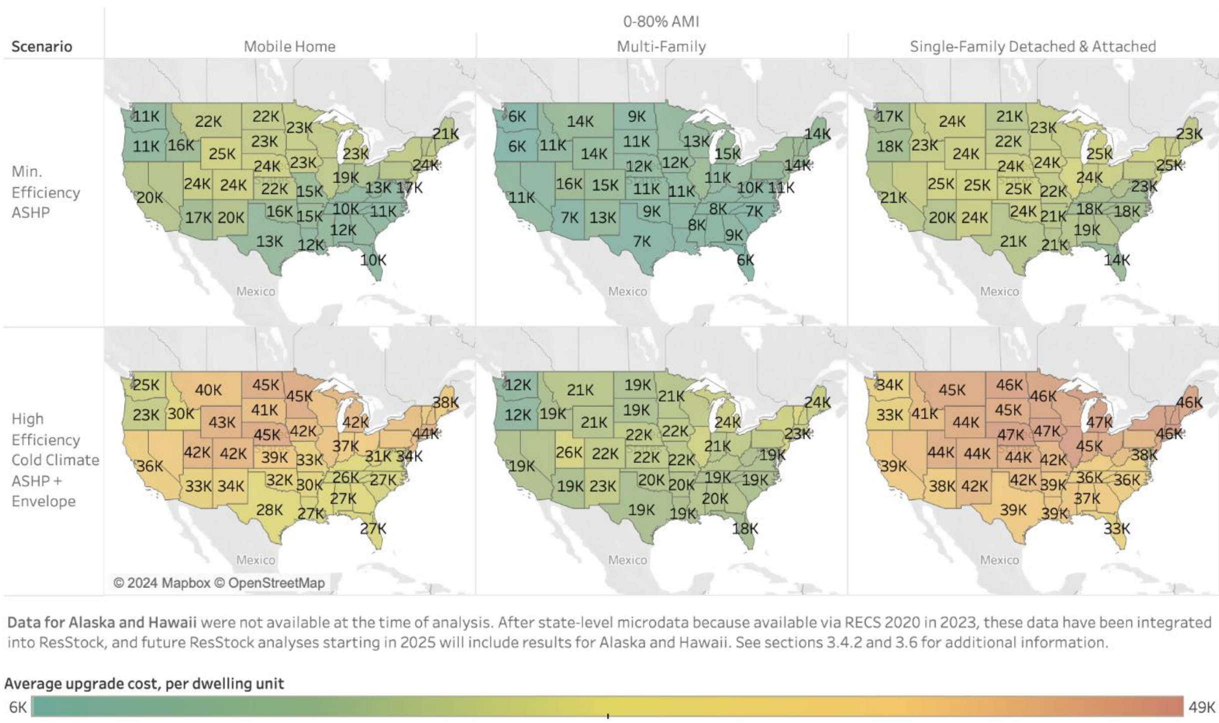

Figure 3. Illustration of the up-front cost benchmark as a map of average up-front costs, per dwelling unit, in each state for the least efficient (top) and most efficient (bottom) of the six modeled upgrade packages across all households making ≤80% AMI

See Figure 13 for state maps of average up-front costs for all six modeled packages and across housing types. As explained in section 3.2, the up-front cost includes a pessimistic assumption of $10,000 in electrical upgrades per dwelling unit for all homes not currently using electricity for heating, as well as duct upgrades for homes in Cold and Very Cold climate zones.

3.3. Develop a Cost-Effectiveness Benchmark

The next step in establishing a cost benchmark was to evaluate the energy cost savings of the six packages across the diversity of the U.S. housing stock. This enabled us to understand in which situations the benchmark upgrades are cost effective—that is, when the present value of the energy cost savings over the useful life of the upgrades is greater than their up-front cost. For each household, annual energy cost savings were calculated by multiplying the difference in energy used in the upgrade case relative to the reference case by the marginal retail price of that energy source, for electricity and for any fuels used on-site. We used state average residential electricity and fuel prices (revenue divided by sales) by state from 2019 EIA data and used regional factors from EIA to convert these 2019 prices to prices representing winter 2021–2022.[92] The average prices for electricity and natural gas were slightly reduced by removing the fixed or customer charge component of bills, resulting in estimates of the average marginal or volumetric $/kWh (kilowatt-hour) and $/therm[vii] rate components in each state (averaged over the utilities in each state and across any seasonal, tiered, or time-of-use differences). See Wilson et al. (2024) for details.

The present value of these cost savings was calculated using an assumed lifetime of 16 years and a real discount rate of 3.4%, which corresponds to a nominal discount rate of 8–11% based on inflation rates of 5–8% in 2021 and 2022 (see Wilson et al. 2024 for further discussion).[93] This present value of energy cost savings was then combined with the incremental up-front cost of the package relative to the reference package, assuming that any equipment being replaced is at or near the end of its useful lifetime, to determine the private NPV of each of the six upgrade packages. The NPV calculation took the perspective of the household; aside from incentives discussed later, no public costs or benefits were accounted for. No non-energy benefits were accounted for. In the case of rental dwelling units, the NPV calculation represents how a building owner may pass the incremental cost of an upgrade on to tenants in the form of higher rent. If the package has a positive NPV, the higher rent is compensated by a larger decrease in tenant energy bills. Similarly, in buildings where heat and/or hot water are included in rent, changes in the building owner's energy costs are transferred to tenants for the purpose of the NPV calculations.

The use of NPV is not intended to represent likely adoption of technologies. A host of economic and non-economic factors cause there to be a significant gap between what is cost-effective and what is adopted in practice. Rather, NPV is used to indicate the level of economic potential adoption that could be achieved with sufficient effort—in the form of financing, incentive programs, and other market transformation work—to reduce the economic and non-economic barriers to adoption. Note that programs may incentivize measures with negative private NPV but with significant public health, climate, and affordability benefits, such as making electricity more affordable by reducing the cost of utility infrastructure.

In some climates and segments of the housing stock, the minimum-efficiency ASHP plus heat pump water heater package may have the lowest life cycle cost and may, in fact, be cost-effective (i.e., have a positive NPV) for consumers today. In some segments, one of the other upgrade packages may have the lowest life-cycle cost and be cost effective today (with or without incentives). In other segments, none of the six packages is expected to have a positive NPV for households today, even with incentives. For the cost-effectiveness benchmark, we use a process that selects the package of the six that has the lowest unsubsidized life-cycle cost for each of the 550,000 representative households. In other words, the cost-effectiveness benchmark defines the "best" package for each household, throughout this analysis, as the package of measures that provides households clean heating and water heating with the most favorable NPV (greatest

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vii A therm is equal to approximately 100,000 British thermal units positive NPV or least negative NPV). In some cases, a more expensive package may save a household more on energy costs, but at a higher up-front cost.

Figure 4 shows a histogram of private unsubsidized NPVs for the set of lowest-life-cycle-cost upgrades described above. With circa-2023 costs, at least one of the six benchmark packages is cost-effective in 45 million homes, 16 million of which are occupied by households with ≤80% AMI. Adding incentives ($4,000 plus $1,200 for packages including envelope upgrades) increases this number to 54 million households, 19 million of which have ≤80% AMI.

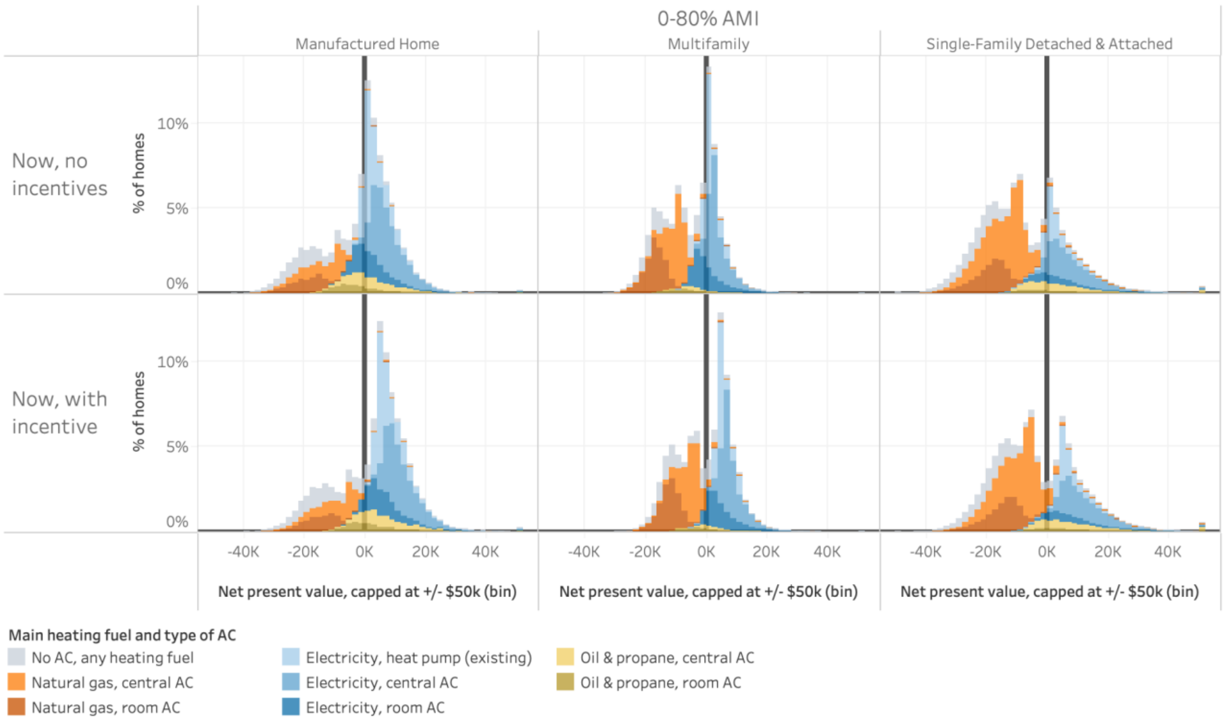

Figure 4. Illustration of the cost-effectiveness benchmark as distributions of dwelling unit NPV (best across the six modeled benchmark packages) for households with ≤80% AMI, with and without incentives ($4,000 plus $1,200 for packages including envelope upgrades)

As explained in section 3.2, the NPV includes a pessimistic assumption of $10,000 in electrical upgrades per dwelling unit and duct upgrades for all homes not currently using electricity for heating, as well as duct upgrades for homes in Cold and Very Cold climate zones.

3.4. Select an Up-Front Cost Reduction Target

The next step in the analysis was to evaluate the level of up-front cost reduction that would be necessary to make at least one of the six benchmark upgrade packages cost-effective. For each household where none of the six packages currently has a positive NPV, we calculate the necessary percentage reduction as the negative NPV divided by the up-front cost of the package in that home. Figure 5 shows a histogram of these values for the best package for each household making less than or equal to 80% of AMI (e.g., lower-efficiency ASHP in warmer climates and cold-climate ASHP with envelope upgrades in cold climates). The histogram bars are colored by the existing main heating fuel and presence/type of AC. The leftmost bin represents all households where the package is already cost-effective. The rightmost bin represents all households that would require cost reductions above 70%, due in part to current energy prices and changes in energy usage that impede cost-effectiveness.

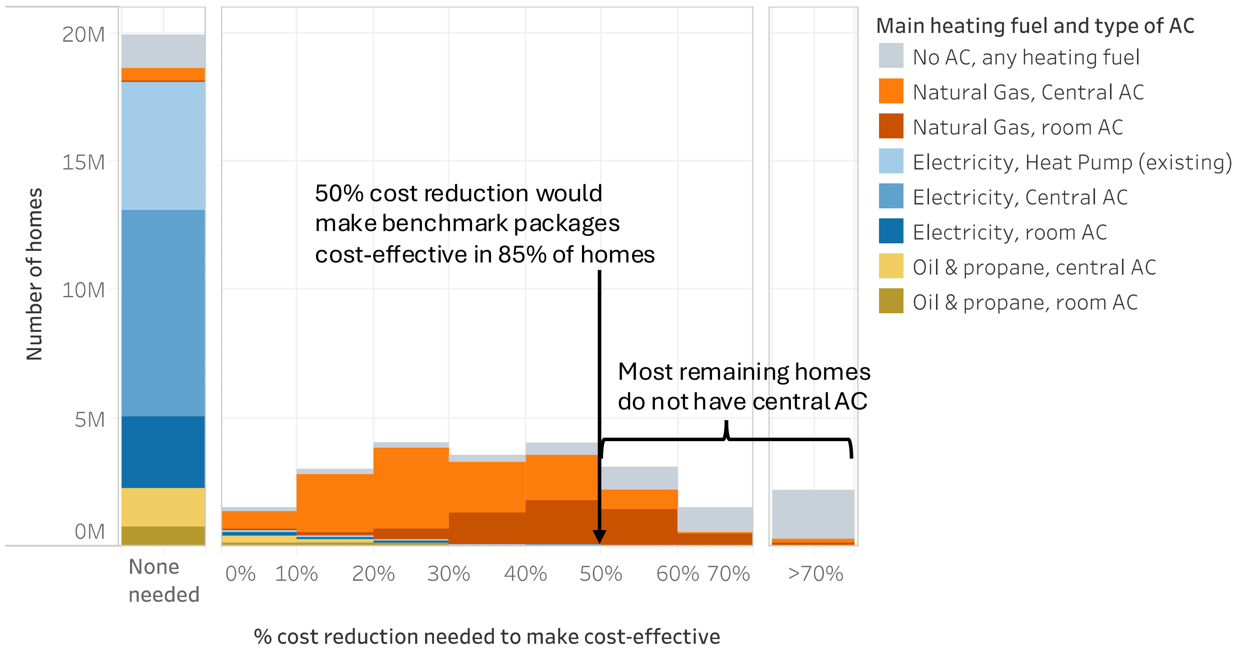

Figure 5. Distribution of the cost reduction needed to make at least one of the six benchmark packages cost-effective across all households making ≤80% AMI, including representative incentives ($2,000 for ASHP, $2,000 for heat pump water heater, and $1,200 for envelope)

The histogram bars are colored by the existing main heating fuel and presence/type of air conditioning (AC). The leftmost bin represents all households where the package is already cost-effective. The rightmost bin represents all households that would require cost reductions above 70%. Homes in gray are those that currently lack any AC; the benchmark packages add AC services to these homes, which add energy usage but also unquantified co-benefits, complicating the use of NPV alone to communicate their value. As explained in section 3.2, the NPV includes a pessimistic assumption of $10,000 in electrical upgrades per dwelling unit for all homes not currently using electricity for heating, as well as duct upgrades for homes in Cold and Very Cold climate zones, so this figure is likely an underestimate of current cost-effectiveness.

Figure 5 shows that about 45% of U.S. households have a benchmark package that is already cost-effective (i.e., positive NPV) with representative incentives ($2,000 for ASHP, $2,000 for heat pump water heater, and $1,200 for envelope). A 50% reduction in the up-front cost of these benchmark packages would result in about 85% of households having a cost-effective package with the representative incentives. Of the remaining 15% of households, most (85%) lack central AC, and the majority (55%) lack access to any AC. Homes without central AC have much lower up-front costs in the reference scenario, which for these homes is limited to replacement costs of the furnace, boiler, and/or window AC. These homes see energy cost increases compared to the reference scenario because we assume they use the benchmark package ASHPs to provide needed AC to their homes. The new AC energy use increases the threshold for the benchmark packages to be cost-effective. However, the homes' new access to whole-home AC also provides an opportunity for increased comfort and protection from extreme heat and associated health risks.[94] This co-benefit was not quantified or included in the cost-effectiveness benchmark used in this analysis, but for this segment of homes, NPV alone does not capture the full value provided by the benchmark upgrade packages.

Further up-front cost reductions of 60% or 70% would make even more of the homes have cost-effective benchmark upgrades, but we ultimately selected a 50% cost reduction target to balance aggressiveness with achievability. While 60% or 70% cost reductions may be possible in some circumstances, this level of cost reduction would often mean that high-efficiency equipment becomes less expensive than today's minimum-efficiency equipment, which may not be realistic based on the literature reviewed in section 2.

We also observe that almost all (93%) of the homes currently using electricity for heating do not need any cost reduction to make benchmark upgrades cost-effective. Such homes are commonly found in warmer Southeast states where electric heating is already common. In fact, a 50% cost reduction may not be possible to achieve in homes that already have electric heat and therefore do not currently require expensive electrical upgrades (assumed to be $10,000 per home in this analysis), which the Affordable Home Energy Shot aims to avoid through innovation in building technologies. Still, other technology innovations that are also the focus of this Energy Earthshot will benefit these homes by reducing the up-front costs and operational costs of these technologies. Figure 6 shows the effect that the 50% cost reduction target would have on distributions of NPV by housing type and heating-fuel type for households with ≤80% AMI. For this illustration, the 50% cost reduction was not applied to the minimum-efficiency upgrade package, with the rationale that it would be difficult to reduce the cost of this package any further.

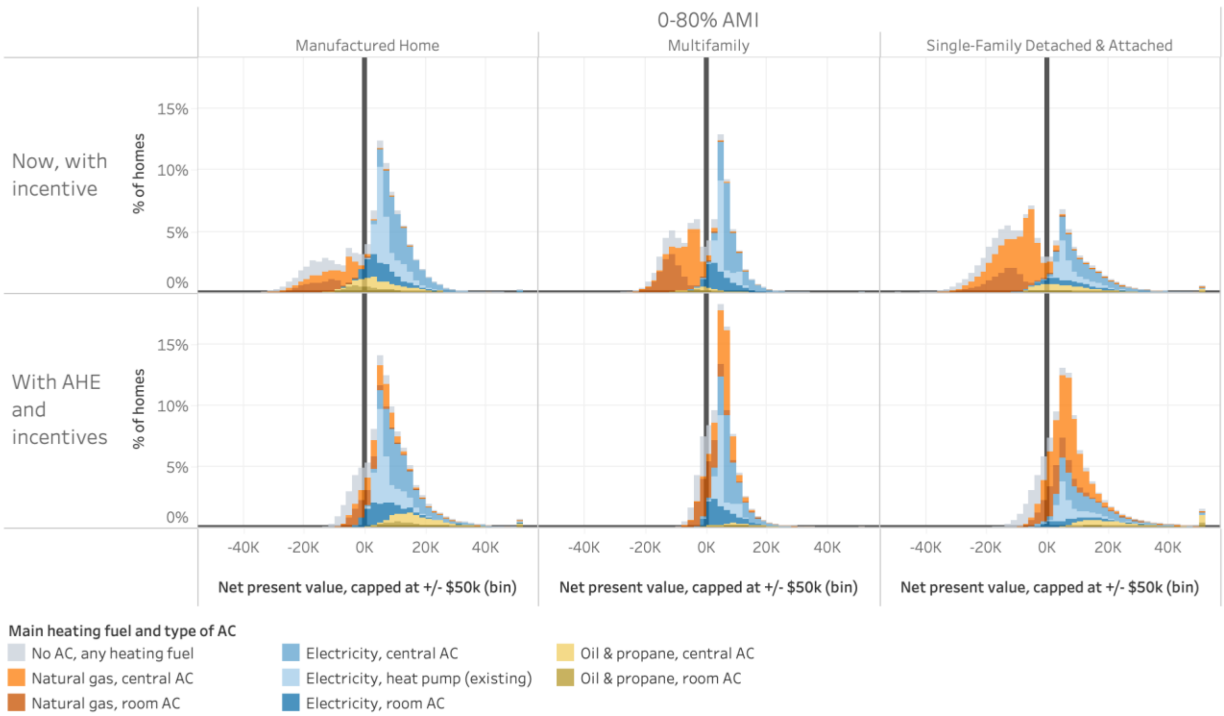

Figure 6. Illustration of the effect of achieving the Affordable Home Energy Shot target on distributions of dwelling unit net present value (best across the six modeled benchmark packages) for households with ≤80% AMI, by housing type, as explained in section 3

3.4.1. Example Justification for 50% Cost Reduction

As explained in the previous section, a 50% cost reduction target was selected to balance aggressiveness with achievability and was informed by the literature review. To illustrate how a 50% up-front cost reduction could be achieved with additional technology granularity, we present in Table 6 an example for a low-rise multifamily building in a cold climate with existing natural-gas heat and AC. In this particular example, a 50% reduction in up-front cost is achieved through the combination of 1) avoiding the need for electrical upgrades, 2) avoiding the need for ductwork upgrades, 3) a 50% lower heat pump water heater installed cost, and 4) a 30% lower ASHP installed cost. The technology package shown in Table 6 is an illustrative example and does not imply that these are the only technologies within the scope of the initiative. As explained in the introduction, the scope of the Affordable Home Energy Shot potentially includes a wide range of technologies across the three pillar areas.

Table 6. Example Justification of the 50% Cost Reduction Target for a Low-Rise Multifamily Building in a Cold Climate With Existing Natural-Gas Heat and AC

Component	Business as usual (BAU) baseline (2022$)	Affordable Clean Homes Earthshot (2022$)	Justification
Envelope improvement (insulation, air sealing)	$3K per dwelling unit[a]	$3K per dwelling unit[a]	Assumes no reduction in cost; technological and business-model innovations are assumed to make envelope upgrades less disruptive to tenants and building owners.
High-efficiency cold climate ASHP	$19K per dwelling unit[b]	$13K per dwelling unit	Assumes 30% lower installed cost due to soft-cost reductions[d] and/or technological innovations[e]
Ductwork upgrade	$1.4K per dwelling unit[a]	$0	Avoided via smaller heating load enabled by envelope improvements and improved load calculation and equipment selection tools
Heat pump water heater	$4K per dwelling unit[b]	$2K per dwelling unit	Assumes 50% lower installed cost reduction due to soft-cost reductions[d] and/or technological innovations[f]
Smart controls	N/A	$0	Assumed to be provided by utility company at no cost[g]
Electrical upgrades	$10K+ per dwelling unit[c]	$0	Avoided via smaller and controllable loads
Total	$37K per dwelling unit $296K for 8-unit building	$18K per dwelling unit $144K for 8-unit building	→ 50% reduction from BAU

[a] Based on median installed cost (2022$) across 20,570 ResStock dwelling unit samples of ≤80% AMI dwelling units in low-rise multifamily buildings or rowhouses with natural-gas heat and existing AC in the Northeast, Mid-Atlantic, East North Central, West North Central, and Mountain (North) census divisions (26 Cold and Very Cold states), using retrofit cost equations from the National Residential Efficiency Measures Database.[95]

[b] Based on median installed cost (2022$) across 20,570 ResStock dwelling unit samples of ≤80% AMI dwelling units in low-rise multifamily buildings or rowhouses with natural-gas heat and existing AC in the Northeast, Mid-Atlantic, East North Central, West North Central, and Mountain (North) census divisions (26 cold and very cold states), using regressions on Berkeley Lab residential decarbonization project cost data.[96]

[c] Assumed based on mode of values from available literature (see Table 2).

[d] Soft-cost reductions could include tools and sales processes that lead to higher customer conversion rates and automated/improved processes for remotely collecting dwelling information, generating project scopes, permitting, inspection, load calculation, and equipment selection. Reference: Satre-Meloy et al. Home Energy Upgrade Cost Reduction Survey Preliminary Findings (presented internally to DOE on April 25, 2023).

[e] Technological innovations that reduce heat pump installed cost could include plug-in 120-volt equipment, snap-together refrigerant lines, and installation quality and fault detection tools that reduce contractor call-back risk. Reference: Satre-Meloy et al. Home Energy Upgrade Cost Reduction Survey Preliminary Findings (presented internally to DOE on April 25, 2023).

[f] Technological innovations that reduce heat pump water heater installed cost could include plug-in 120-volt equipment and smaller tank sizes with mixing valves. Reference: Satre-Meloy et al. Home Energy Upgrade Cost Reduction Survey Preliminary Findings (presented internally to DOE on April 25, 2023).

[g] It is common practice for utility companies or third-party aggregators to provide discounted or no-cost controls, such as smart thermostats, to customers in exchange for periodically allowing the utility or aggregator to control the device.

3.4.2. Regional Analysis Results

The U.S. housing stock spans a diverse range of climates, housing types, and energy prices. To understand how the need for a 50% up-front cost reduction target varies across these parameters, we examined state-level results for several metrics. The percentage cost reduction results from Figure 5 are presented as state averages in Figure 7. One can see that the highest cost reductions are necessary in colder states where natural-gas heating is common. Southeastern states with warmer climates and where electric heating is common need much less cost reduction on average.

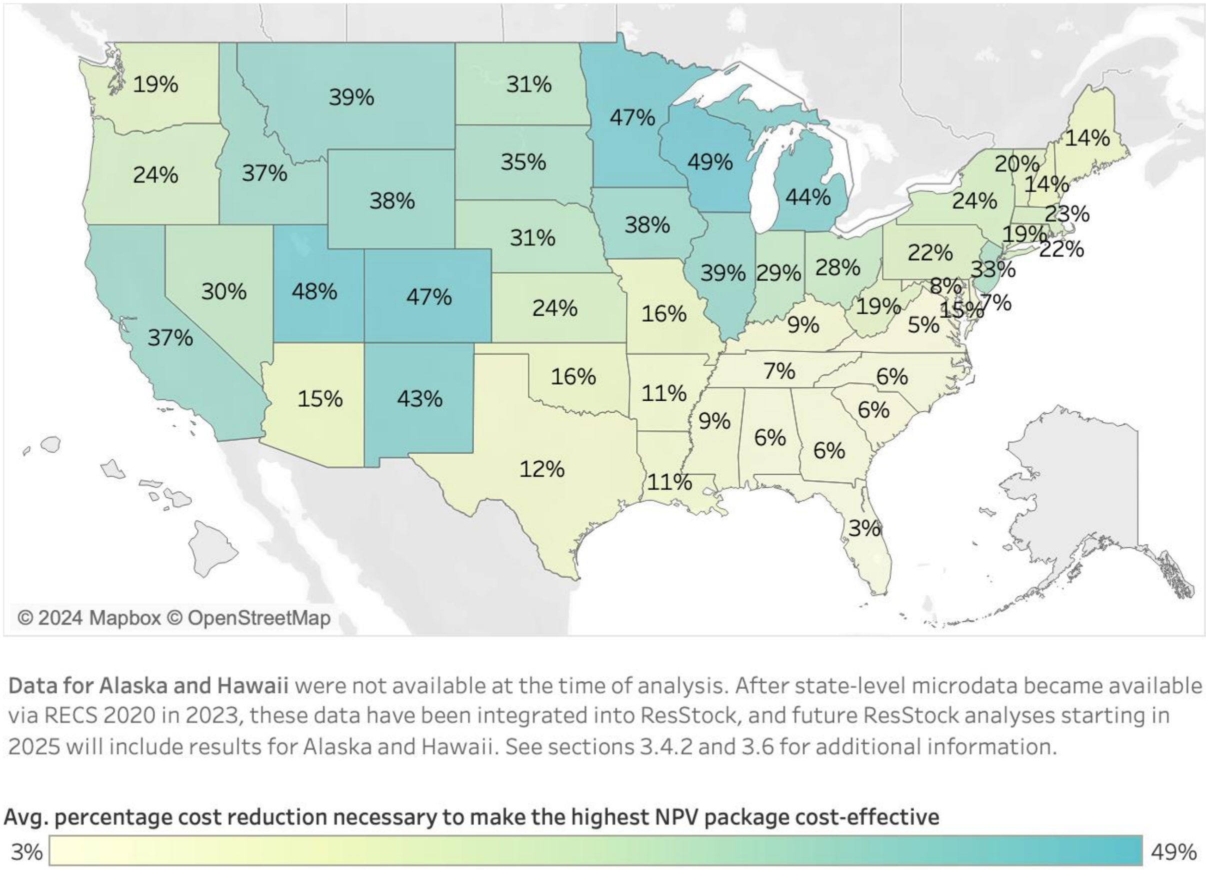

Figure 7. State average percentage cost reduction needed to make the highest NPV across the six modeled benchmark packages cost-effective across all households making ≤80% AMI, including representative incentives ($2,000 for ASHP, $2,000 for heat pump water heater, and $1,200 for envelope)

The averages include homes where packages are already cost-effective. As explained in section 3.2, the NPV includes a pessimistic assumption of $10,000 in electrical upgrades per dwelling unit for all homes not currently using electricity for heating, as well as duct upgrades for homes in Cold and Very Cold climate zones

ResStock data for Alaska and Hawaii were not yet available at the time of this analysis, but they will be included in ResStock results datasets going forward (see section 3.6 for additional details). In lieu of analysis results for these two states, we describe how such challenges may be similar or different from other states. For example, Figure 8 plots the ratio of electricity price and fuel (average of natural gas, fuel oil, and propane weighted by use) price per unit of energy against the number of heating degree days (base 65 ºF)—a general indicator of need for heating—for homes in each state. Homes with more heating degree days and higher relative electricity rates will be more challenging to decarbonize (top right corner of graph) while homes with fewer heating degree days and lower relative electricity rates will be easier to decarbonize (bottom left corner of graph). Alaska has much higher average heating degree days than any other state, but also has a wide range of climates with zones ranging from Cool Humid (5A) to Subarctic (8).[97] Alaska has relatively high electricity prices compared to other states and relatively average fuel prices, although natural gas service is only available in some areas and a relatively large portion (24%) of homes use fuel oil, which is more expensive.

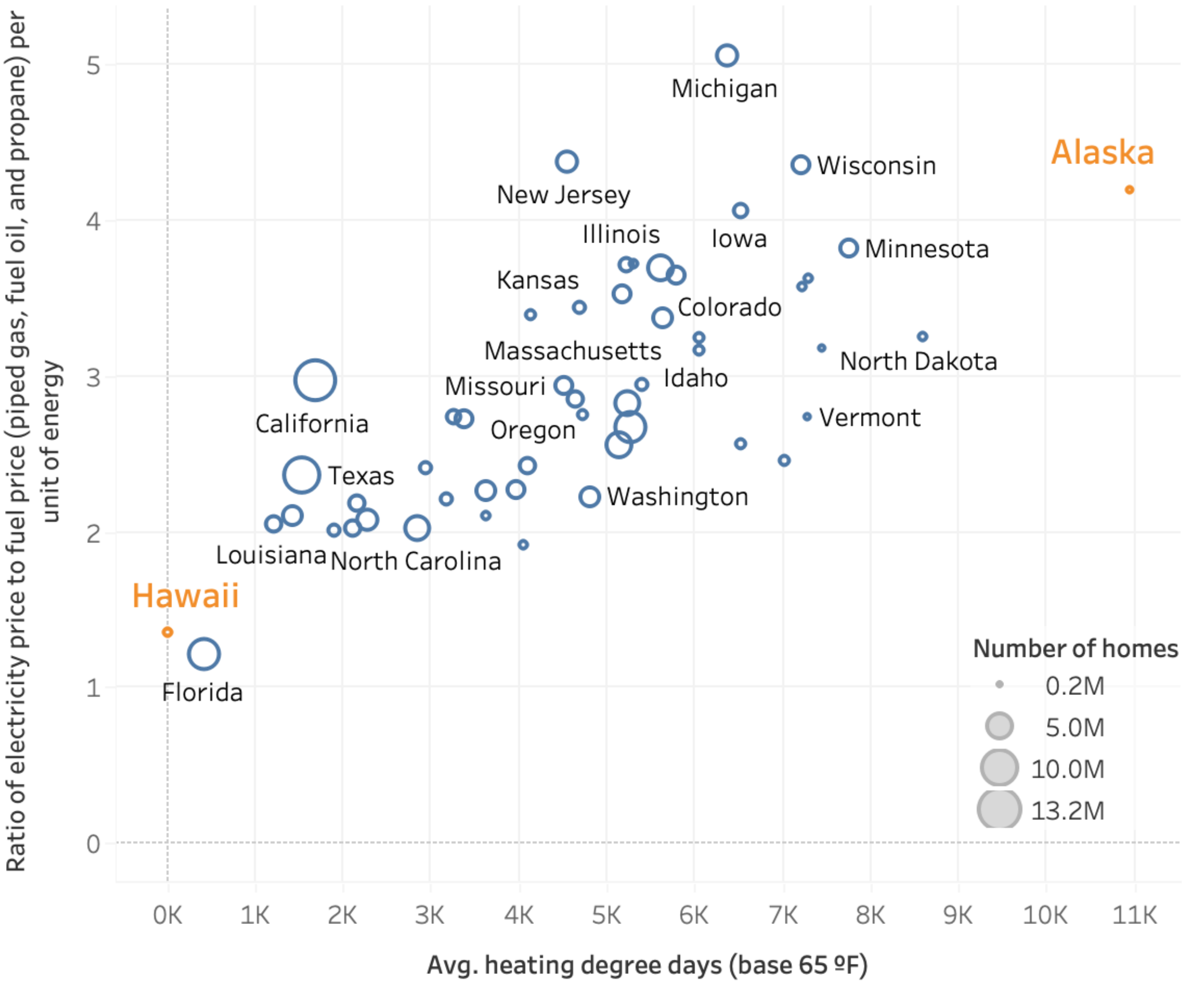

Figure 8. Cost ratio of the average electricity rates and fuel rates for homes in each state as a function of the number of heating degree days according to microdata from the 2020 RECS.[98]

Hawaii is unique among states in that only 6% of homes use space-heating systems according to the 2020 RECS.[99] Of those homes, 90% have electric heating and the remainder use fuel-fired heating. In Hawaii, about 100 times more energy is used for domestic water heating than for space heating, so water-heater energy use is much more important for affordable home energy. About two-thirds of homes have electric water heaters, 18% have solar thermal water heating, and the remaining 16% use a fuel-fired water heater. In Hawaii, 55% of homes do not use AC, which is much higher than the national average and is exceeded only by Alaska's 93%. Hawaii is also unique in that it is the state with both the most expensive electricity and the most expensive fuels, meaning that despite the mild climate and very low usage of home heating and AC, it stands to benefit from Affordable Home Energy Shot innovations, particularly on water-heating efficiency and smart controls.

Figure 9 illustrates how the 50% up-front cost reduction target impacts the average NPV of benchmark packages for three housing types (manufactured, multifamily buildings of any height, and single-family detached and attached) in each state. One can see that, on average, the target results in a positive NPV in every state. As was assumed for Figure 6, the 50% cost reduction was not applied to the minimum efficiency package that often has the highest NPV in warmer states. However, reductions in the costs of the more efficient packages can benefit those homes in warmer states by delivering greater energy cost savings.

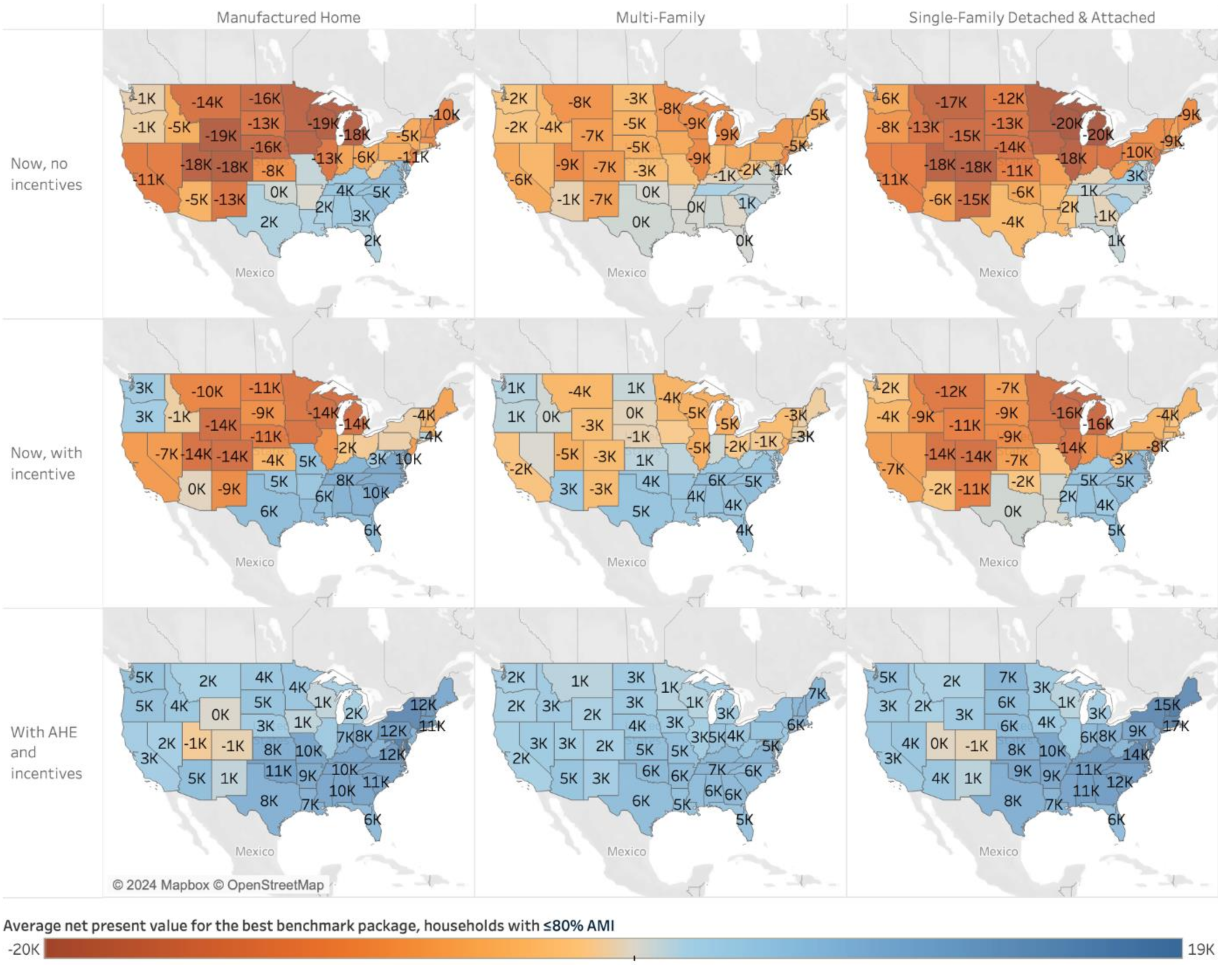

Figure 9. Illustration of the effect of the Affordable Home Energy Shot on the state average NPV of the best of six benchmark packages across households with ≤80% AMI, for three housing types (multifamily includes all sizes of multifamily buildings)

As explained in section 3.2, the NPV includes a pessimistic assumption of $10,000 in electrical upgrades per dwelling unit for all homes not currently using electricity for heating, as well as duct upgrades for homes in Cold and Very Cold climate zones. Incentives include $2,000 for ASHP, $2,000 for heat pump water heater, and $1,200 for envelope.

Figure 10 illustrates the effect of the cost reduction target on the state average up-front cost for the highest-efficiency of the six benchmark upgrade packages for homes that currently use natural gas, oil, or propane heat. This efficiency level and the associated 50% reduction are not necessarily needed in all states, although some homes will likely benefit from the cost reductions of the more efficient package.

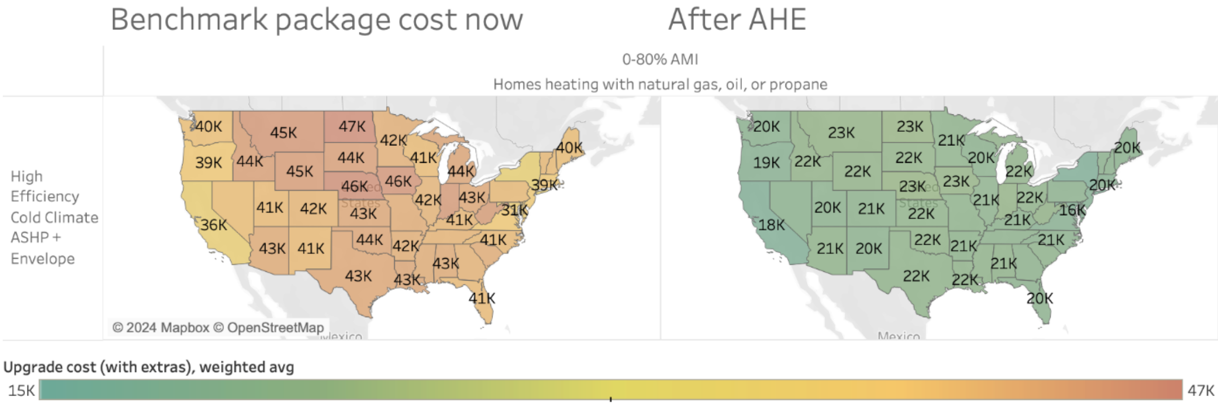

Figure 10. Illustration of the effect of the Affordable Home Energy Shot on the state average up-front cost for the highest-efficiency of the six benchmark upgrade packages for homes using natural gas, oil, or propane heat and occupied by households with ≤80% AMI

As explained in section 3.2, the up-front cost includes a pessimistic assumption of $10,000 in electrical upgrades per dwelling unit for all homes not currently using electricity for heating, as well as duct upgrades for homes in Cold and Very Cold climate zones. Incentives include $2,000 for ASHP, $2,000 for heat pump water heater, and $1,200 for envelope.

3.5. Determine an Energy Cost Savings Target

The second component of the Affordable Home Energy Shot target is to decrease residents' energy costs by at least 20% within a decade. We discuss the historical context for this target before documenting the target selection process. Specifically, rates of change in consumer energy bills can be assessed using EIA's RECS. Between the 2009 and 2020 survey years, energy consumption and inflation-adjusted energy expenditures per household fell by 14% and 24%, respectively (RECS 2009, 2020). The Affordable Home Energy Shot goal of a 20% reduction in costs in the next decade is therefore carrying forward this historical trend in cost reduction even as building decarbonization technologies are more widely deployed than in the past.

Residential energy costs are a function of both energy use and retail energy prices. Retail electricity prices depend on several factors, including the costs of electricity generation, transmission, and distribution. In some locations, retail electricity prices have increased significantly due to increased utility spending on infrastructure upgrades to mitigate wildfire risk. Wholesale natural gas, propane, and oil prices are affected by global markets, while retail prices can be affected by natural gas utility revenue requirements and thus the number of customers served. There is also the rebound effect, where less-expensive energy results in more energy being used.

All these factors make prediction of future energy costs difficult. After adjusting for inflation over the last two decades, monthly national average electricity prices in major U.S. cities have varied by -14% to +11% over the median price, while natural gas prices have varied by -20% to +71%.[100,101] Exogenous drivers such as those described above could be more significant than any technical achievements by the Affordable Home Energy Shot. However, the Affordable Home Energy Shot includes an energy cost reduction target to emphasize the importance of energy affordability, particularly for residents of subsidized and naturally occurring affordable housing. For the purpose of setting the energy cost savings target, energy prices are assumed to increase at the same rate as inflation, starting from the baseline of winter 2021–2022 prices described in section 3.3.

To select the energy cost savings target, this analysis focused on the most challenging segment of affordable housing stock: low-rise multifamily and attached housing located in cold-climate states[viii] and currently using natural gas for space heating. This segment was further focused on just those buildings with existing AC to ensure that providing universal access to safe indoor temperatures does not count against the target objectives.

Figure 11 shows the median and interquartile (25th to 75th percentile) ranges of operational energy-cost savings for the winter 2021–2022 baseline and for the two highest efficiency of the six benchmark upgrade packages of currently available technologies introduced in section 3.2. As noted above, these packages of ASHP and envelope upgrades are just one possible set of technologies that the Affordable Home Energy Shot aims to transform. They represent technology performance levels that are available today; the Affordable Home Energy Shot may advance performance levels and thus energy savings potential for these technologies as well as a wide variety of other technologies, including geothermal heat pumps and innovative envelope technologies. Figure 12 shows a state map with the interquartile ranges of percentage energy-cost savings labeled for each state.

[viii] For this analysis, cold-climate states are defined as the 26 states located in the Northeast, Mid-Atlantic, East North Central, and West North Central census divisions as well as the northern portion of the Mountain census division (Colorado, Idaho, Montana, Utah, and Wyoming).

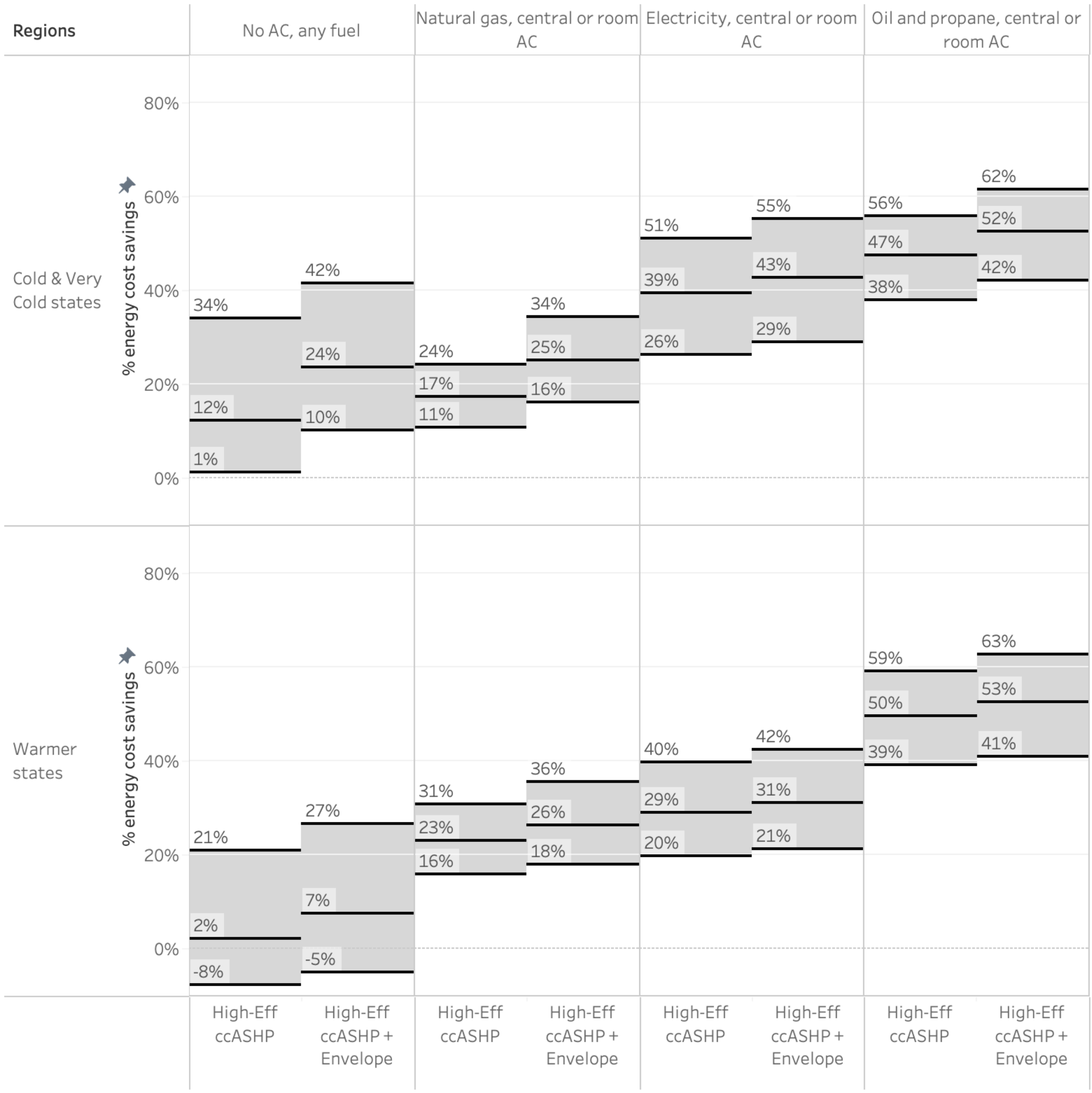

Figure 11. Annual energy costs and percentage cost savings for the baseline compared with two of the six benchmark upgrade packages modeled in this analysis

The graphs show the median and interquartile range (25th to 75th percentile) across all ResStock dwelling unit samples. The top row of Cold & Very Cold states includes 26 states in the Northeast, Mid-Atlantic, East North Central, West North Central, and Mountain (North) census divisions and the bottom row includes all remaining states. The four columns disaggregate by AC type and heating fuel.

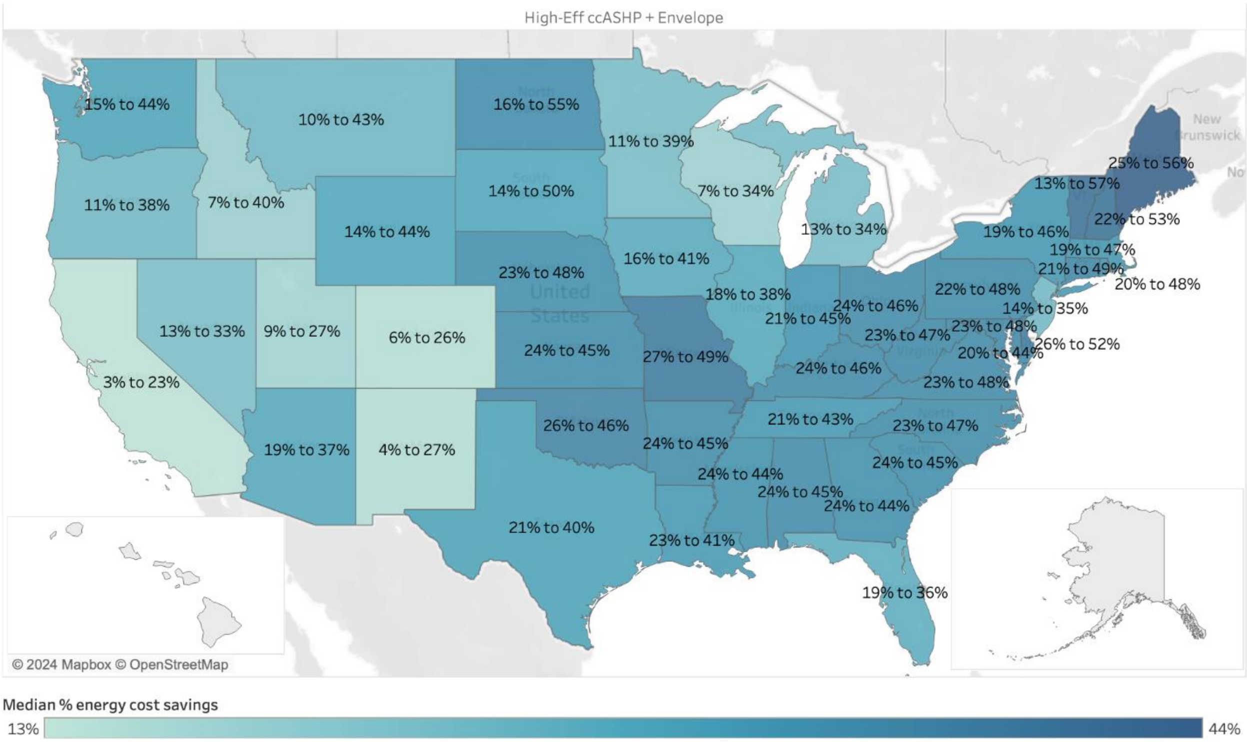

Figure 12. Map of annual energy-cost savings for the highest-efficiency benchmark upgrade package (high-efficiency cold-climate ASHP plus envelope), across all households regardless of income

The map shows the median as color and interquartile range (25th to 75th percentile) as text.

Data for Alaska and Hawaii were not available at the time of analysis. After state-level microdata became available via RECS 2020 in 2023, these data have been integrated into ResStock, and future ResStock analyses starting in 2025 will include results for Alaska and Hawaii. See sections 3.4.2 and 3.6 for additional information.

Table 7 provides more detail by disaggregating the ranges of operational energy costs by end use and providing justification for these cost reductions.

Table 7. Affordable Home Energy Shot operational cost assumptions

Component	BAU baseline	Affordable Home Energy Shot	Justification
Heating and AC	$400 to $1,000 per dwelling unit per year	$200 to $500 per dwelling unit per year	Based on calculated annual energy costs for 20,570 ResStock dwelling unit samples. For upgrade and simulation details see Wilson et al. (2024).[102]
Domestic water heating	$100 to $200 per dwelling unit per year	$100 to $200 per dwelling unit per year	This analysis assumes no change in water heating costs. Other analysis has shown median energy cost savings of $15 when switching from natural gas to a heat pump water heater across the segment and states used here.[103]
Other end uses	$600 to $1000 per dwelling unit per year	$600 to $1000 per dwelling unit per year	This analysis assumes no change in consumption or costs for other energy end-uses.

Component	BAU baseline	Affordable Home Energy Shot	Justification
Total	$1,200 to $2,100 per dwelling unit per year*	$1,000 to $1,700 per dwelling unit per year*	Result: 11% to 26% reduction from BAU
*Note that these ranges come directly from ResStock results and are not the sum of the ranges in the rows above because of correlations between end uses.			
All energy costs based on energy prices consistent with Winter 2021-22. All ranges shown are interquartile (25th to 75th percentiles) ranges that estimate energy costs for the middle 50% of homes. All values are rounded to the nearest $100.			

3.6. Limitations and Caveats

Analysis of Alaska and Hawaii in ResStock

EIA's RECS is a key data source used in ResStock. Prior to RECS 2020, released in 2023, data was reported at the Census Division (n = 10) or Reportable Domain (n = 26) level rather than the state level, and Alaska and Hawaii were aggregated into the Pacific Census Division in the survey data. Alaska and Hawaii have distinctive housing features, and the ResStock team did not have additional data to support development of representative models for these states at that time. As a result, ResStock was unable to model Alaska and Hawaii at the time of the target-setting analysis presented in this report.

However, via the DOE Arctic Energy Office, the ResStock team has since added Alaska to the ResStock model using newer RECS 2020 data and data from the Alaska Retrofit Information System (ARIS). This effort included staff from the National Renewable Energy Laboratory (NREL) Fairbanks campus who have deep familiarity with the Alaska housing stock. The Alaska residential building stock characterization has been completed and merged into the ResStock model such that Alaska can be included in the next ResStock standard data release.

Hawaii is also being added to the ResStock model using state-level RECS 2020 data. Some technologies, such as solar water-heating and natural ventilation, are common in the Hawaiian housing stock and uncommon elsewhere. To ensure the quality of the Hawaii results, ResStock will be compared to existing data sources and will gather expert input on assumptions and results. Hawaii is expected to be fully integrated into the ResStock model in the next year and be ready for the next ResStock standard data release. Completion of this integration will make it possible to include Alaska and Hawaii in future ResStock analyses related to tracking the progress of the Affordable Home Energy Shot.

Electrical Upgrade Costs

Another important caveat is that the assumption that all dwelling units with fossil-fuel heat will require $10,000 in electrical upgrades may be too high. A survey (N = 2,950) conducted August–October 2022 for all home types across all U.S. census regions found that only 21% had a main electrical panel with a 100-A-or-lower main breaker, although the percentage is higher (33%) if filtering out homes where respondents could not find a main breaker or amperage label.[104] The share is higher in older homes, smaller homes, and in the Northeast and Midwest.

Centralized Systems

The housing stock included in this analysis includes all residential building types, including single-family detached, single-family attached (rowhomes, side-by-side duplexes, triplexes, etc.), manufactured homes, and all types of multifamily buildings. Some multifamily dwelling units (38%) are served by heating, cooling, or water-heating equipment that serves multiple units.[105] However, for this analysis, all benchmark package equipment was assumed to be equipment that serves individual dwelling units. This was a limitation of the analysis capabilities and cost data that were available at the time.

In some cases, this assumption of decentralized equipment is feasible and aligns with current practice. For example, some multifamily buildings with centralized heating systems like steam boilers with radiators may decide to use decentralized ductless heat pumps as a replacement instead of replacing the steam boiler and radiators with a centralized heat pump boiler. In other cases, the decentralized heating/cooling solutions may be feasible but may not align with current practice. For example, multifamily buildings that use a hot-water boiler connected to baseboard radiators, fan coil units, or water-source heat pumps in each unit may decide that it makes sense to keep the centralized system and replace the boiler with a heat pump boiler to dwelling units with clean heat. In the case of centralized domestic hot water (DHW), there is usually not space to put an individual heat pump water heater tank in each unit, so most shared DHW systems will likely seek centralized solutions, which were not modeled here.

In the cases where individual systems would not be feasible or practical, we still include these homes in the analysis, and we use the up-front cost and energy performance of individual systems as a proxy for the cost of centralized solutions. We acknowledge this as a source of uncertainty; centralized systems may cost more or less than decentralized solutions, and their energy performance may differ as well.

4. Conclusion

This report describes the procedure used to generate the cost reduction targets of the Affordable Home Energy Shot. The Affordable Home Energy Shot aims to reduce the up-front cost of decarbonizing a home by at least 50% while reducing energy bills by 20% within a decade. This aggressive but achievable target focuses on innovations in three technical areas—building envelope, efficient electrification, and smart controls— to achieve these goals. Achieving the Affordable Home Energy Shot target would roughly double the percentage of affordable homes with economically viable decarbonization pathways from 45% to 85%, an increase of 20 million residences. Innovations supporting the Affordable Home Energy Shot will also provide spillover benefits to homes beyond affordable housing.

To set the target, a literature review was conducted to define the range of feasible cost reductions among building technologies. Then, a DOE model of the U.S. residential building stock (ResStock) was adapted for the analysis. Six benchmark upgrade packages of representative building technologies were applied to this model to study how up-front installed costs vary by geography, building type, and upgrade package. Longitudinal energy costs of each upgrade package were also assessed in ResStock via building energy modeling and projected utility rates. Together, up-front installed costs and longitudinal energy costs were used to estimate the net present value of potential upgrades across the building stock. A target of 50% reduction in the up-front installed cost was selected as a balance between aggressiveness and achievability as informed by the literature review. A target 20% reduction in energy bills was selected based on the median energy cost reduction resulting from benchmark upgrade packages in the most challenging climate and housing stock segment. Together, these selections result in most affordable homes in all states (85% of affordable homes nationally) achieving economically viable decarbonization. Most of the remaining 15% of homes lack whole-home central AC and could still benefit from Affordable Home Energy Shot innovations through programs like the Weatherization Assistance Program that cover the full up-front cost of weatherization upgrades.

This target-setting procedure also reveals the importance of considering at high resolution how technology deployment pathways impact populations. The cost and performance of upgrade packages varied substantially by region, building type, and household demographics. It is therefore critical to examine at high resolution each region and subpopulation so that the most relevant technologies can be determined and the most promising R&D opportunities can be identified, prioritized, and accelerated. Through the Affordable Home Energy Shot, DOE is supporting such R&D and expects to evaluate the Affordable Home Energy Shot for progress against its goals every few years over the 10-year target window.

Appendix A: Supplemental Figures

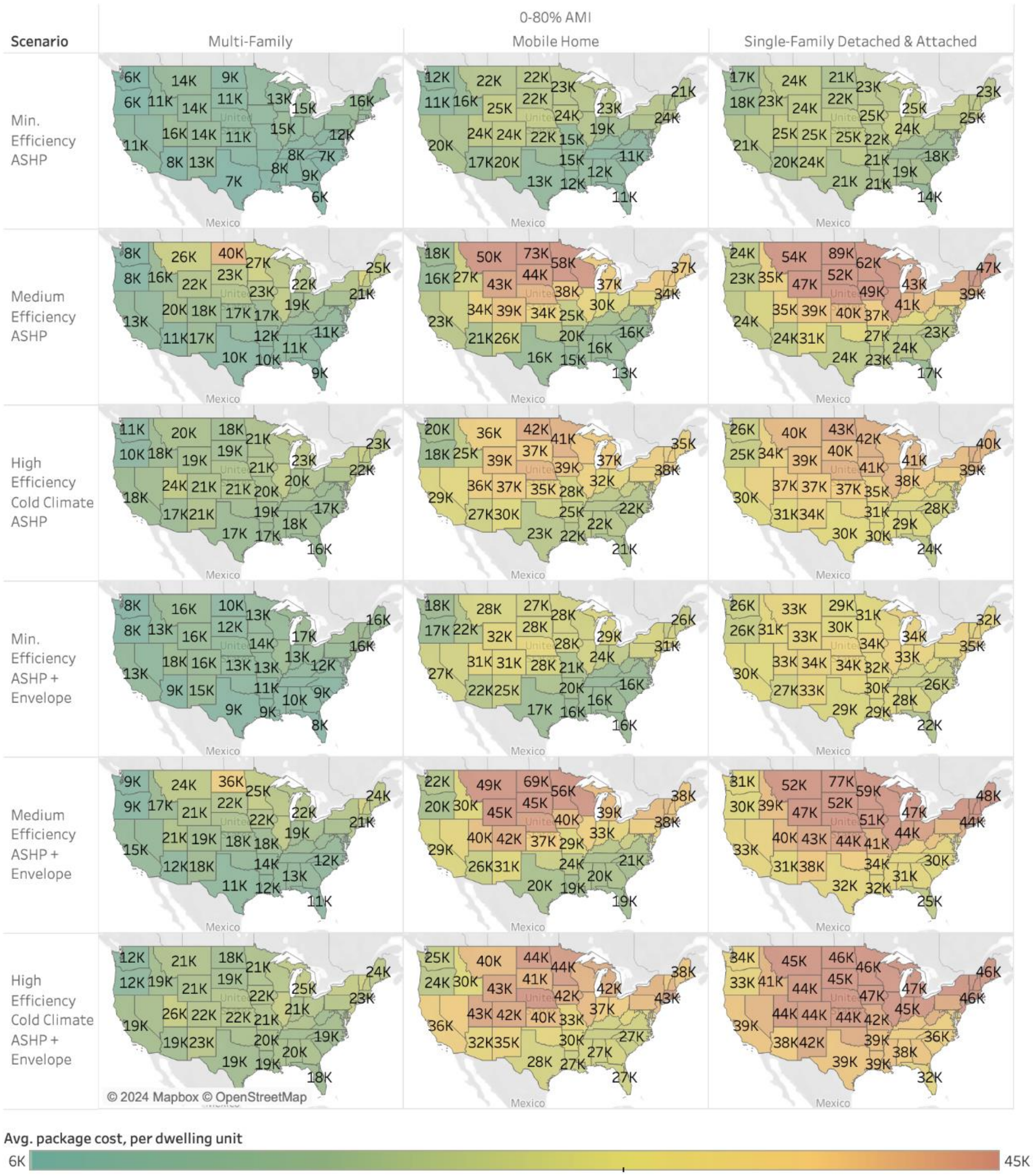

Figure 13. State average up-front costs for all six modeled upgrade packages and across housing types for households with ≤80% AMI

As explained in section 3.2, the NPV includes a pessimistic assumption of $10,000 in electrical upgrades per dwelling unit for all homes not currently using electricity for heating, as well as duct upgrades for homes in Cold and Very Cold climate zones. Note that the medium-efficiency packages are often more expensive than both the minimum and high-efficiency cold-climate ASHP packages because the medium-efficiency ASHPs are sized for heating (unlike the minimum-efficiency ASHPs) and do not have good cold-climate performance and therefore require much larger—and thus more expensive—systems in colder climates.

Data for Alaska and Hawaii were not available at the time of analysis. After state-level microdata became available via RECS 2020 in 2023, these data have been integrated into ResStock, and future ResStock analyses starting in 2025 will include results for Alaska and Hawaii. See sections 3.4.2 and 3.6 for additional information.

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