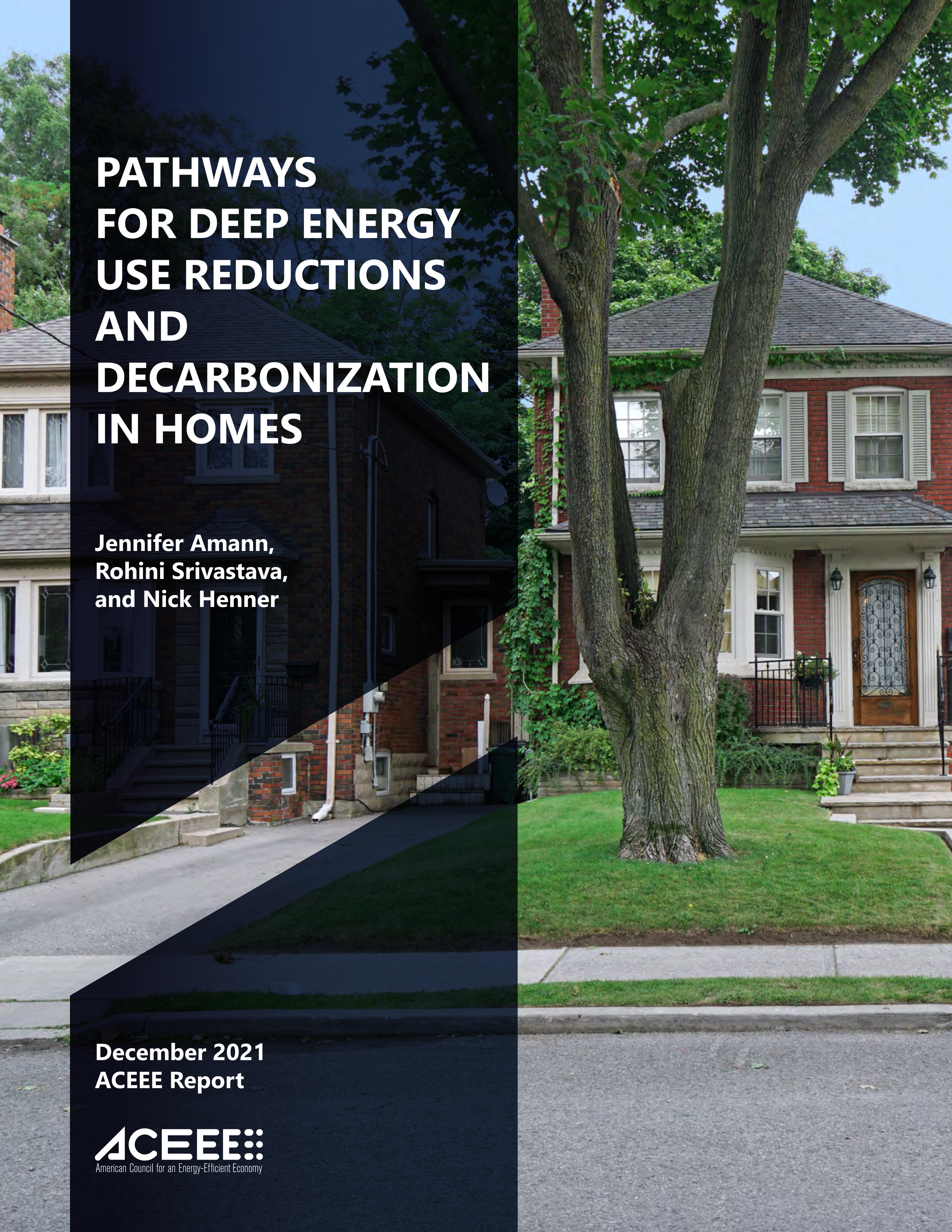

PATHWAYS FOR DEEP ENERGY USE REDUCTIONS AND DECARBONIZATION IN HOMES

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Contents

About ACEEE

The **American Council for an Energy-Efficient Economy** (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

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Executive Summary

KEY FINDINGS

- Retrofit packages incorporating comprehensive envelope upgrades, heat pump and heat pump water heating upgrades, and other targeted efficiency measures present the best opportunity to achieve deep energy savings and emissions reductions in residential buildings.
- According to our analysis, deep retrofit packages result in estimated source energy (i.e., energy used on site plus electricity generation, transmission, and distribution losses) savings of 31% to 59% depending on climate region and home vintage; corresponding carbon reductions range from 32% to 56%. Site energy savings range from 58% to 79%, reflecting the impact of electrification measures that eliminate the vast majority of onsite fossil fuel use.
- Staged retrofits can make the retrofit process and associated investments manageable and attractive to homeowners; they also provide an opportunity to incorporate efficiency measures into other home improvement projects, such as siding or roof replacement.
- In all climates, a high-efficiency heat pump system can meet the reduced space-cooling needs with less than half the electricity used in the pre-retrofit scenario.
- Envelope measures are critical in the heating-dominant cold, mixed-humid, and marine climate regions. Older homes in those regions benefit the most from comprehensive envelope upgrades, which account for the vast majority of energy savings.
- In the hot-humid and hot-dry regions, which have milder winters and newer housing stock, retrofit packages timed to coincide with equipment replacement yield the largest savings and may be especially appealing to customers.
- Heat pump water heaters present the best opportunity for energy savings through electrification in warmer climates, where space heating loads are smaller.
- Several alternative measures (e.g., storm windows, cellular shades, thermostatic restrictor valves, and drain water heat recovery) provide opportunities for meaningful savings at lower cost, increase savings in the near term, and address comfort and other occupant needs.

Residential energy retrofits present an enormous opportunity for energy savings and emissions reductions. A 2021 International Energy Agency report projects that existing residential buildings need to be retrofitted at the rate of 2.5% each year to reach the goal of net-zero emissions by 2050. This is 25 times the current rate of home retrofits completed through the leading U.S. programs: Home Performance with ENERGY STAR and the Weatherization Assistance Program.

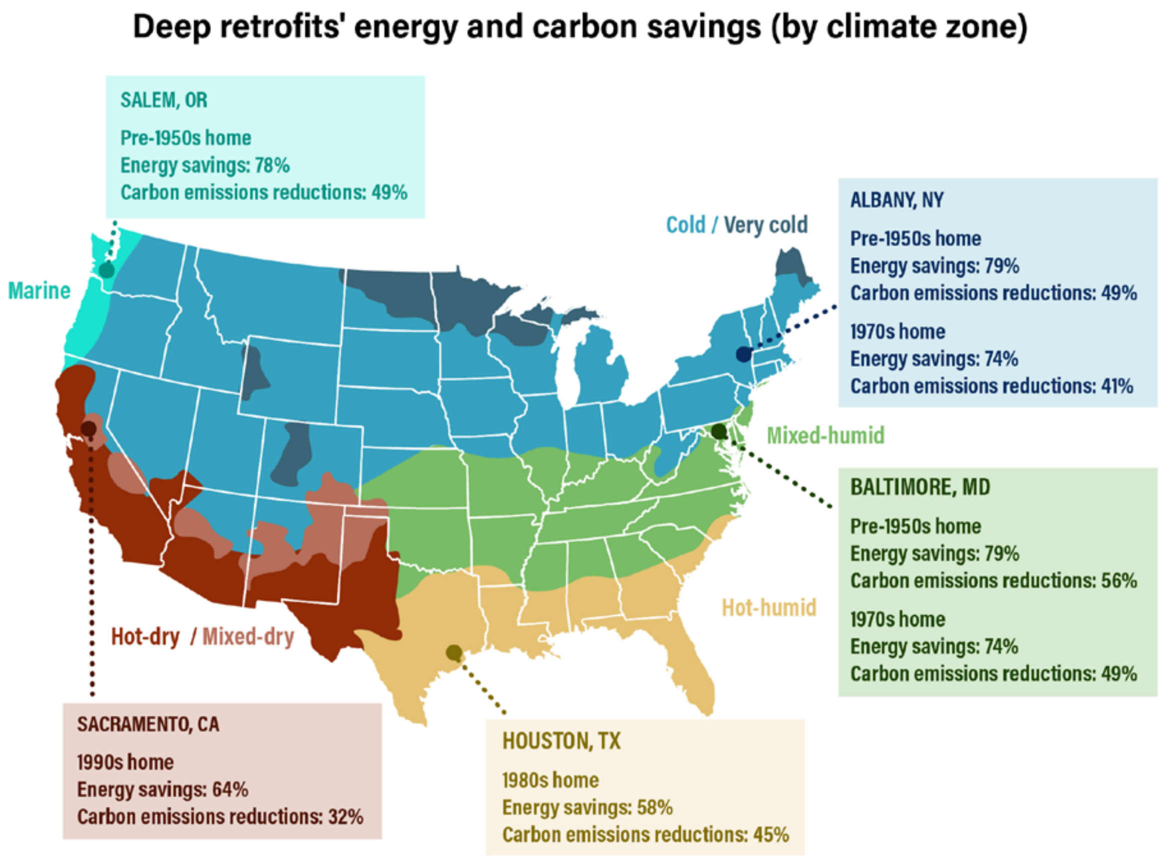
Home retrofits generally result in high levels of consumer satisfaction, as they offer consumers a number of high-value benefits beyond energy savings, including increased comfort, improved indoor air quality, and reduced noise. However, increasing adoption of home retrofit programs has proved to be a persistent challenge for program administrators, policymakers, and the contractors who deliver efficiency services. Many homeowners do not invest in a comprehensive home retrofit because of cost, disruption to daily life, confusion about the best measures, or uncertainty about the overall benefits. In this report, we present an analysis of several retrofit scenarios designed to increase customer interest and participation while achieving significantly higher energy savings and emissions reductions relative to common practice today.

TECHNOLOGY PACKAGES FOR DEEP ENERGY SAVINGS AND DECARBONIZATION

The deep energy and decarbonization retrofit packages and delivery approaches developed and analyzed in this report can reduce home energy use by more than 50% and are designed to address customers' interests and needs as well as provide flexibility in timing. The retrofit packages include envelope measures, heat pump and heat pump water heater replacements, and a few alternative measures. They are modeled as a single, comprehensive project and as two staged retrofit scenarios to evaluate how sequencing of the package in two phases affects the realization of energy and carbon savings and the distribution of project costs. According to the modeling analysis, homeowners can expect source energy savings of 31% to 59% depending on climate region and home vintage, with corresponding carbon reductions of 32% to 56%. Site energy savings range from 58% to 79%. Estimated project costs run from $42,600 to $56,750. Several alternative measures (e.g., storm windows, cellular shades, dehumidifiers, ceiling fans, thermostatic restrictor valves, and drain water heat recovery) included in the analysis provide opportunities for meaningful savings at lower cost, help increase energy savings in the near term, and deliver nonenergy benefits as well.

CLIMATE-SPECIFIC FINDINGS

The selection and sequencing of retrofit packages that deliver deep savings depend on both regional climate and housing characteristics. Older homes in cold, mixed-humid, and marine climates benefit most from envelope upgrades, which reduce heating and cooling loads significantly and contribute the majority of the savings. In these climates, a staged retrofit approach—one that prioritizes envelope upgrades in the first phase—delivers greater near-term gas savings than in warmer climates, with even more savings in subsequent phases when HVAC and water heating are electrified. However, the priority envelope upgrades also account for the largest share of project costs. For newer housing stock in hot-humid and hot-dry climates, a combination of equipment replacement and select envelope measures (e.g., attic insulation) is likely to reduce heating and cooling loads and contribute to energy and carbon savings. A staged approach that combines some equipment replacement and envelope efficiency measures in the first phase can be a good option for homeowners who are ready to upgrade their heating system. In all climates, a high-efficiency heat pump system can meet the reduced space-cooling needs with less than half the electricity used in the pre-retrofit scenario.



Adapted from the Department of Energy's Building America Climate Zone Map

FINANCING DEEP RETROFITS

Affordable financing at a below-market interest rate can go a long way in helping homeowners pay for deep retrofit projects. Aligning accessible financial solutions with the different project goals and economic situations of households undertaking an energy retrofit can further encourage projects. Homeowners are likely to benefit most from a combination of favorable financing terms and some form of upfront incentive to cover the capital required for a major retrofit. Although there are many different programs and financial instruments in the market that specifically fund energy efficiency upgrades, further innovation in program design will likely be required to make deep energy reductions accessible for a majority of households. Design of a financing program that scales deep residential retrofits will need to incorporate many elements, including—but not limited to—

inclusivity, attractive financing terms (rates and duration), a simple application process, convenience, contractor-friendliness, and strategic public–private partnerships.

CHALLENGES TO DEEP ENERGY REDUCTIONS AND DECARBONIZATION

Experience to date shows that retrofit approaches requiring extensive disruption to occupants or focusing on envelope and major systems alone will not increase adoption or result in savings of 50% or more. While the technology for deep savings exists, technical challenges to scaling up the number of projects remain. These include the limited range of heat pump products that deliver high efficiency at lower cost than conventional systems, lack of standardized insulation packages that reduce time and error, and the limited use of passive technologies to decrease building loads. The pool of contractors undertaking deep retrofit projects also remains fairly small. Many contractors are understandably overwhelmed by the added complexity of selling and delivering deep retrofit projects while simultaneously meeting program requirements; consequently, they decide to forgo participation. Last, the cost of deep retrofit projects makes them unaffordable for many households. Further development of retrofit-ready equipment designed to work on existing outlets and in smaller spaces would reduce the cost and inconvenience of deep retrofits, and financing and incentives would help lower the cost barrier as well.

EFFECTIVE STRATEGIES FOR DESIGNING RETROFIT PROGRAMS

A number of residential retrofit programs have incorporated one or more of the strategies examined in our analysis. These programs are attempting to address the persistent barriers to deeper savings and greater program participation. Our analysis identifies several effective strategies program administrators can adopt to help deep retrofit programs best serve their customers and the grid:

- *Standardizing retrofit packages.* Developing a set of standard measure packages to address common home needs and opportunities can ensure significant energy savings. It also reduces the time, cost, and inconvenience associated with a typical customized approach to whole-home retrofits.

- *Staging retrofits*. Splitting a deep retrofit project into two or more stages can make the process (and the investment) less overwhelming than it might otherwise be. It also allows homeowners to tackle immediate needs first while providing a mechanism for ongoing engagement to support completion of the full retrofit over time.

- *Undertaking electrification.* Coupling electrification with deep retrofit projects can increase cost effectiveness, maximize emissions reductions, and improve overall home performance. Electrification facilitates the transition to a decarbonized building stock.

- *Offering financing and incentives.* Affordable financing approaches and incentives can help reduce the cost barrier. They can help lock in the full project and encourage homeowners who decide to split the deep retrofit project into phases to follow through with later stages.

Introduction

Residential energy retrofits present an enormous opportunity for energy savings and emissions reductions, but increasing their adoption has proved to be a persistent challenge for program administrators, policymakers, and the contractors who deliver efficiency services to this market. ACEEE's recent *Halfway There* analysis (Nadel and Ungar 2019) found that home energy retrofits could deliver 3.8 quadrillion Btus in energy savings and 148 million metric tons in U.S. carbon emissions reductions by 2050. Globally, the International Energy Agency (IEA) projects that existing residential buildings need to be retrofitted at a rate of at least 2.5% each year to reach the goal of net-zero emissions by 2050, roughly 25 times the current rate of home retrofits currently completed through the leading U.S. programs: Home Performance with ENERGY STAR and the Weatherization Assistance Program (IEA 2021; DOE 2020; WAP 2016). In light of the important role of residential retrofits in achieving the greenhouse gas reductions imperative to preventing the worst impacts of climate change, ACEEE has committed to work on scalable models and techniques to at least double the rate of retrofits by 2030 relative to 2019 levels (ACEEE 2020).

To achieve the energy and carbon savings in the *Halfway Ther*e analysis, the authors assumed retrofit projects would deliver average savings of at least 30% of whole-home energy use in 65% of homes by 2050 (roughly 2% of homes each year from 2020 to 2050). For each year in which retrofit activity and/or savings lag, participation and savings must ramp up just to stay on track. At present, typical whole-home retrofit strategies (e.g., home performance, weatherization) deliver average savings of roughly 20–25% of whole-home energy use—about $500 in annual energy costs—per project (Dunn 2019). Most program implementers find their program participation rates plateau at around 1% per year after several years, regardless of changes to program design and the level of incentives or financing offered (Cluett and Amann 2014).

The barriers to greater adoption of whole-home retrofits are significant and well documented (Hoffmeyer 2016; Cluett and Amann 2016; Fuller et al. 2010). Despite these barriers, research shows that home retrofits offer consumers a number of high-value benefits beyond energy savings (e.g., increased comfort, improved indoor air quality, reduced noise) and generally result in high levels of consumer satisfaction. These benefits may be even more attractive to consumers in the post-COVID world as interest in ensuring a healthy, safe, and productive home environment grows.

Considering the current low rate of retrofit activity and savings achieved relative to the pressing need to decarbonize buildings, improve occupant health and comfort, increase grid flexibility, and make homes more affordable, we aim to identify measures that can increase near-term savings while meeting consumer needs and a broader set of longer-term goals. In this report, we present an analysis of various retrofit scenarios designed to increase customer interest and participation while achieving significantly higher energy savings and emissions reductions than are being realized today.

Current Retrofit Activity and Practices

It is difficult to estimate the number of U.S. homes that have been retrofitted to date or the annual rate of retrofitting. There is no single retrofit program or systematic method for collecting data from the dozens of efficiency programs and thousands of contractors delivering home retrofits around the country. Data from Home Performance with ENERGY STAR® (HPwES) and the Weatherization Assistance Program (WAP), both led by the U.S. Department of Energy (DOE), provide a good starting point for understanding the scale of home retrofit activity and trends over time. These programs focus on comprehensive home retrofits rather than projects involving a single efficiency measure or incorporating an efficiency measure as part of another home improvement.

From its inception in 2002 through 2019, a total of 878,703 projects were completed through HPwES, including 103,535 in 2019 (DOE 2020). Figure 1 shows projects completed each year and the cumulative total over the life of the program. Thirty-nine local program sponsors and a network of 1,300 participating contractors serve customers in 27 states and the District of Columbia (Dunn 2019). While the program is offered in every region of the country, activity is concentrated in the Northeast, where 65% of all HPwES projects in 2019 were completed in just four states (Connecticut, Massachusetts, New Jersey, and New York) (DOE 2020). The program aims to achieve energy savings of 25% or more per project; recent project savings have averaged 25% (Dunn 2019).

WAP provides home retrofits to an average of 35,000 low-income households each year free of charge. This is a minuscule fraction of the roughly 40 million households eligible for WAP services (WAP 2016).

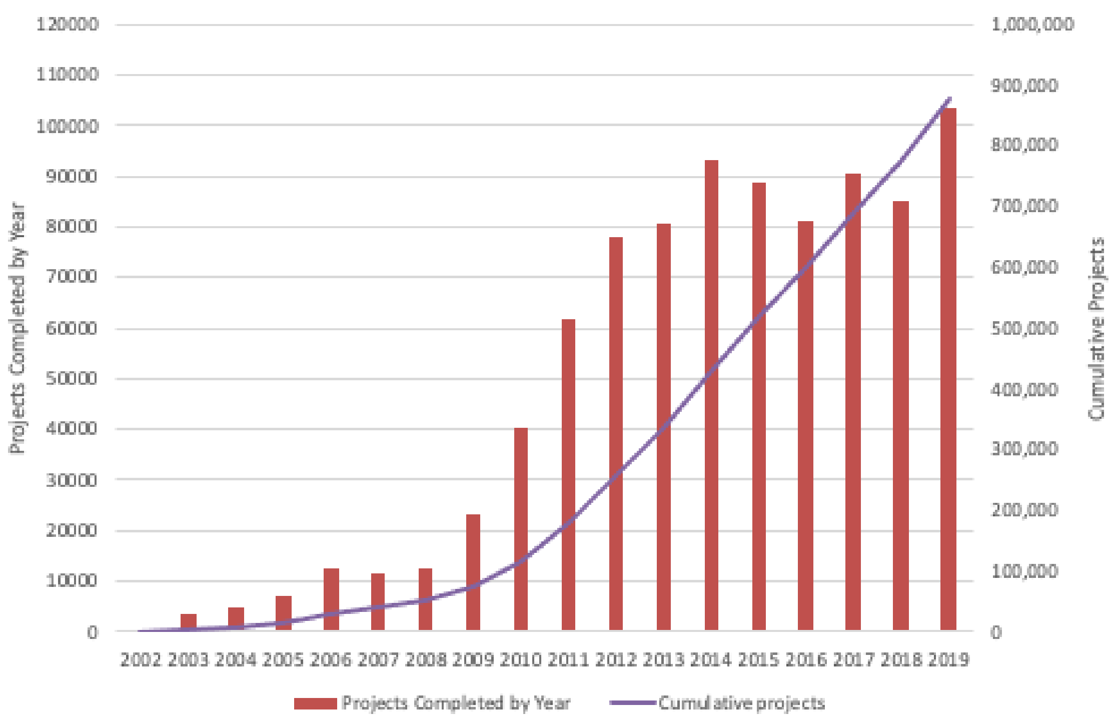


Figure 1. Home Performance with ENERGY STAR projects, by year and cumulatively (DOE 2020)

Whole-home retrofit projects deliver a set of measures designed to meet the specific needs of a home based on baseline energy use, customer input on comfort and other performance issues, and the results of diagnostic testing of air leakage, duct leakage, and thermal performance. The specific package of measures installed may depend on the specific knowledge and expertise of the contractors involved, or, in the case of programs, it may reflect the broader set of measures approved by the program administrator (and its regulator).

Terminology

Whole-home retrofit (or home performance) projects address deficiencies in the building envelope and necessary upgrades to major building systems (e.g., HVAC, water heating, and lighting). Typical project savings range from 15% to 30% of whole-home energy use.

Deep retrofits are whole-home projects that incorporate more extensive envelope and equipment upgrades with the goal of achieving whole-home energy savings of 50% or more.

Deep energy reduction projects expand on the range of measures targeted in retrofit projects to include behavioral measures and a more comprehensive set of end uses with the goal of achieving at least a 50% reduction in energy use. This approach can be particularly attractive when deep retrofits are uneconomical or overly disruptive and in mild climates where HVAC savings opportunities are limited.

Decarbonization encompasses a host of strategies for reducing building-related carbon emissions. Key approaches include beneficial electrification, energy efficiency, passive design, peak demand reduction, load shifting/control, and distributed energy resources.

Other home improvement transactions (e.g., remodeling, additions, equipment replacement) present opportunities for contractors and programs to engage customers on efficiency upgrades that can readily be incorporated into their planned projects. Adding efficiency upgrades can deliver a variety of nonenergy benefits and address health, safety, and durability issues along with utility bill savings and carbon reductions.

Homeowners, contractors, program administrators, and policymakers need to understand how various retrofit measures affect home energy use and how the timing of measure installation impacts the realization of energy and carbon savings overall. Many homeowners will not invest in the full, ideal, comprehensive home performance approach because of cost, disruption to daily life, confusion about the best course of action, or skepticism about the overall benefits. When a customer wants to do envelope upgrades now and system replacements later, the path forward is clear; otherwise, we need scalable options that will be implemented because they address these customers' interests and needs. Table 1 presents common customer interests and concerns along with potential solutions.

In this study, we analyze energy savings from comprehensive deep retrofit packages designed to save more than 50% of home energy use in each of the five main climate regions of the United States. We then analyze the savings from these packages when delivered in different stages. We also compare them with some alternative measures to identify options that can deliver a similar level of energy savings and carbon reductions at lower cost or in a series of smaller projects that better meet customer needs, interests, and preferences.

Table 1. Customer interests and potential solutions

Consumer interest/concern	Solution
Customer needs equipment replacement but does not see the value and benefit of addressing envelope issues at the same time	Recognize the customer's view and propose an approach that incorporates only the highest priority envelope measures
Customer has a list of priority projects or repairs to complete before considering an efficiency retrofit	Take advantage of every home improvement project to incorporate related efficiency measures when added costs and inconvenience are lowest
Consumer is willing to undertake some added upgrades but is reluctant to adopt new technologies that are still evolving	Focus on other measures to generate near-term savings and pave the way for more savings in the future
Customer balks at the price, inconvenience, or uncertainties but is open to measures with lower cost, less disruption, and/or nonenergy benefits of particular value to the household	Incorporate a broader range of program measures that include options to address customer interests in energy and/or nonenergy benefits

Research Methodology

To inform the design of decarbonization packages for different climate zones (including energy and carbon reduction measures, delivery approaches, financing mechanisms, and incentive policies), we analyzed a select set of retrofit scenarios for the most common pre-2000 housing types in the major U.S. climate zones, using energy models, engineering analyses, and economic analyses. The energy modeling and evaluation of various retrofit scenarios helped prioritize the core efficiency measures included in the decarbonization packages. The engineering analyses helped identify alternative measures that can deliver similar savings at lower cost than the core energy efficiency measures but cannot be easily modeled in the thermal dynamic simulations. These alternative measures are also included in the decarbonization packages. Finally, the economic analyses provided insight into the financing mechanisms and the level of upfront capital needed to fund these projects.

MODELING RETROFIT SCENARIOS

A literature review was our starting point to identify the building characteristics, primary fuel use, typical heating and cooling equipment, and household appliances in single-family homes. We reviewed more than 50 published reports and peer-reviewed papers on deep energy retrofit programs and initiatives, case studies of individual projects, and recent literature on alternative technologies and approaches that have proved successful in delivering deeper energy savings and emissions reductions. We used the information to establish the baseline conditions and develop the retrofit packages for our analyses.

We created seven baseline models. To evaluate retrofit and decarbonization packages in each of the major U.S. climates, we selected a representative city in each of the five Building

America climate regions.[1] We then identified the most common pre-2000 housing vintages in each climate region using data from the Energy Information Administration's (EIA) 2015 *Residential Energy Consumption Survey* (EIA 2018). In two of the five climate regions, two different housing vintages were prevalent, so we created baseline models for both vintages. Then we modeled the retrofit packages and scenarios for these seven climate-vintage combinations. Appendix A provides additional detail on how we selected the building vintages and developed the baseline models.

The model characteristics varied according to the climate and housing vintages (i.e., pre-1950s, 1970s, 1980s, and 1990s). Table 2 shows the building characteristics that differ across baseline models. Pre-retrofit conditions (i.e., baselines) were based on publicly available data from the National Renewable Energy Laboratory's (NREL) ResStock Analysis tool, the EIA's Residential Energy Consumption Survey, the National Residential Efficiency Measures Database, and the Building America Research Benchmark Definition (Hendron and Engebrecht 2010). We used this information in our modeling to evaluate pre-retrofit energy use and carbon emissions and the impacts of different retrofit scenarios.

Table 2. Building structure and system categories and measures that differ in the seven baseline models

Building structure and system category	Building structure and system measures
Envelope	Wall insulation
	Attic insulation
	Roof material
	Basement/foundation/crawl space insulation
	Window replacement
Heating	Heating equipment (furnace/boiler/heat pump)
	Heating set point
Cooling	Cooling equipment (room/central air conditioner)
	Cooling set point
Ventilation	Whole-house mechanical ventilation
	Air sealing (air changes)
	Space conditioning duct insulation

[1] Building America is a U.S. Department of Energy program for residential buildings. Under the program, for reporting purposes, U.S. climate zones are combined into five climate categories: hot-humid, hot-dry/mixed-dry, mixed-humid, marine, and cold/very cold. For details, see www.energy.gov/eere/buildings/climate-zones.

Building structure and system category	Building structure and system measures
Water heating	Water heating equipment (gas boiler/furnace)
	Distribution system insulation
Lighting	100% LED lamps

Using the literature on comprehensive retrofits and case studies, we developed three deep retrofit scenarios. As a starting point, for each of the five Building America climate regions we used recommendations for deep retrofits put forth by the Lawrence Berkeley National Laboratory (LBNL) (Less and Walker 2015). We made modifications to reflect more recent research findings and products available in the market. The three retrofit scenarios include a comprehensive retrofit project where all measures are installed at one time (Retrofit A), and a pair of alternatives for completing the retrofits in two stages (Retrofits B and C). In the two-stage retrofits (B and C), the sequencing of efficiency measures is varied. We describe the details of the packages later in this report, in the "Modeled Deep Energy Retrofit Packages and Scenarios" section.

We modeled the three whole-home retrofit scenarios in the Building Energy Optimization Tool (BEopt) relative to the seven baseline models and examined the pre- and post-retrofit performance. BEopt is a residential building energy simulation software tool developed by NREL. It has a plug-and-play interface that uses the EnergyPlus simulation engine to evaluate building designs and identify energy efficiency packages for both new construction and existing home retrofits. Because BEopt can compare user-defined designs with some custom options for building measures listed in table 2, the simulation results allowed us to assess and refine the different retrofit packages.

We estimated the energy savings and emissions reductions from the different retrofit packages by comparing the simulation results of the pre-retrofit building model to the improved building model for each retrofit scenario described in the "Technology Packages" section below. We used the default BEopt source and site energy and carbon emissions values, which reflect the regional grid generation fuel mix from 5–10 years ago. Because the tool does not adjust for improvements to the grid over time, our values for energy and carbon emissions savings are conservative. The energy modeling tool also provided the breakdown of electricity and gas use pre- and post-retrofit, which supported our analysis of the potential for achieving near-term savings from efficiency and electrification measures.

ENGINEERING ANALYSIS

Following the energy simulations, we completed an engineering analysis to compare and evaluate savings from alternative or supplemental retrofit measures. The analysis assessed whether savings from a diverse set of measures that typically are not included in whole-home retrofit projects (e.g., window attachments, ceiling fans, and heat recovery) deliver the same level of energy savings and carbon reductions as the measures in table 2, but at a much lower cost. We calculated the savings by combining the results from our annual building energy simulation and findings from peer-reviewed research and reports on energy savings, costs, and other benefits.

Since it is challenging to model some of the alternative and supplementary measures in BEopt (e.g., interior shading devices like cellular shades and solar screens), we chose to use engineering calculations instead of simulations in this step. For the few measures we could have modeled (e.g., ceiling fans and home appliances), the options in the BEopt software library do not reflect the most efficient models available in the market. Further, the last update of the BEopt software was in 2018, and since that time, other upgrade options that yield more savings may have been introduced. Other measures that we analyzed, such as drain water heat recovery, tub spout diverters, and valves, cannot be modeled in BEopt but offer significant energy savings and a host of other benefits to consumers.

This analysis also helped prioritize the alternative measures that are relevant in each climate and building type. A number of these represent opportunities to electrify end uses or reduce internal loads, which can make heat pumps more feasible and affordable.

ANALYZING FINANCING SOLUTIONS

For the seven baseline model homes, we analyzed three financing options to cover the cost of deep retrofit projects. One was cash-flow neutral; another represented an additional cost of $75/month for a household; and the third an additional cost of $150/month. We used a discounted cash-flow analysis that models project and financing costs against the estimated energy savings from the deep retrofits, along with a regression analysis to understand the level of upfront capital required to fund the deep retrofit projects under the three financing options.

Technology Packages for Deep Energy Savings and Decarbonization

Deep retrofits have long been considered mainly a niche opportunity attractive only to the deepest-green “true believers” or those seeking to live entirely off the grid. The imperative of climate change, combined with growing interest in technologies that can significantly reduce energy use while improving indoor health and comfort, are driving a broader discussion on ways to move homes toward low- or zero-energy use targets.

While the overall cost and commitment required for deep retrofits continue to limit investment in what are often complex projects, there are savings that can be captured from a range of underutilized retrofit measures (e.g., window attachments, electronics and other plug loads, heat recovery) as part of efficiency retrofits or other home renovation and repair projects. These measures provide homeowners looking to phase in a deep retrofit over a number of years with options to achieve much-needed and valuable near-term energy and carbon reductions while production-level approaches to full-scale envelope upgrades (as well as full envelope/major system upgrades) are being developed and introduced to the broader U.S. market.

MODELED DEEP ENERGY RETROFIT PACKAGES AND SCENARIOS

The significant body of research covered in our literature review draws on advances in building science, experience from deep energy retrofit programs and initiatives, and case studies of individual projects to document the technologies and approaches that have proved most successful in achieving significant energy savings and improved home performance. Building on this body of research, LBNL published specific recommendations for deep retrofits in each of the five Building America climate regions (Less and Walker 2015).

We used LBNL's recommendations as a starting point for our comprehensive deep retrofit packages, with some modifications reflecting more recent research findings. Table 3 presents the primary retrofit measures modeled in our analysis, noting deviations from the LBNL recommendations. We modeled these whole-home deep retrofit packages in seven homes representing common construction, vintage, and characteristics for each of the five Building America climate regions using the BEopt software developed by NREL.

Table 3. Comprehensive deep energy retrofit packages

	Cold	Mixed-humid	Hot-humid	Hot-dry	Marine
Walls	R-30 assembly	R-20 assembly	*R-13 cavity*	*R-13 cavity*	R-30 assembly
Attic	R-60 insulation	R-49 insulation	R-38 insulation	R-38 insulation	R-38 insulation
	All climates: Convert to unvented attic, if feasible. If not, seal to ensure continuous air barrier at attic floor.				
Roof	No treatment	Reflective roof coating or membrane	Reflective roof coating or membrane	Reflective roof coating or membrane	No treatment
Foundation/ basement	Basement: R-20 continuous	Basement: R-10 continuous	Slab foundation: no treatment	Slab foundation: no treatment	Crawl space: R-15 continuous
	Basement/crawl spaces: Seal walls and vents, seal and insulate rim joists, install continuous vapor barrier in all exposed crawl spaces.				
Windows[a]	*ENERGY STAR Northern*	*ENERGY STAR North–Central*	*ENERGY STAR Southern*	*ENERGY STAR South–Central*	*ENERGY STAR Northern*
Air leakage	All climates: air sealing to ACH ≤ 7.0 (measured at 50 pascals of pressure)				
Mechanical ventilation	HRV/ERV: >75% heat recovery	None	None	None	HRV/ERV: 70% heat recovery
(whole house)	All climates: ASHRAE 62.2 compliant ventilation				

	Cold	Mixed-humid	Hot-humid	Hot-dry	Marine
Space conditioning (air source heat pump)[b]	*NEEP cold climate or better*	*NEEP cold climate*	*ENERGY STAR Most Efficient*	*ENERGY STAR Most Efficient*	*NEEP cold climate*
	All climates: Ducts insulated and sealed; smart thermostats installed				
Water heating	All climates: Install heat pump water heater *EF 3.45*; insulate pipes; repair all leaks; install low-flow fixtures (1.5 gpm or less)				
Lighting	All climates: 100% LED—*focus on specialty bulb types*				

Source: Less and Walker 2015 (LBNL) and ACEEE analysis. Variations from LBNL recommendations are in italics; additional details can be found in Appendix A.

[a] ENERGY STAR Residential Windows, Doors, and Skylights V6.0: www.energystar.gov/sites/default/files/asset/document/Windows_Doors_and_Skylights_Program_Requirements%20v6.pdf.

[b] ENERGY STAR Most Efficient 2021: www.energystar.gov/sites/default/files/CAC_ASHP_GHP%20ENERGY%20STAR%20Most%20Efficient%202021%20Final%20Criteria.pdf **and NEEP Cold Climate ASHP:** neep.org/heating-electrification/ccashp-specification-product-list.

As noted above, many homeowners are reluctant or unable to invest in a one-time comprehensive home performance project designed to optimize delivery of energy efficiency and building performance improvements. Scalable deep retrofit strategies will be implemented in large numbers when and if they meet customers' interests, needs, and preferred timing. A number of contractors and program administrators are exploring staged retrofit approaches that balance customer preferences, program objectives, and a sound building science approach to ensure successful outcomes. Contractors and programs work with customers to develop a staged retrofit approach that identifies priority retrofit measures for initial investment and a detailed plan for completing the retrofit in one or more additional stages in the future.

After modeling our deep retrofit and decarbonization package as a single comprehensive project in each of our seven homes, we modeled two staged retrofit scenarios to see how sequencing of the package in two phases impacts the realization of energy and carbon savings. Location and vintage of the homes and the retrofit scenarios modeled are presented in table 4. Our retrofit scenarios include:

- **Retrofit A:** Comprehensive project installing the full package of measures at one time.
- **Retrofit B:** Staged retrofit conducted in two main phases, with full envelope upgrades first and equipment upgrades deferred to the second phase. This is often considered the preferred order for a staged retrofit approach. By addressing the full envelope first, subsequent equipment upgrades can be properly sized to match the

reduced heating and cooling load, thereby delivering equipment cost and efficiency improvements. This approach may appeal to customers who are experiencing comfort issues and high energy bills but do not need to replace their HVAC or water heating systems for several years.

- **Retrofit C:** Staged retrofit conducted in two main phases, with a mix of envelope and equipment measures installed in each phase. This scenario may appeal to customers who need an equipment replacement but are not willing to take on the full set of envelope measures at the same time. With a staged approach, these customers may be persuaded to couple priority envelope measures with the initial equipment upgrade and make a plan to complete the remaining envelope measures later, perhaps in conjunction with additional equipment replacement projects.

Table 4. Details of retrofit scenarios modeled

Climate region, vintage, representative location				
Cold	Mixed-humid	Hot-humid	Hot-dry	Marine
Pre-1950s and 1970s	Pre-1950s and 1970s	1980s	1990s	pre-1950s
Albany, NY	Baltimore, MD	Houston, TX	Sacramento, CA	Salem, OR

Retrofit scenarios		
Retrofit A:	Retrofit B:	Retrofit C:
Comprehensive envelope and equipment upgrade completed in single stage	Two-stage retrofit Year 1: full envelope Year 5: full equipment	Two-stage retrofit Year 1: partial envelope and equipment Year 5: remaining envelope and equipment

Figure 3 lists the specific measures included in each retrofit scenario. For each measure, technology and energy efficiency align with the deep energy retrofit and decarbonization package specifications outlined above in table 2.

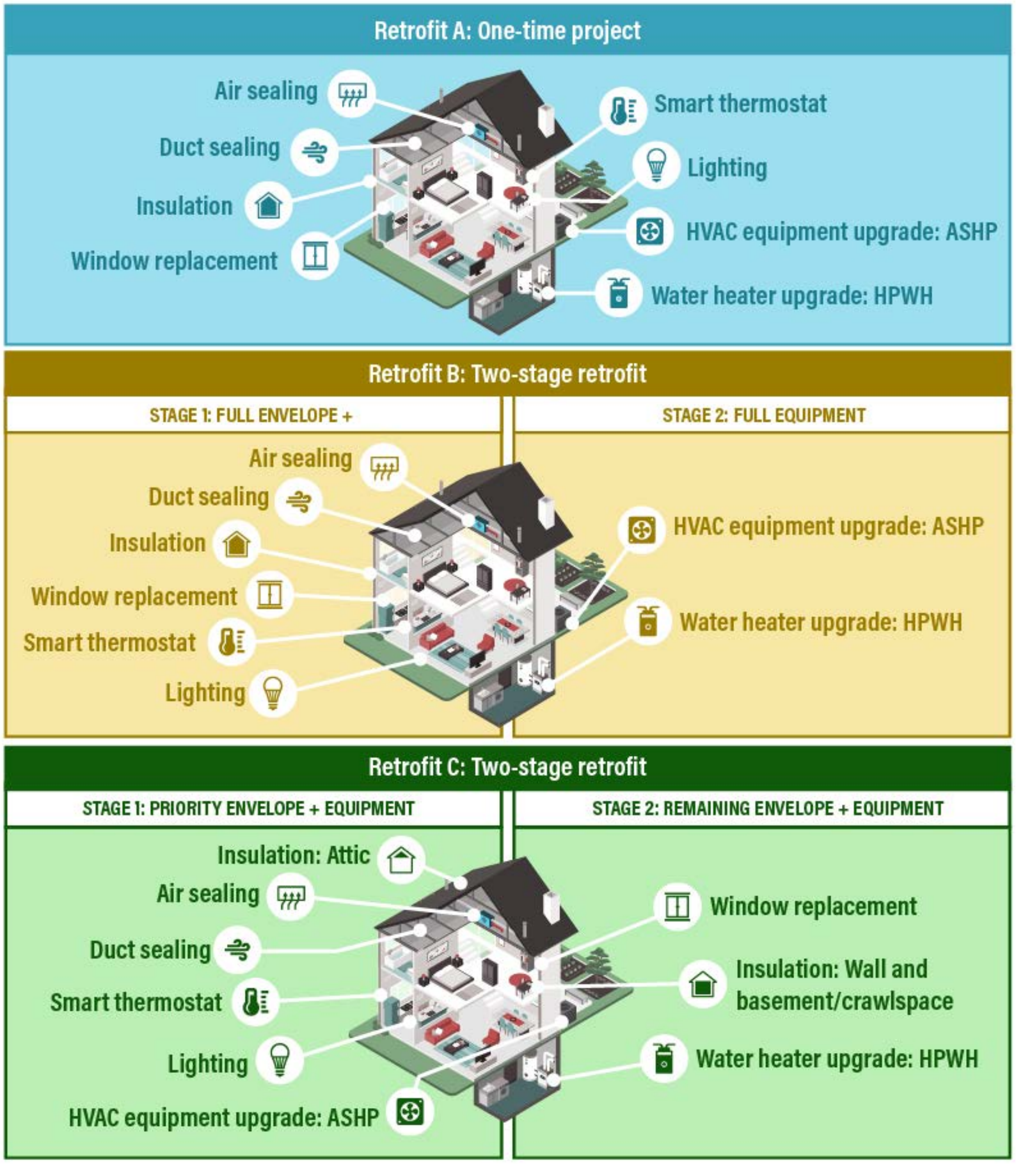


Figure 3. Modeled retrofit scenarios

ENERGY AND CARBON SAVINGS FOR MODELED RETROFIT PACKAGES

Modeling analysis of deep retrofit and decarbonization packages resulted in estimated source energy savings of 31% to 59%, depending on climate region and home vintage; corresponding carbon reductions are 32% to 56%. Site energy savings range from 58% to 79%, reflecting the impact of electrification measures that eliminate the vast majority of on-site fossil fuel use. Table 5 provides source and site energy savings for the full package of retrofit measures in each climate and housing vintage modeled.[2] As noted in the methodology, our modeling approach resulted in the same energy and carbon savings at the end of each project whether completed at one time or in stages. More details on energy savings by fuel and end use are included in climate-specific sections later in this report.

Figure 4 shows the percentage of total site energy savings and carbon reductions achieved in each stage of the Retrofit B and C scenarios. Results demonstrate the importance of envelope measures in the heating-dependent cold, mixed-humid, and marine climate regions. Older homes in these regions benefit the most from comprehensive envelope upgrades, which account for the vast majority of energy savings.

In the staged retrofit scenarios, the majority of carbon reductions are captured in Stage 1 in the colder climates, particularly in Retrofit B, demonstrating the significant near-term gas savings associated with comprehensive envelope upgrades. In the longer term, the reduced home heating load will improve the performance of the heat pump system during the coldest days of the year. Installation of high-efficiency heat pumps and heat pump water heaters in Stage 2 of Retrofit B results in minor additional carbon reductions—and a loss of some energy and carbon savings in the older cold climate home—both reflecting the impact of electrification and the addition of air-conditioning capacity in some homes.

Table 5. Total project source and site energy and carbon savings (%)

Region	Vintage	Source energy savings (%)	Site energy savings (%)	Carbon emissions reductions (%)
Cold	Pre-1950s	52%	79%	49%
	1970	44%	74%	41%
Mixed-humid	Pre-1950s	59%	79%	56%
	1970	51%	74%	49%
Hot-humid	1980	46%	58%	45%
Hot-dry	1990	31%	64%	32%
Marine	Pre-1950s	52%	78%	49%

In the hot-humid and hot-dry regions, with milder winters and a newer housing stock, envelope measures play a smaller role in driving energy savings. Retrofit packages timed to

[2] Site energy refers to the energy consumed onsite by the building including electricity, natural gas, and any other fuels consumed. Source energy (sometimes referred to as primary energy) includes site energy as well as energy losses through the generation, transmission, and distribution of electricity to the site.

coincide with equipment replacement yield greater savings and may be more appealing to customers in these regions. Stage 1 of Retrofit C accounts for more of the energy savings and carbon reductions in these homes than the envelope-focused initial stage of Retrofit B. Heat pump water heaters present the best opportunity for electrification in homes where space heating loads are smaller and gas heating systems are less common.

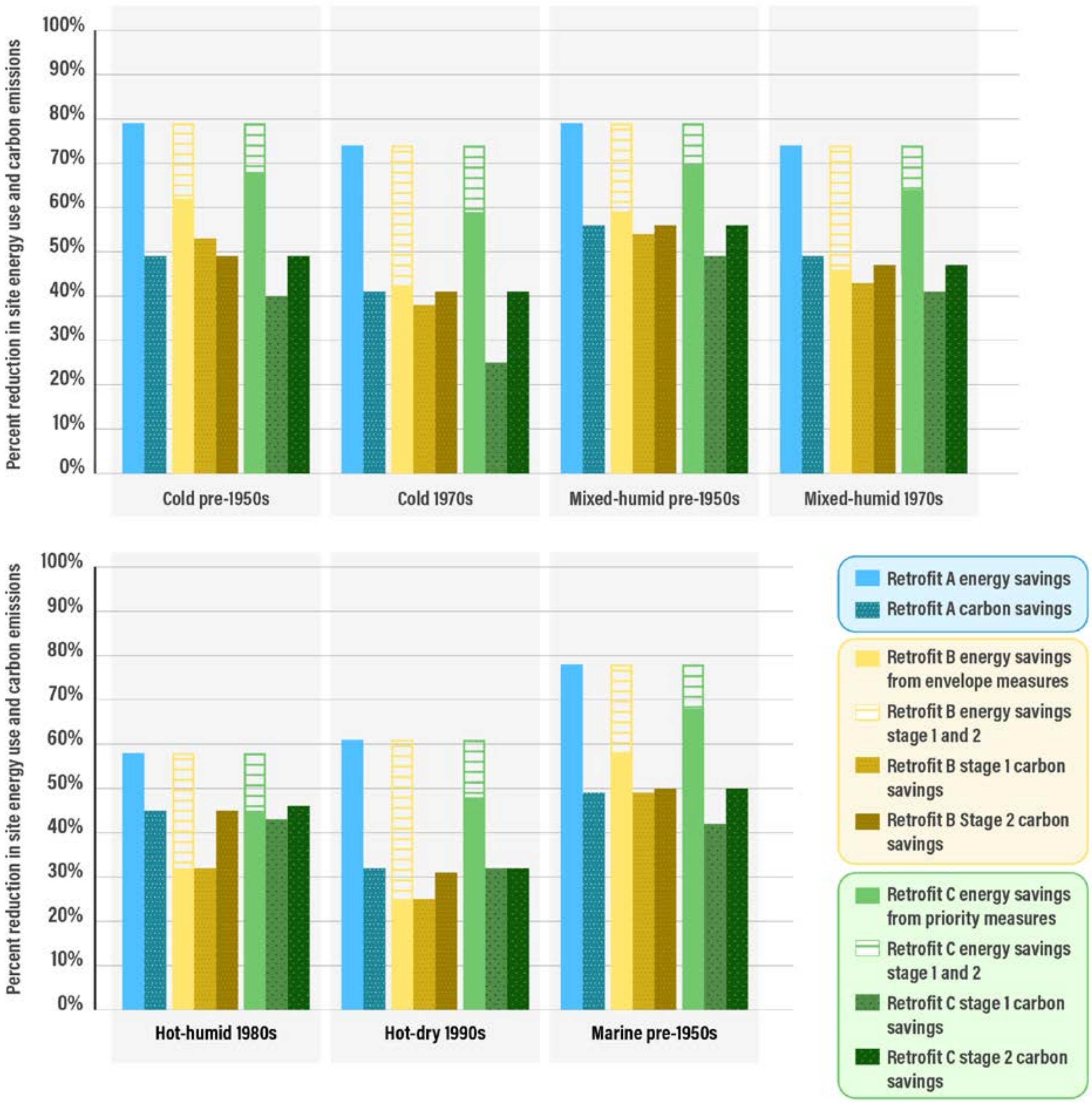


Figure 4. Indexed site energy savings and carbon reductions achieved in Retrofit A and in each stage of the Retrofit B and C scenarios.

PROJECT COSTS

Total project costs range from $42,582 for the hot-dry region home to $56,748 for the 1970s-vintage mixed-humid climate home. Costs for each modeled scenario are presented in table 6. Our modeling does not account for any added transaction costs associated with the staged approach in Retrofits B and C. In the colder climate regions (cold, mixed-humid, and marine), the cost burden is concentrated in the first phase of Retrofit B, which accounts for more than 80% of total project costs. Costs are more evenly distributed between the two phases for the hot-humid and hot-dry regions with Retrofit B, and in all climates with Retrofit C.

Table 6. Project costs (and % of total) by stage

	Retrofit A	Retrofit B		Retrofit C	
		Stage 1	Stage 2	Stage 1	Stage 2
Cold: pre-1950s	$53,223	$43,173 (81%)	$10,050 (19%)	$26,132 (48%)	$27,768 (52%)
Cold: 1970s	$53,657	$45,211 (84%)	$8,446 (16%)	$32,972 (61%)	$20,685 (39%)
Mixed-humid: pre-1950s	$46,569	$38,704 (83%)	$7,865 (17%)	$22,426 (48%)	$24,143 (52%)
Mixed-humid: 1970s	$56,748	$48,379 (85%)	$8,369 (15%)	$28,526 (50%)	$28,222 (50%)
Hot-humid	$45,159	$26,486 (59%)	$18,673 (41%)	$24,075 (53%)	$21,083 (47%)
Hot-dry	$42,582	$24,161 (57%)	$18,420 (43%)	$23,122 (54%)	$19,711 (46%)
Marine	$50,683	$42,089 (83%)	$8,595 (17%)	$28,813 (56%)	$22,446 (44%)

Modeled project costs are consistent with actual costs from deep retrofit projects. Vermont's Zero Energy Now program achieved 39% energy savings (64% fossil fuel and grid electricity savings) with an average project cost $54,000 (Stebbins, Perry, and Faesy 2020). A 2014 review of 116 deep retrofit projects across all climate regions found average costs of $40,420 for the 59 projects with cost data but also documented significant variability in costs across and within climate regions (Less and Walker 2014).

ALTERNATIVE AND SUPPLEMENTAL MEASURES FOR DEEP SAVINGS PACKAGES

Core strategies for deep retrofits focus on the building envelope improvements and major equipment upgrades discussed above. Heating, cooling, water heating, and lighting have traditionally been the largest energy uses in homes, but other energy uses (e.g., appliances, electronics, and other plug loads) now account for roughly one-quarter of home energy consumption in all climate regions, as shown in figure 5. Achieving energy savings of 50% or more requires attention to space conditioning and water heating loads in all climates, but targeting these loads alone is unlikely to achieve deep energy savings in any climate (Casey and Booten 2011). Other energy-saving strategies are needed, particularly in mild and moderate climates.

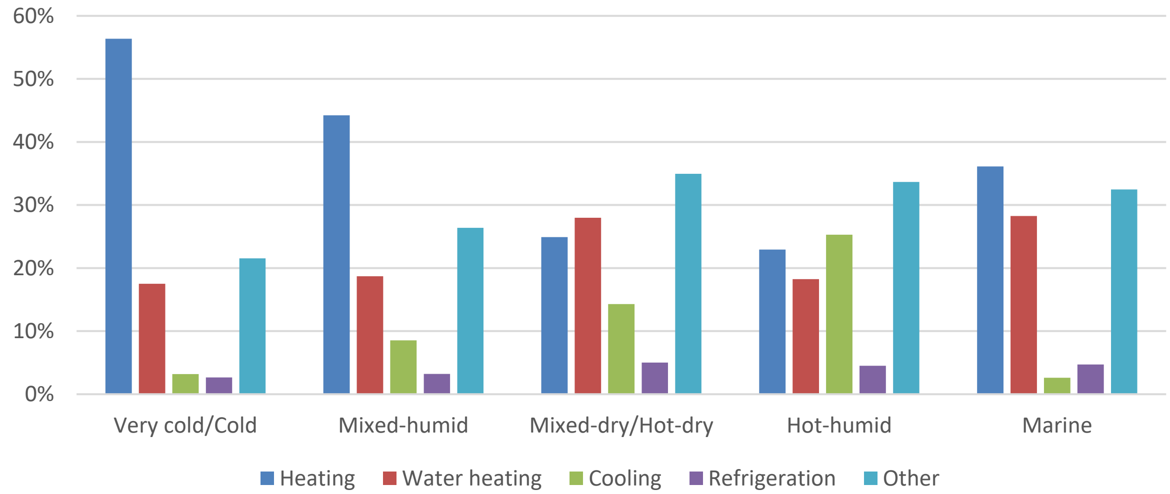


Figure 5. Household site energy consumption by end use for each climate region (EIA 2018)

To identify other strategies to achieve deep reductions, we developed a list of measures that have the potential to deliver energy savings, reduce project costs, and meet a broader set of consumer needs and interests but are rarely included in home performance programs or recommended in deep retrofit packages. These measures fall into two main categories: alternatives to traditional measures addressing heating, cooling, water heating, and lighting (e.g., drain water heat recovery, ceiling fans) and supplemental measures that save energy in other end-use categories (e.g., consumer electronics). While few of these measures offer the same order of savings as the core measures in our deep retrofit packages, they provide opportunities to capture meaningful savings at lower cost, help consumers increase energy savings in the near term, and appeal to consumers by offering a range of nonenergy benefits.

We collected data on energy savings, costs, and other benefits associated with each alternative and supplemental measure. Some measures are better suited to particular climates or housing types (e.g., dehumidifiers), and we developed energy savings estimates for each of our modeled prototypes where relevant. Brief descriptions of several promising measures are provided in the following section.

Window Attachments

High-performing window attachment products including low-e storm windows (interior and exterior), cellular shades, and solar screens can improve existing windows and achieve energy performance equivalent to that of ENERGY STAR–qualified windows at less than one-third of the cost. The Attachments Energy Rating Council (AERC) provides rating, certification, and labeling of window attachment products with energy performance scores to simplify consumer comparisons of heating and cooling season performance across products and categories. Published U-value, solar heat gain coefficient (SHGC), and visual transmittance data also allow comparison to replacement windows. ENERGY STAR–qualified storm windows offer another opportunity for consumers and programs looking for high-efficiency alternatives.

Window attachments costs and benefits	
Heating savings	6.5% to 22%
Cooling savings	3.5% to 16.5%
Costs	$50–500+ per window Consumer installation option for many products
Other benefits	Aesthetic improvement (for decorative products) Improved visual and thermal comfort Reduced noise Privacy

Sources: AERC 2017; Petersen et al. 2016

Dehumidifiers

Dehumidifiers improve indoor air quality (IAQ) and address moisture issues that pose health concerns, exacerbate pest problems, and compromise durability. Installing a new dehumidifier or replacing an existing unit with a high-efficiency model can remedy these issues while reducing latent load demand on the air conditioner. Installation in a home without a dehumidifier may increase electricity consumption, whereas replacement will likely reduce energy use through efficiency improvements. We analyze savings for ENERGY STAR Most Efficient–qualified (ESME) portable dehumidifiers with a water removal capacity of 50 pints per day or less.

Dehumidifier costs and benefits	
Baseline energy use: existing stock	950 kWh/yr
Baseline energy use: new model	≤25 pints/day: 511 kWh/yr 25.01–50 pints/day: 771 kWh/yr
ENERGY STAR Most Efficient	≤25 pints/day: 375–414 kWh/yr 25.01–50 pints/day: 563–650 kWh/yr
Costs	Baseline models: $125–286 ESME: $175–350
Other benefits	Improved occupant comfort and health Reduced incidence of mold, allergens, and other IAQ issues

Sources: EPA 2018; EIA 2018; retailer websites

Ceiling Fans

Ceiling fans can eliminate the need for air-conditioning in milder climates and in regions with short summers. They also reduce the need for air-conditioning in shoulder seasons and may allow occupants to maintain comfort with a warmer thermostat set point when air-conditioning is used. In recent decades, builders have routinely included ceiling fans in new homes; they are also relatively common in older homes and a simple addition in homes where they are not present.

New high-efficiency ceiling fans with improved controls present a savings opportunity in new installations and as upgrades to older fans. Energy savings depend on the number of fans per home, annual operating hours, and proper use (i.e., operating a fan only when a room is occupied, increasing the air-conditioning set point when fans are in use). We analyze fan-related energy savings for 52-inch-diameter ESME-qualified ceiling fans.

Ceiling fan costs and benefits	
Baseline energy use	65–155 kWh/yr per fan 130–465 kWh/yr per household
ENERGY STAR Most Efficient	25–55 kWh/yr per fan 50–165 kWh/yr per household
Costs	Baseline models: $60–1,200+ ESME models: $185–1,400
Other benefits	Improved airflow Improved controls; smart home integration Higher lighting efficacy and performance (for fans with lighting)

Sources: Kantner et al. 2013; retailer websites

Drain Water Heat Recovery

Drain water heat recovery (DWHR) utilizes a copper heat exchanger to capture waste heat from a shower's drain line. The reclaimed heat is used to preheat cold water as it is delivered to the showerhead or the water heater. By capturing and using waste heat, DWHR reduces energy used for water heating by 20–45%. Early DWHR devices were designed for vertical installation, limiting their use to multistory homes or homes with a basement (allowing adequate vertical drop in the drainpipe). Newer systems are available in both horizontal and vertical configurations, expanding the applicability of the technology to single-story and slab-on-grade construction. While DWHR is most commonly installed in new construction, retrofits are feasible in homes where drainpipes are accessible without too much disruption, or at the time of remodeling.

The technology has been used primarily in colder climates with lower inlet water temperatures throughout the year, but adoption in more moderate climates is increasing. Energy savings are dependent on inlet water temperature, DWHR efficiency, the number of fixtures, and configuration ("equal flow" units direct preheated water to the water heater *and* shower; "unequal flow" units direct it to one or the other). DWHR is particularly beneficial when used with a heat pump water heater. Effectively increasing the amount of hot water that can be provided in heat pump mode means there is less need for the backup electric resistance unit and the efficiency of the heat pump water heater is maximized.

We analyze savings for a DWHR unit with efficiency of 42% with an existing gas water heater (as specified in each of our modeled scenarios) and with a heat pump water heater to account for near-term and post-retrofit energy savings and life cycle cost effectiveness.

DHWR costs and benefits	
Baseline energy savings (gas water heater)	25–95 therms/yr (2.5–9.5 MMBtu/yr)
Post-retrofit savings (HPWH)	95–1,051 kWh/yr (0.65–3.6 MMBtu/yr)
Costs	$650–1,000 (equipment and labor)
Other benefits	Faster water heater recovery No maintenance over long lifetime (30+ years) Potential to extend water heater life

Sources: CASE 2017; Buchalter 2019

Tub Spout Diverters and Thermostatic Restrictor Valves

Tub spout diverters (TSDs) and thermostatic restrictor valves (TSVs) present energy and water savings opportunities above and beyond low-flow showerheads. Faulty TSDs are a common source of energy and water waste in combination bathtub-showers, with leaky units wasting an average of 0.8 gallons of hot water per shower. Replacements can save 100–400 kWh or 5–15 therms per fixture each year (Taitem Engineering 2011).

TSVs deliver savings by eliminating energy and water wasted in the lag time between hot water reaching the fixture and the user beginning to shower. We analyzed savings for TSVs integrated with a high-efficiency showerhead or tub spout diverter. Systems that include technology to purge cold water from the hot-water line can eliminate most of the lag time while providing additional water savings during the warm-up cycle.

TSD and TSV costs and benefits	
Baseline energy savings (gas water heater)	TSDs: 2–16 therms/yr (1.5–15.5 MMBtu/yr) TSVs: 10–22 therms/yr (0.97–2.2 MMBtu/yr)

TSD and TSV costs and benefits	
Post-retrofit savings (HPWH)	TSDs: 1–7 therms/yr (0.07–7.5 MMBtu/yr) TSVs: 50–165 kWh/yr (0.2–0.6 MMBtu/yr)
Costs	TSDs: $35–45 (equipment and labor) TSVs: $100–200 (equipment and labor)
Other benefits	Significant water savings (1,800–2,500 gallons/yr) Convenience and time savings Improved showerhead water pressure

Sources: CPUC 2013; Wood and D'Acquisto 2015

These measures may also serve to address comfort, health, or other occupant needs and interests. In a staged retrofit, alternative measures can be installed in the first stage of the project to increase near-term savings at a relatively low cost. For example, in a staged retrofit in which a water heater upgrade is deferred to a later stage, an alternative measure that reduces water heating energy use (e.g., a thermostatic restrictor valve or drain water heat recovery) could be installed to provide energy savings and other benefits prior to the water heater replacement.

Envelope and HVAC equipment upgrades to reduce space-conditioning loads are central to deep retrofit and decarbonization projects. They also tend to be the most expensive and most disruptive measures and can be difficult to sell to homeowners who are unfamiliar with the products and technologies or skeptical of the benefits. Our analysis includes several measures that provide heating and/or cooling savings at lower cost, with less disruption and greater appeal to consumers.

Table 7 summarizes the measures discussed above as well as others we screened as part of our initial review. The table shows levels of energy savings and costs—high (H), medium (M), or low (L). It also provides specifics on installation or distribution channels and key nonenergy benefits.

Table 7. Alternative and supplemental measures

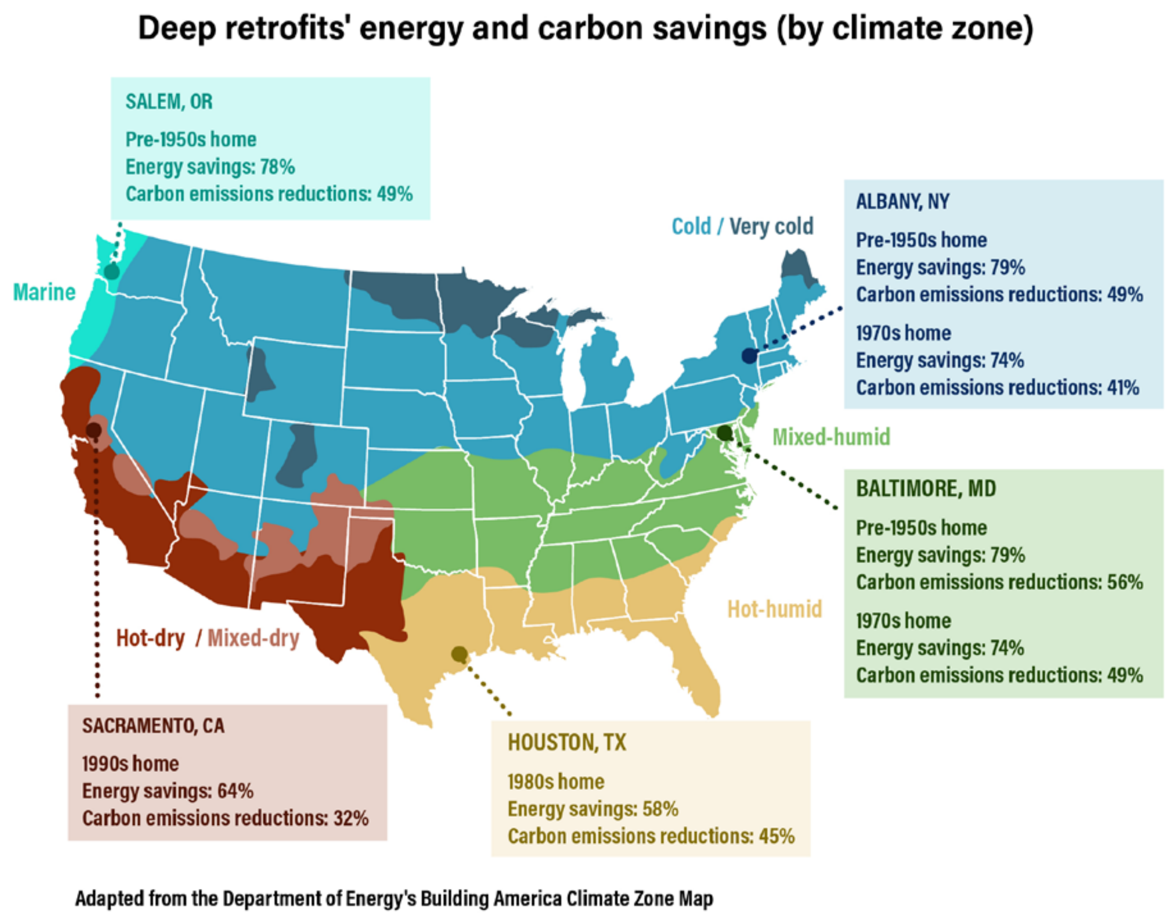
Measure	Savings	Cost	Contractor installed	Retail	Nonenergy benefits
Space conditioning					
Window attachments*	H	L–M	X	X	Aesthetics, visual/thermal comfort, privacy
Advanced controls	M	L	X		Comfort

Dehumidifiers*	M	M	X	X	IAQ, health, comfort, reduced odors
Ventilation fans	L–M	M	X		IAQ, health, comfort, reduced odors
Ceiling fans*	L–H	L–M		X	Comfort, aesthetics, convenience
Water heating and distribution					
Drain water heat recovery*	H	M	X		
Demand recirculation	M	M	X	X	Water savings, convenience, time savings
Tub spout diverters and/or valves*	M	L	X		Water savings
Point-of-use water heaters	L–M		X		Water savings, convenience, time savings
Lighting					
Sensors/controls	L	L		X	Aesthetics, convenience
Appliances					
Refrigerator	M	H		X	Aesthetics, convenience, performance
Freezer	M	H		X	Aesthetics, convenience, performance
Induction cooktop/range*	L–M	H		X	Aesthetics, safety, IAQ, electrification
Heat pump/hybrid dryer*	H	H		X	Aesthetics, convenience, performance
Air purifier/air cleaner*	L–M	L–H		X	IAQ, health, reduced odors
Small appliances	L–M	L		X	Convenience, performance
Other plug loads					
APS/smart outlets	L–M	L	X	X	Convenience
HEMS	L–H	L–H	X	X	Comfort, convenience
Consumer electronics*	L–M	L–M		X	
Sump pump	L–M	L–M	X	X	Noise reduction, reliability
Pool/spa system upgrade	M–H	M–H	X		Performance, convenience, reliability

***Measures discussed in report text.**

Climate-Specific Findings and Recommendations

Our analysis provides insights into measure selection and sequencing for retrofit packages designed to meet energy efficiency and decarbonization objectives considering regional climate and housing characteristics. The following sections summarize key findings for each climate region.



COLD CLIMATE

Summary of modeling results for cold climate		
	Pre-1950s home	1970s home
Source energy savings	52%	44%
Site energy savings	79%	74%
CO_2 emissions reductions	49%	41%
Change in electricity use	+71%	+51%
Change in gas use	–98%	–98%

The estimated source energy savings from the deep retrofit scenarios in the cold climate region range from 44% to 52%, depending on the age of the home. The savings are based on two home vintages modeled in Albany, New York. The first baseline model is a two-story pre-1950s home, which represents approximately 26% of the U.S. cold and very cold climate housing stock; the second is a one-story 1970s home, representative of 15% of the cold climate housing stock. Both baseline homes are 2,000 square feet in area, with an uninsulated basement and an unfinished, vented attic. Both use natural gas for heating. While the pre-1950s home has a gas boiler and room air conditioners, the 1970s unit is modeled with a gas furnace and a central air-conditioning system. More details of the baseline models are included in table A1 in Appendix A.

Pre-1950s Retrofit

The modeled retrofit package for this housing vintage cuts source energy consumption and carbon emissions in half and reduces site energy use by 79%. Remaining gas consumption is 2% of pre-retrofit and limited to the gas range. Replacement of the gas boiler and water heater with a ductless heat pump and heat pump water heater increases electricity use by 71%. The high-efficiency heat pump system meets space cooling needs with less than half the electricity required by the room air conditioners that served only part of the home in the pre-retrofit scenario. Table 8 shows the breakdown of energy use pre- and post-retrofit and for each stage in our staged approaches.

Table 8. Pre-1950s cold climate: pre- and post-retrofit energy consumption by end use (MMBtu/year)

	Pre-retrofit	Retrofit A	Retrofit B		Retrofit C	
			Phase 1: envelope	Phase 2: equipment	Phase 1: priority	Phase 2: remaining
Heating	155.5	13.8	35.1	13.8	22.1	13.8
Hot water	21.2	3.9	20.5	3.9	20.6	3.9
Cooling	2.7	1.2	0.8	1.2	1.7	1.2
Appliances	8.9	8.9	8.9	8.9	8.9	8.9
Lighting	4.7	3.2	3.2	3.2	3.2	3.2
Ventilation/fans	0.1	0.2	0.2	0.2	0.2	0.2
Miscellaneous	7.7	7.6	7.6	7.6	7.6	7.6

Envelope upgrades reduce heating loads considerably and contribute the majority of energy savings, carbon reductions, and utility bill savings. They also account for the largest share of the $53,223 project cost. Figure 6 summarizes the breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios. More than 75% of savings are captured in the first stage of the project under each scenario, but project costs are split more evenly in Retrofit C because the expensive envelope upgrades are split between Stages 1 and 2.

Retrofit B, which prioritizes envelope measures in the first phase, delivers near-term gas savings, with even more savings in subsequent phases with the electrification of HVAC and water heating loads. Higher annual energy bill savings after the first stage of Retrofit B reflect lower natural gas prices relative to electricity. A small portion of the energy bill savings and carbon reductions are lost with the installation of electrification measures in stage 2. Retrofit C, which combines some equipment replacement and envelope efficiency measures in the first phase, gives customers slightly more energy savings than Stage 1 of Retrofit B and can be a good option for homeowners who are ready to upgrade their heating system.

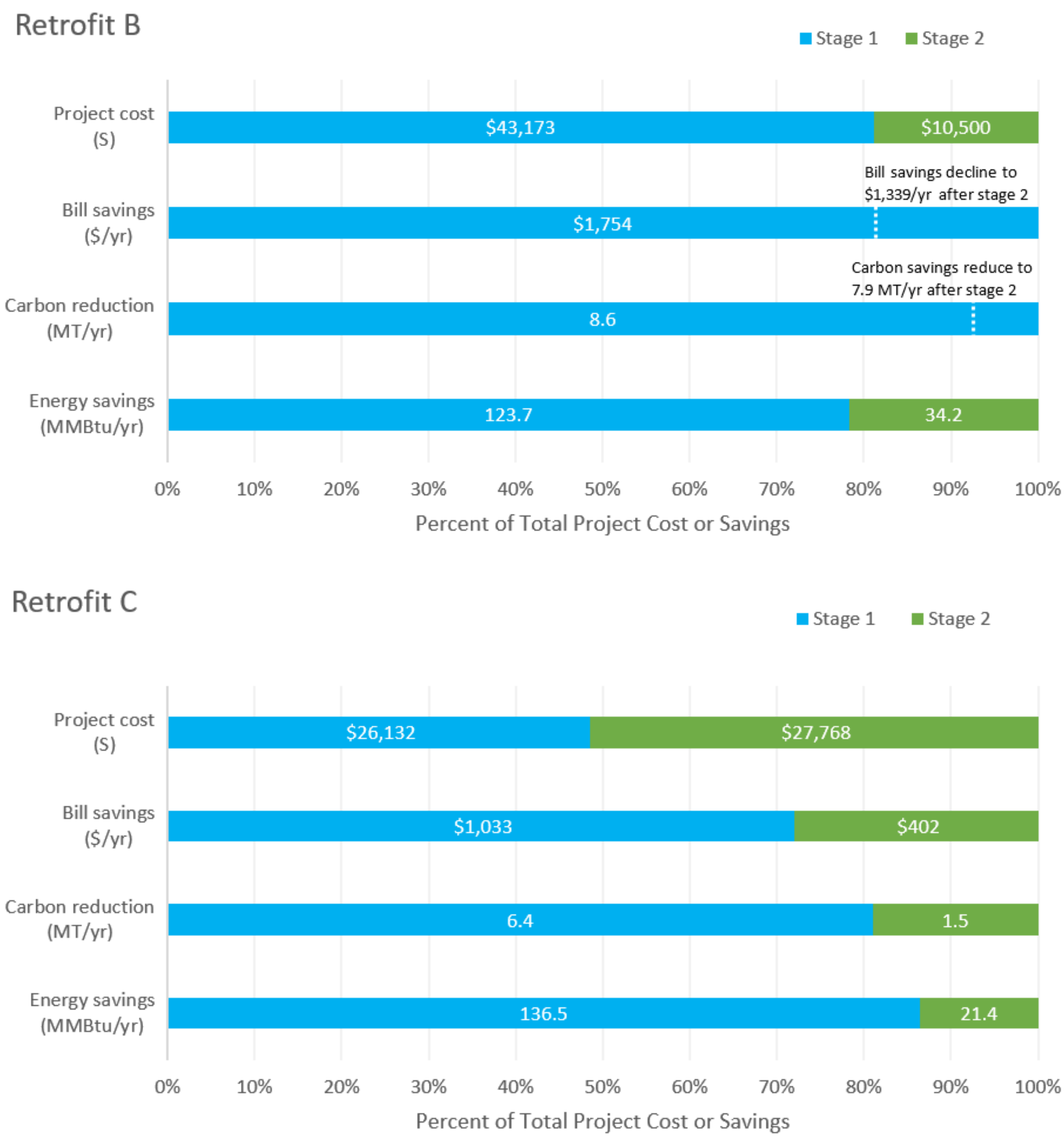


Figure 6. Pre-1950s cold climate: breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios

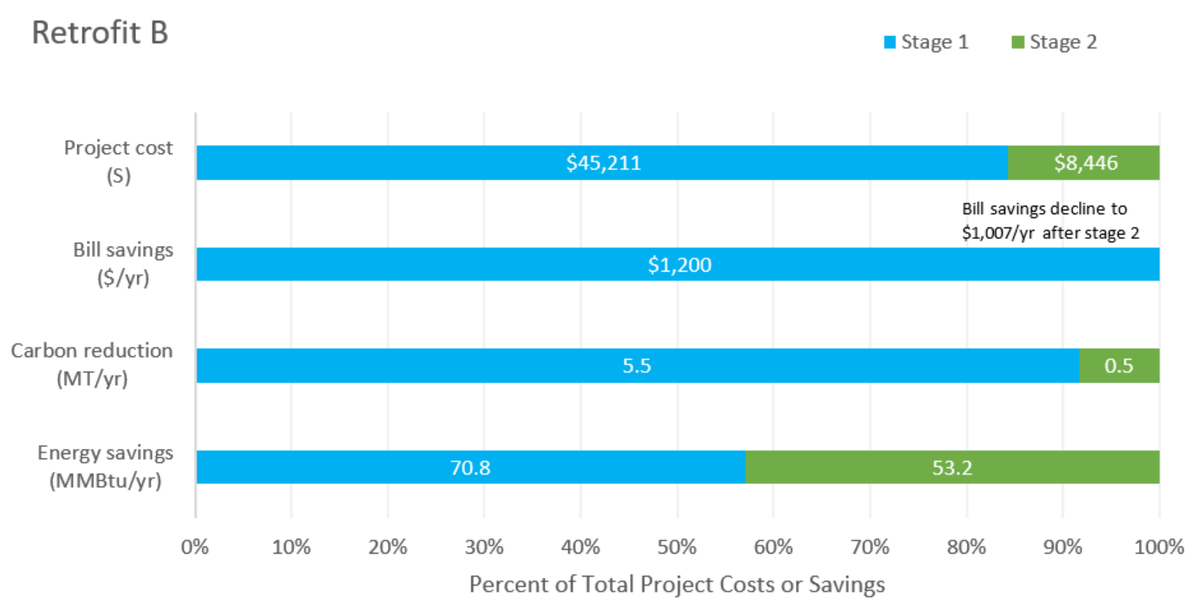
1970s Retrofit

The modeled retrofit package for this housing vintage cuts source energy consumption and carbon emissions by more than 40% and reduces site energy use by 74%. Remaining gas consumption is 2% of pre-retrofit and limited to the gas range. Replacement of the gas furnace and water heater with a central heat pump and heat pump water heater increases electricity use by 51%. The high-efficiency heat pump system meets the reduced space cooling needs using one-quarter of the electricity consumed by the central air conditioner in the pre-retrofit scenario. Table 9 shows the breakdown of energy use pre- and post-retrofit and for each stage in our staged scenarios.

Table 9. 1970s cold climate: pre- and post-retrofit energy consumption by end use (MMBtu/year)

	Pre-retrofit	Retrofit A	Retrofit B		Retrofit C	
			Phase 1: envelope	Phase 2: equipment	Phase 1: priority	Phase 2: remaining
Heating	120.5	16.1	55.2	16.1	27.0	16.1
Hot water	20.5	3.4	20.6	3.4	20.6	3.4
Cooling	5.2	1.1	1.5	1.1	1.5	1.1
Appliances	9.5	9.5	9.5	9.5	9.5	9.5
Lighting	4.8	3.3	3.3	3.3	3.3	3.3
Ventilation/fans	0.1	0.1	0.1	0.1	0.1	0.1
Miscellaneous	7.8	7.6	7.6	7.6	7.6	7.6

Envelope upgrades reduce heating and cooling loads and contribute the majority of energy savings, carbon reductions, and utility bill savings. They also account for the largest share of the $53,657 project cost. Figure 7 summarizes the breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios. More than 60% of carbon and bill savings are captured in the first stage of the project under each scenario, but project costs are split more evenly in Retrofit C. Energy savings are higher after completion of the first stage of Retrofit C—80% of savings versus 58%—due to replacement of the HVAC system. Bill savings are significantly lower because of the higher cost of electricity.



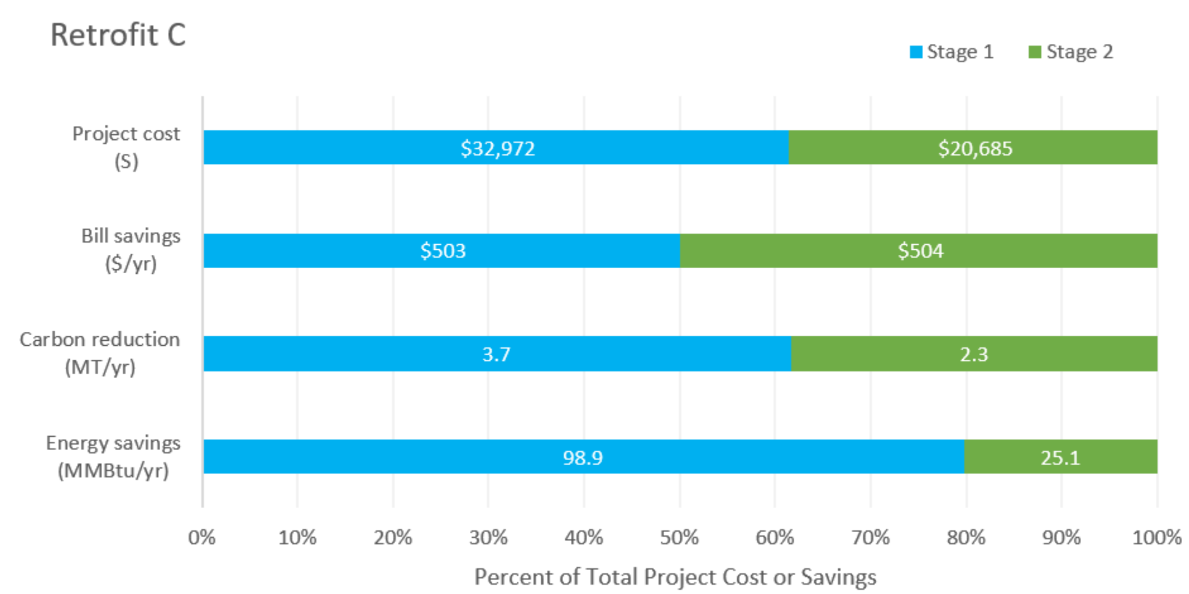


Figure 7. 1970s cold climate: breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios

Alternative and Supplemental Measures for Cold Climate Homes

Substituting or expanding measure options for cold climate homes can significantly reduce costs while delivering meaningful energy savings. Promising measures include:

- Window attachments: ENERGY STAR storm windows or high U-value cellular shades can improve the thermal performance of existing windows—bringing overall performance up to or close to ENERGY STAR levels for less than half the cost of window replacement, making projects more feasible. Replacement windows are the most expensive measure in our cold climate retrofit scenarios: $14,574 for a pre-1950s home and $9,080 for a 1970s home.

- Dehumidifier: In cold climates, 25% of homes have dehumidifiers. Replacing an older, standard-efficiency dehumidifier with a new ENERGY STAR Most Efficient model can save 0.33 to 0.71 MMBtu/year and provide improved dehumidification to maintain healthy humidity levels.

- Drain water heat recovery: This technology can reduce hot-water energy consumption by 6.5 MMBtu/year on average in cold climate homes with conventional gas water heaters. Two-story homes and one-story homes with basements in cold climates are strong candidates for DWHR. Even though savings drop to roughly 1.2 MMBtu/year upon installation of a heat pump water heater, energy bill savings drop by a much smaller margin given higher electric rates.

MIXED-HUMID CLIMATE

The source energy savings from deep retrofit packages in the mixed-humid climate range from 50% to 59%, depending on the age of the home and the associated building characteristics. The savings are calculated from modeling analysis of two home vintages in Baltimore, Maryland. The first is a two-story pre-1950s home, which represents approximately 17% of the U.S. mixed-humid climate housing stock. The second is a one-story 1970s-era home, representing 16% of the mixed-humid climate housing stock. Both baseline homes are 2,000 square feet in area, with unfinished, vented attics, central air-conditioning systems, and natural gas furnaces and water heaters. The baseline models have different types of foundations: The pre-1950s home has a vented crawl space, while the 1970s unit has an uninsulated basement. Other details for the baseline model are included in Appendix A.

Summary of results for mixed-humid climate		
	Pre-1950s home	1970s home
Source energy savings	59%	51%
Site energy savings	79%	74%
CO_2 emissions reductions	56%	49%
Change in electricity use	–8%	+6%
Change in gas use	–98%	–98%

Pre-1950s Retrofit

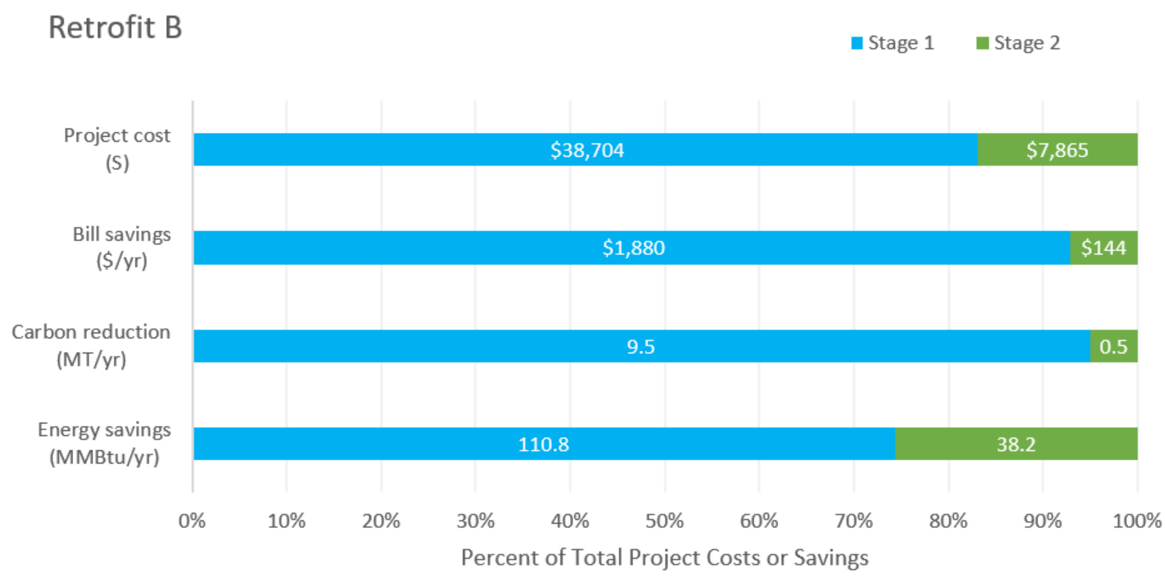
The modeled retrofit package cuts source energy consumption and carbon emissions by more than half and reduces site energy use by 79%. Remaining gas consumption is 2% of pre-retrofit and limited to the gas range. Replacement of the gas furnace and water heater with a central heat pump and heat pump water heater decreases electricity use by 8%. The high-efficiency heat pump system meets space cooling needs, which are higher than in the pre-1950s home in a cold climate, with less than one-quarter the electricity used by the central air conditioner in the pre-retrofit scenario. Table 10 shows the breakdown of energy use pre- and post-retrofit and for each stage in our staged scenarios.

Table 10. Pre-1950s mixed-humid: pre- and post-retrofit energy consumption by end use (MMBtu/year)

	Pre-retrofit	Retrofit A	Retrofit B		Retrofit C	
			Phase 1: envelope	Phase 2: equipment	Phase 1: priority	Phase 2: remaining
Heating	133.0	12.1	37.1	12.1	16.1	12.1
Hot water	16.2	2.6	16.2	2.6	16.2	2.6
Cooling	16.8	2.7	4.9	2.7	4.1	2.7
Appliances	9.5	8.7	8.7	8.7	9.5	8.7
Lighting	4.7	3.2	3.2	3.2	3.2	3.2
Ventilation/fans	0.1	0.2	0.2	0.2	0.2	0.2
Miscellaneous	8.5	7.8	7.8	7.8	7.8	7.8

Envelope upgrades with an emphasis on humidity control reduce heating and cooling loads considerably and contribute the majority of energy savings, carbon reductions, and utility bill savings. They also account for the largest share of the $46,569 project cost. Figure 8 summarizes the breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios. More than 70% of savings are captured in the first stage of the project under each scenario, but project costs are split more evenly in Retrofit C.

Retrofit B, which prioritizes envelope measures in the first phase, delivers near-term gas savings, with even more savings in subsequent phases with the electrification of HVAC and water heating loads. Higher annual energy bill savings after the first stage of Retrofit B reflect lower natural gas prices relative to electricity. Retrofit C, which combines some equipment replacement and envelope efficiency measures in the first phase, gives customers slightly more energy savings but lower cost savings after Stage 1 and can be a good option for homeowners who are ready to upgrade their heating system.



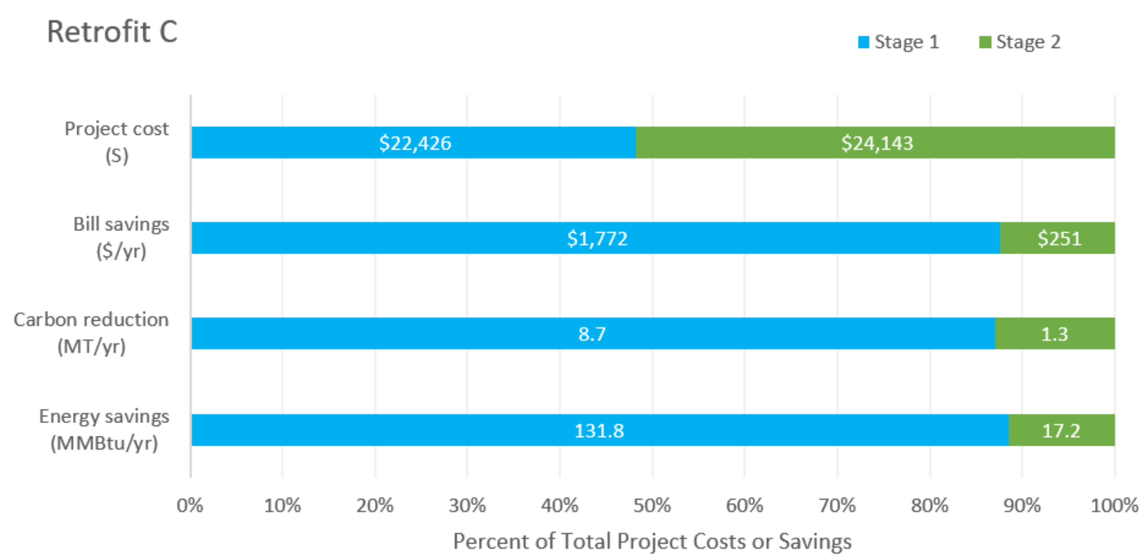


Figure 8. Pre-1950s mixed-humid: breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios

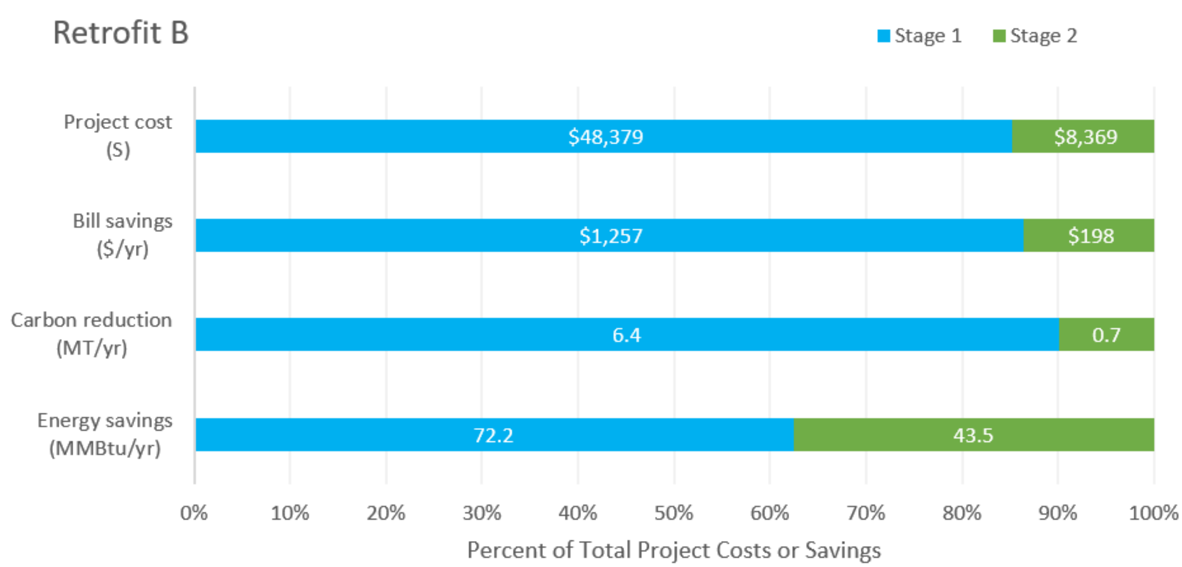
1970s Retrofit

The modeled retrofit package cuts source energy consumption and carbon emissions by half and reduces site energy use by 74%. Remaining gas consumption is 2% of pre-retrofit and limited to the gas range. Replacement of the gas furnace and water heater with a central heat pump and heat pump water heater increases electricity use by 6%. The high-efficiency heat pump system meets the reduced space cooling needs using less than one-quarter of the electricity consumed by the central air conditioner in the pre-retrofit scenario. Table 11 shows the breakdown of energy use pre- and post-retrofit and for each stage of our staged scenarios.

Table 11. Mixed-humid: pre- and post-retrofit energy consumption by end use (MMBtu/year)

	Pre-retrofit	Retrofit A	Retrofit B		Retrofit C	
			Phase 1: envelope	Phase 2: equipment	Phase 1: priority	Phase 2: remaining
Heating	102.9	11.2	41.6	11.2	14.9	11.2
Hot water	17.5	3.0	17.7	3.0	17.6	3.0
Cooling	13.4	2.6	4.2	2.6	3.7	2.6
Appliances	9.5	9.5	9.5	9.5	9.5	9.5
Lighting	4.9	3.3	3.3	3.3	3.3	3.3
Ventilation/fans	0.1	0.2	0.2	0.2	0.2	0.2
Miscellaneous	8.2	7.8	7.8	7.8	7.8	7.8

Envelope upgrades reduce heating and cooling loads and contribute the majority of energy savings, carbon reductions, and utility bill savings. They also account for the largest share of the $56,748 project cost. Figure 9 summarizes the breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios. More than 80% of carbon and bill savings are captured in the first stage of the project under each scenario, but project costs are split more evenly in Retrofit C. Energy savings are higher after completion of the first stage of Retrofit C.



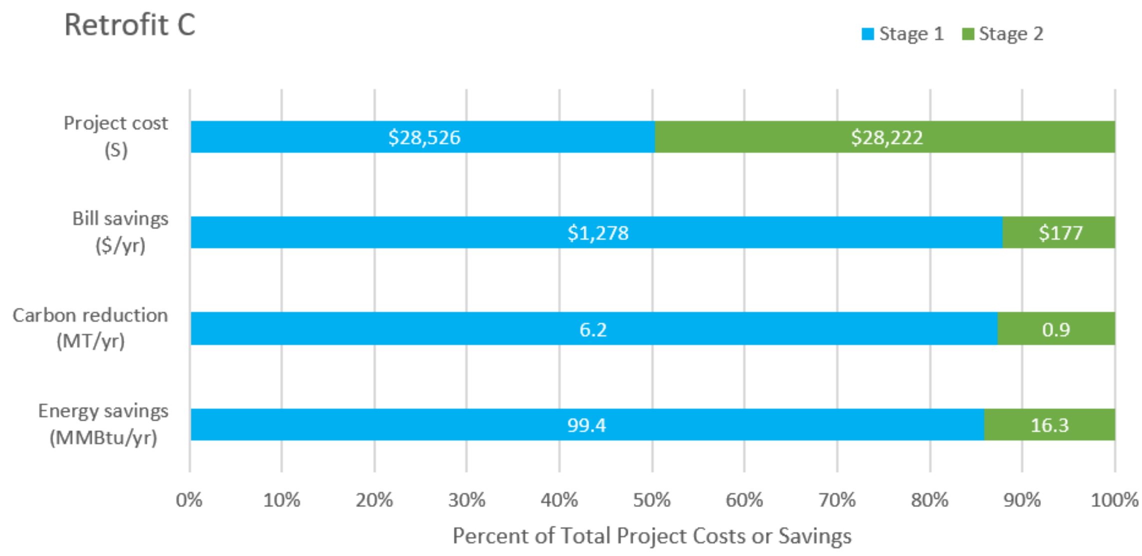


Figure 9. 1970s mixed-humid: breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios

Alternative and Supplemental Measures for Mixed-Humid Climate Homes

Substituting or expanding measure options for mixed-humid climate homes can significantly reduce costs while delivering meaningful energy savings. Promising measures include:

- Window attachments: Low-e storm windows and high-performance cellular shades are good options in the mixed-humid climate. Shades have the added benefit of providing air-conditioning savings in the summer months, further improving the return on investment. Replacement windows are the most expensive measure in our mixed-humid climate retrofit scenarios: $11,254 for pre-1950s homes and $9,008 for 1970s homes.

- Dehumidifier: Although less common in mixed-humid climate homes (14%) than in cold climate homes, dehumidifiers are typically used for a greater portion of the year in this climate: 41% are used for 4–6 months, and 30% are used for more than 6 months. Replacing an older, standard-efficiency dehumidifier with a new ENERGY STAR Most Efficient model can save 0.33 to 0.71 MMBtu/year. Homes without a dehumidifier, particularly those with unfinished basements or crawl spaces, may reap air-conditioning savings and enjoy improved indoor air quality with installation of a high-efficiency unit.

- Drain water heat recovery: This technology can reduce hot-water energy consumption by 5.5 MMBtu/year on average in mixed-humid climate homes with conventional gas water heaters. Two-story homes and homes with basements or crawl spaces are strong candidates for DWHR. Even though savings drop to roughly 0.9 MMBtu/year upon installation of a heat pump water heater, energy bill savings drop by a much smaller margin given higher electric rates.

HOT-HUMID CLIMATE

These savings are based on the modeling analysis of a relatively new 1980s home in Houston, Texas. The baseline model is a 2,000-square-foot single-level home, which represents approximately 18% of the hot-humid climate housing stock. The home has a slab-on-grade foundation and an unfinished, vented attic. The HVAC system comprises a central air-conditioning system and natural gas furnace, and the home has a gas storage water heater. More details of the baseline model are included in table A1 in Appendix A.

Summary of results for hot-humid climate 1980s home	
Source energy savings	46%
Site energy savings	58%
CO_2 emissions reductions	45%
Change in electricity use	–35%
Change in gas use	–91%

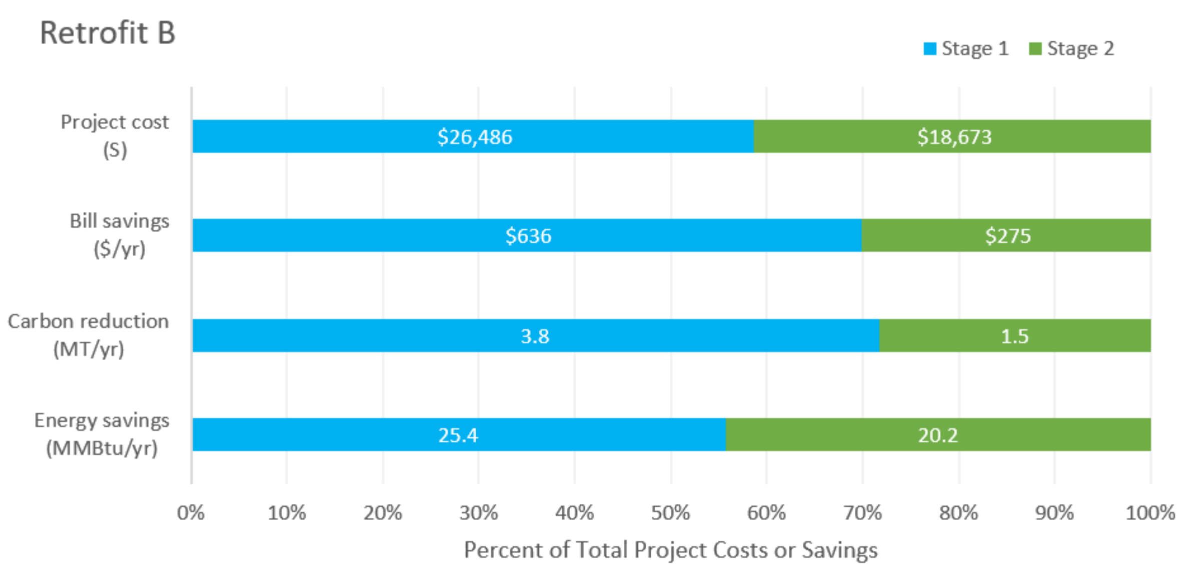
The modeled retrofit package cuts source energy consumption and carbon emissions by more than 40% and reduces site energy use by 58%. Remaining gas consumption is 9% of pre-retrofit and limited to the gas range. Attic sealing and insulation and addition of a cool roof account for close to 50% of the $45,159 project cost. Envelope upgrades and replacement of the existing central air conditioner with a high-efficiency heat pump decreases electricity use by 35%, even with electrification of heating and water heating. The high-efficiency heat pump system meets reduced space cooling needs with less than half the electricity consumed by the central air conditioner in the pre-retrofit scenario. Table 12 shows the breakdown of energy use pre- and post-retrofit and for each stage of our staged scenarios.

Table 12. Hot-humid: pre- and post-retrofit energy consumption by end use (MMBtu/year)

	Pre-retrofit	Retrofit A	Retrofit B		Retrofit C	
			Phase 1: envelope	Phase 2: equipment	Phase 1: priority	Phase 2: remaining
Heating	16.7	1.5	6.1	1.5	1.4	1.5
Hot water	12.6	1.6	12.6	1.6	12.5	1.6
Cooling	16.2	7.5	13.8	7.5	8.5	7.5
Appliances	9.5	9.5	9.5	9.5	9.5	9.5
Lighting	4.9	3.3	3.3	3.3	3.3	3.3
Ventilation/fans	0.1	0.3	0.3	0.3	0.3	0.3
Miscellaneous	9.1	8.0	8.1	8.0	8.1	8.0

As expected, our analysis shows that envelope upgrades contribute a smaller portion of the energy savings in this climate. It is, however, the combination of equipment replacement with select envelope measures that is likely to reduce heating and cooling loads considerably and contribute to energy savings, carbon reductions, and utility bill savings. Figure 10 summarizes the breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios. More than 70% of carbon and bill savings are captured in the first stage of the project under each scenario, and the project costs are split fairly evenly in both retrofit scenarios.

Retrofit B, which prioritizes envelope measures in the first phase, delivers some near-term gas savings, with the majority of savings in subsequent phases with the electrification of HVAC and water heating loads. Because space heating accounts for a smaller portion of home energy use than air-conditioning, the gas savings are smaller. The lower annual energy bill savings after the first stage of Retrofit B also reflects lower natural gas prices relative to electricity. Retrofit C, which combines some equipment replacement and envelope efficiency measures in the first phase, gives customers more savings than Retrofit B and can be a good option for homeowners ready to upgrade their cooling or heating systems.



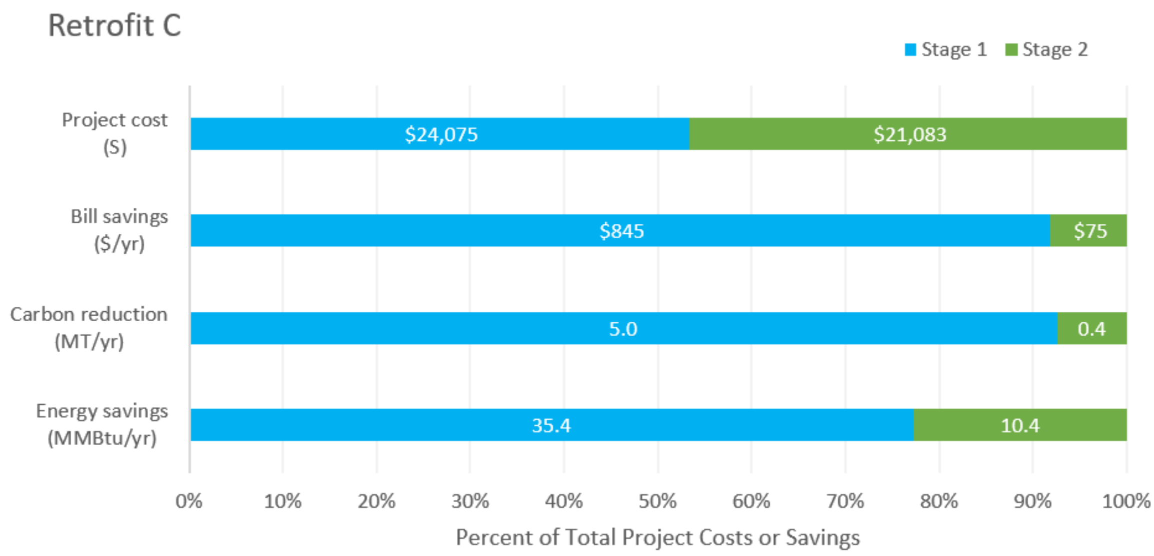


Figure 10. Hot-humid: breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios

Alternative and Supplemental Measures for Hot-Humid Climate Homes

Substituting or expanding measure options for hot-humid climate homes can significantly reduce costs while delivering meaningful energy savings. Promising measures include:

- Window attachments: High-performance window treatments (e.g., cellular shades) offer a high level of savings in both heating and cooling season in the hot-humid climate at a much lower cost than a $9,000 window replacement. In staged retrofits where HVAC upgrades are deferred to a later stage, window attachments can provide valuable near-term savings at relatively low cost with strong customer appeal.

- Ceiling fans: Homes in the hot-humid climate have an average of three ceiling fans. Upgrading these fans to ENERGY STAR Most Efficient saves 240 kWh/year (1.7% of pre-retrofit electricity use) in fan energy use. An LED light kit provides additional electricity savings.

- Tub spout diverters or thermostatic restrictor valves with high-efficiency showerhead: In homes where DWHR installation is challenging, TSDs or TSVs provide another option for water heater energy savings. Each fixture with a TSD or TSV will achieve pre-retrofit gas savings of 1.2 MMBtu/year (almost 10% savings) and post-retrofit electricity savings of 0.2 MMBtu/year and estimated water savings of 2,150 gallons.

HOT-DRY CLIMATE

Summary of results for hot-dry climate 1990s home	
Source energy savings	34%
Site energy savings	61%
CO_2 emissions reductions	32%
Change in electricity use	8%
Change in gas use	–95%

These savings are based on the analysis of a 1990s home in Sacramento, California. The baseline model is a 2,000-square-foot single-level home, representing 17% of the hot-dry climate housing stock. The home has a slab-on-grade foundation with an unfinished, vented attic. The HVAC system consists of a central air-conditioning system, natural gas furnace, and a gas storage water heater. More details for the baseline model are included in Appendix A.

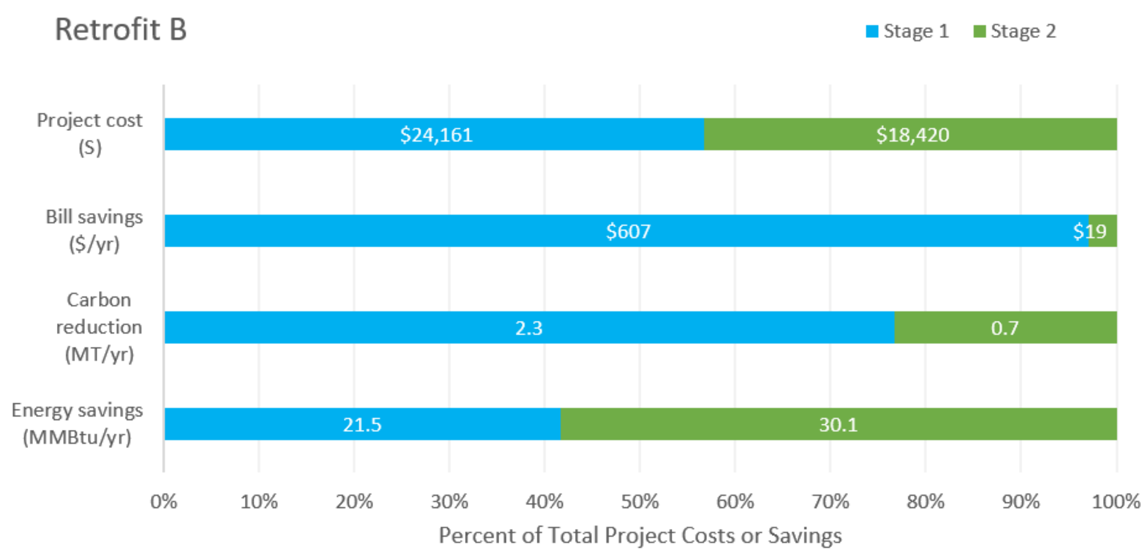
The modeled retrofit package cuts source energy consumption and carbon emissions by more than 30% and reduces site energy use by 61%. Remaining gas consumption is 5% of pre-retrofit and limited to the gas range. Replacement of the gas furnace and water heater with a central heat pump and heat pump water heater increases electricity use by 8%. The high-efficiency heat pump system meets space cooling needs with one-quarter of the electricity used by the central air conditioner in the pre-retrofit scenario. Table 13 shows the breakdown of energy use pre- and post-retrofit and for each stage of our staged scenarios.

Table 13. Hot-dry: pre- and post-retrofit energy consumption by end use (MMBtu/year)

	Pre-retrofit	Retrofit A	Retrofit B		Retrofit C	
			Phase 1: envelope	Phase 2: equipment	Phase 1: priority	Phase 2: remaining
Heating	38.2	4.9	23.0	4.9	4.7	4.9
Hot water	16.6	2.7	16.6	2.7	16.6	2.7
Cooling	7.1	1.7	2.7	1.7	2.1	1.7
Appliances	9.5	9.5	9.5	9.5	9.5	9.5
Lighting	4.9	3.3	3.3	3.3	3.3	3.3
Ventilation/ fans	0.1	0.3	0.3	0.3	0.3	0.3
Miscellaneous	8.1	7.7	7.7	7.7	7.7	7.7

A combination of equipment replacement and select envelope measures reduces heating and cooling loads considerably and contributes to a majority of the energy savings, carbon reductions, and utility bill savings in this $42,582 project. As expected, comprehensive envelope upgrades contribute to a smaller portion of the savings in this climate. Figure 11 summarizes the breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios. More than 75% of carbon and bill savings are captured in the first stage of the project under each scenario. Project costs are split fairly evenly in both retrofit scenarios.

Retrofit B, which prioritizes envelope measures in the first phase, delivers some near-term gas savings, with more savings in subsequent phases with the electrification of HVAC and water heating loads. Because winters are mild, space heating and water heating needs account for a smaller portion of home energy use, and envelope measures do not reduce these loads considerably. Thus, the bill savings after the first stage of Retrofit B are lower and reflective of lower natural gas prices relative to electricity. Retrofit C, which combines some equipment replacement and envelope efficiency measures in the first phase, gives customers more savings than Retrofit B and can be a good option for homeowners who are ready to upgrade their heating and cooling systems. Higher annual energy bill savings after the first stage of Retrofit C reflect a combination of natural gas and electricity savings. A small portion of energy bill savings, however, is lost with the installation of the heat pump water heater in Stage 2.



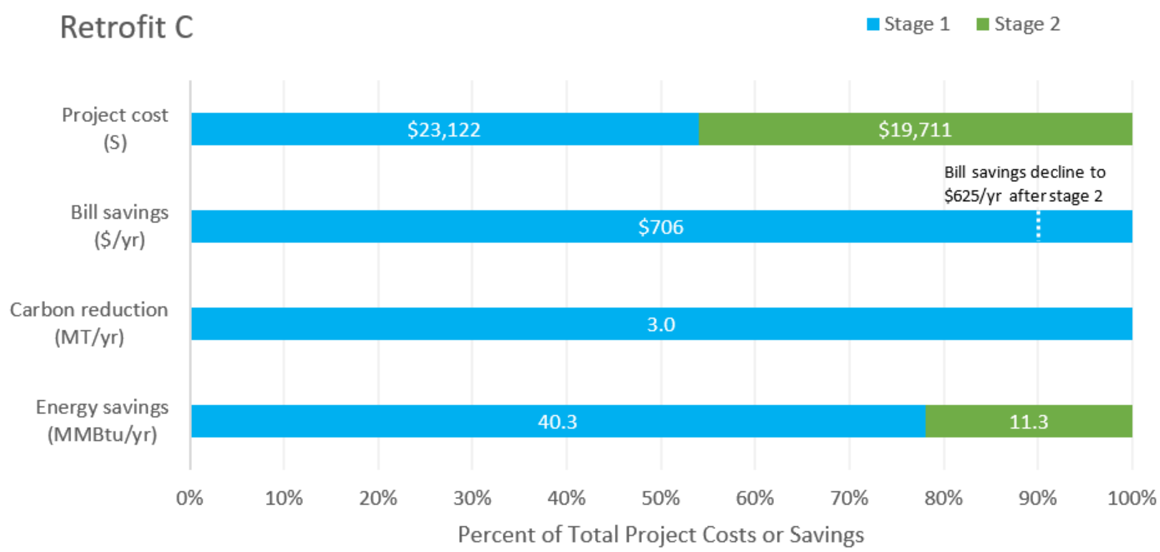


Figure 11. Hot-dry: breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios

Alternative and Supplemental Measures for Hot-Dry Climate Homes

Substituting or expanding measures options for hot-dry climate homes can significantly reduce costs while delivering meaningful energy savings. Promising measures include:

- Window attachments: High-performance window treatments (e.g., cellular shades) offer a high level of savings in both heating and cooling seasons in the hot-dry climate at lower cost than window replacements. In staged retrofits where HVAC upgrades are deferred to a later stage, window attachments can provide valuable near-term savings at relatively low cost with strong customer appeal.

- Ceiling fans: Homes in a hot-dry climate have an average of three ceiling fans. Upgrading these fans to ENERGY STAR Most Efficient saves 300 kWh/year (3.7% of pre-retrofit electricity use) in fan energy use. An LED light kit provides additional electricity savings.

- Tub spout diverters or thermostatic restrictor valves with high-efficiency showerhead: In homes where DWHR installation is challenging, TSDs or TSVs provide another option for water heater energy savings. Each fixture with a TSD or TSV will achieve pre-retrofit gas savings of 1.3 MMBtu/year (7.8% savings) and post-retrofit electricity savings of 0.23 MMBtu/year. Estimated water savings of 2,150 gallons make this a particularly attractive upgrade in hot-dry climates.

MARINE CLIMATE

Summary of results for marine climate Pre-1950s home	
Source energy savings	52%
Site energy savings	78%
CO_2 emissions reductions	49%
Change in electricity use	+50%
Change in gas use	–98%

These savings are based on modeling of a pre-1950s home in Salem, Oregon. This vintage of home represents 25% of the marine climate housing stock. It is a single level of 2,000 square feet, with an uninsulated crawl space and an unfinished, vented attic. The HVAC system consists of room air conditioners, a gas furnace, and a gas storage water heater. More details of the baseline model are included in Appendix A.

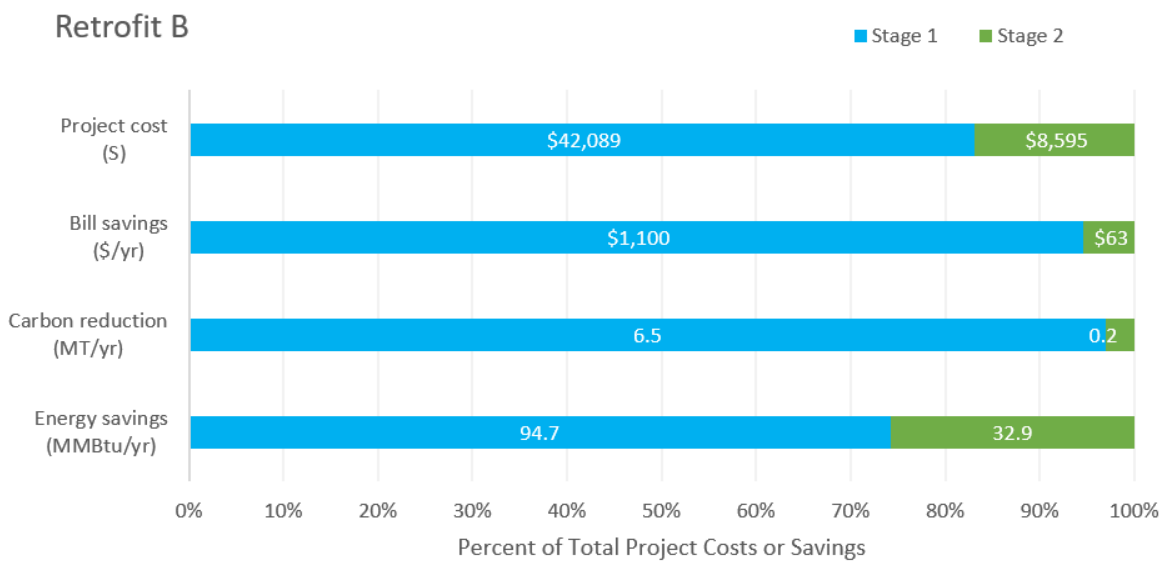
The modeled retrofit package cuts source energy consumption and carbon emissions in half and reduces site energy use by 78%. Remaining gas consumption is 2% of pre-retrofit and limited to the gas range. Replacement of the gas furnace and water heater with a ductless heat pump and heat pump water heater increases electricity use by 50%. The high-efficiency heat pump system meets space cooling needs with less than one-tenth of the electricity consumed by the room air conditioners that served only part of the home in the pre-retrofit scenario. Table 14 shows the breakdown of energy use pre- and post-retrofit and for each stage of our staged scenarios.

Table 14. Marine: pre- and post-retrofit energy consumption by end use (MMBtu/year)

	Pre-retrofit	Retrofit A	Retrofit B		Retrofit C	
			Phase 1: envelope	Phase 2: equipment	Phase 1: priority	Phase 2: remaining
Heating	119.9	7.6	28.3	7.6	13.0	7.6
Hot water	18.7	3.0	18.3	3.0	18.3	3.0
Cooling	1.2	0.1	0.1	0.1	0.5	0.1
Appliances	9.5	9.5	9.5	9.5	9.5	9.5
Lighting	4.8	3.3	3.3	3.3	3.3	3.3
Ventilation/fans	0.1	0.2	0.2	0.2	0.2	0.2
Miscellaneous	7.7	7.6	7.6	7.6	7.6	7.6

Similar to the results for the pre-1950s homes in cold and mixed-humid climates, comprehensive envelope upgrades in this region provide the majority of the energy savings. Envelope upgrades reduce heating loads considerably and contribute the majority of energy savings, carbon reductions, and utility bill savings. They also account for the largest share of the $50,683 project cost. Figure 12 summarizes the breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios. More than 70% of all savings are captured in the first stage of the project under each scenario, but project costs are split more evenly in Retrofit C.

Retrofit B, which prioritizes envelope measures in the first phase, delivers near-term gas savings, with even more savings in subsequent phases with the electrification of HVAC and water heating loads. Higher annual energy bill savings after the first stage of Retrofit B reflect lower natural gas prices relative to electricity. A very small portion of the energy bill savings is lost with the installation of electrification measures in Stage 2. Retrofit C, which combines some equipment replacement and envelope efficiency measures in the first phase, gives customers slightly more savings than Stage 1 of Retrofit B and can be a good option for homeowners who are ready to upgrade their heating system.



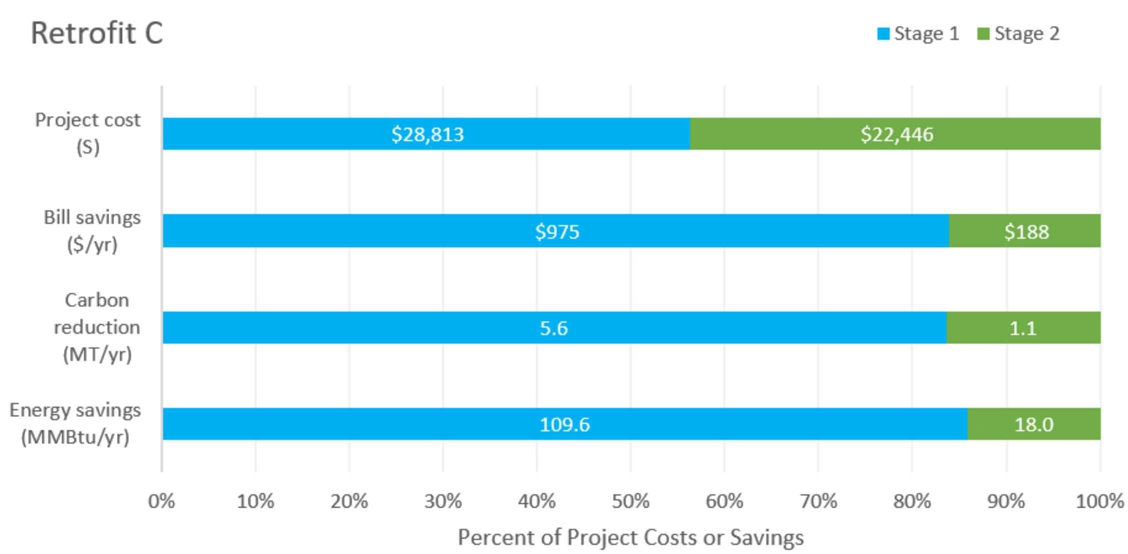


Figure 12. Marine: breakdown of energy savings, carbon reductions, and energy bill savings as well as overall project costs for each stage of Retrofit B and C scenarios

Alternative and Supplemental Measures for Marine Climate Homes

Substituting or expanding measure options for marine climate homes can significantly reduce costs while delivering meaningful energy savings. Promising measures include:

- Window attachments: Low-e storm windows and high-performance cellular shades are good options in a marine climate. Shades have the added benefit of providing air-conditioning savings in the summer months, further improving the return on investment. Replacement windows are the most expensive measure in our marine climate retrofit scenarios, at $12,173.

- Drain water heat recovery: This technology can reduce hot-water energy consumption by 6.1 MMBtu/year on average in marine climate homes with conventional gas water heaters. Two-story homes and homes with basements or crawl spaces are strong candidates for DWHR. Average savings drop below 1.0 MMBtu/year upon installation of a high-efficiency heat pump water heater.

Mechanisms to Finance Deep Retrofits

Goals and outcomes for home energy upgrades can vary greatly from household to household, and how these upgrades are paid for also vary. Financial solutions need to be appropriate to the differing goals and financial situation of each household that undertakes an energy retrofit. Because the significant upfront capital required to perform a deep retrofit is generally the highest barrier to participation, affordable financing solutions are needed that have relatively low interest rates and long repayment terms. Past experience indicates, however, that favorable financing alone will not be enough to scale deep residential energy retrofits; some form of accessible and upfront incentive will also be needed for the majority of households to invest in a major energy retrofit.

FINANCIAL ANALYSIS

For the seven retrofit scenarios modeled in this research, we analyzed three different financial outcomes:

- The project is cash-flow neutral to the household.

- The project results in a maximum monthly cost increase of $75 to the household.

- The project results in a maximum monthly cost increase of $150 to the household.[3]

For each of the seven homes, we utilized a discounted cash-flow analysis that modeled project and financing costs versus estimated energy savings resulting from the upgrades. (See table 15 for details on project costs and energy savings for each of the analyzed homes.) Our financial estimates do not take into account the improved home equity value as a result of the project, potential insurance savings, or any other nonenergy benefits (e.g., improved health, comfort, etc.). Accordingly, all estimates should be used for research purposes only and are not investment grade.

We used a regression analysis to determine the level of upfront capital required to cover the cost of the project for each of the three financial outcomes. The independent variables are the project costs and the energy savings resulting from the efficiency improvements. The loan duration, ranging from 10 to 20 years, and the interest rate, ranging from 0.0% to 5.0%, represent the dependent variables. For simplicity, we limited the financial analysis to a one-time whole-home project (Retrofit A).

Table 15. Project costs and energy savings for the seven modeled homes

Climate	Project cost	Pre-retrofit costs ($/month)		Post-retrofit costs ($/month)		Savings ($/month)
		Electric	Gas	Electric	Gas	
Cold, pre-1950s	$ 53,223	$ 112.47	$ 203.83	$ 187.04	$ 17.69	$ 111.56
Cold, 1970	$ 53,657	$ 131.21	$ 150.29	$ 194.49	$ 17.69	$ 69.32
Mixed-humid, pre-1950s	$ 46,569	$ 135.21	$ 172.07	$ 125.50	$ 13.16	$ 168.61
Mixed-humid, 1970	$ 56,748	$ 121.54	$ 141.57	$ 125.95	$ 13.16	$ 124.01
Hot-humid	$ 45,159	$ 143.34	$ 43.98	$ 95.43	$ 16.00	$ 75.88
Hot-dry	$ 42,582	$ 146.70	$ 71.82	$ 158.03	$ 8.37	$ 52.12
Marine	$ 50,683	$ 66.47	$ 133.05	$ 96.12	$ 7.59	$ 95.81

CASH-FLOW NEUTRAL

For a loan with a 10-year duration, even at a below-market 2.5% interest rate, the upfront capital required ranges from $30,318 to $47,157, or 65–88% of the total project cost, if we

[3] Monthly costs are calculated as the sum of the total monthly loan payment and utility bill resulting from the retrofit project.

want the project to be cash-flow neutral for the seven homes in this research. If the loan duration stretches to 20 years, the upfront capital required ranges from $17,568 to $41,907, or 38–78%. More information on the different financing and upfront requirements for the cash-flow neutral outcome can be seen in table 16.

Table 16. Cash-flow neutral outcome

	Upfront capital required					
	0% interest loan		2.5% interest loan		5.0% interest loan	
Climate	10 YR	20 YR	10 YR	20 YR	10 YR	20 YR
Cold - 1950	$45,473	$33,723	$43,223	$37,723	$45,473	$40,723
Cold - 1970	$46,407	$38,657	$47,157	$41,907	$47,907	$38,657
Mixed - 1950	$28,318	$9,818	$30,318	$17,568	$32,068	$23,318
Mixed - 1970	$43,498	$29,998	$44,998	$35,748	$46,248	$39,998
Hot-humid	$36,409	$27,659	$37,409	$31,409	$38,409	$34,159
Hot-dry	$37,832	$33,082	$38,332	$35,082	$38,832	$36,582
Marine	$39,433	$28,433	$40,683	$33,183	$41,933	$36,683

Monthly Additional Cost of $75

For a loan with a 10-year duration, even at a below-market 2.5% interest rate, the upfront capital required ranges from $22,318 to $39,157, or 48–73% of the total project cost, to result in an additional cost of $75 for the seven homes in this research. If the loan duration stretches to 20 years, the upfront capital required ranges from $3,568 to $27,907, or 8–52%. More information on the different financing and upfront requirements for the cash-flow neutral outcome can be seen in table 17.

Table 17. Additional cost of $75/month outcome

	Upfront capital required					
	0% interest loan		2.5% interest loan		5.0% interest loan	
Climate	10 YR	20 YR	10 YR	20 YR	10 YR	20 YR
Cold - 1950	$34,223	$15,223	$36,473	$23,223	$38,223	$29,223
Cold - 1970	$37,407	$20,907	$39,157	$27,907	$40,657	$20,907
Mixed - 1950	$19,318	$ -	$22,318	$3,568	$25,068	$12,068
Mixed - 1970	$34,498	$12,248	$36,998	$21,748	$39,248	$28,498
Hot-humid	$26,580	$9,909	$28,519	$17,409	$30,216	$22,909
Hot-dry	$21,635	$14,832	$22,760	$20,832	$23,886	$25,082
Marine	$26,688	$10,433	$28,645	$18,933	$30,168	$25,183

Monthly Additional Cost of $150

For a loan with a 10-year duration, even at a below-market 2.5% interest rate, the upfront capital required ranges from $14,318 to $31,157, or 31–58% of the total project cost, to result in an additional cost of $150 for the seven scenarios in this research. If the loan duration stretches to 20 years, the upfront capital required ranges from $0 to $13,657, or 0–25%. More information on the different financing and upfront requirements for the cashflow neutral outcome can be seen in table 18.

Table 18. Additional cost of $150/month outcome

	Upfront capital required					
	0% interest loan		2.5% interest loan		5.0% interest loan	
Climate	10 YR	20 YR	10 YR	20 YR	10 YR	20 YR
Cold - 1950	$25,223	$0	$28,473	$9,223	$31,223	$22,769
Cold - 1970	$28,157	$3,157	$31,157	$13,657	$33,657	$3,157
Mixed - 1950	$10,068	$0	$14,318	$ -	$17,818	$568
Mixed - 1970	$25,498	$0	$28,998	$7,498	$31,998	$17,248
Hot-humid	$17,852	$0	$20,761	$3,159	$23,428	$11,409
Hot-dry	$14,694	$0	$16,757	$6,582	$18,446	$13,582
Marine	$18,860	$0	$21,687	$4,683	$24,079	$13,683

PROGRAM DESIGN

Our analysis confirms that energy bill savings resulting from deep retrofit and decarbonization projects are—by themselves—unlikely to cover the full cost of the investments without a very long payback period or otherwise motivate homeowners to participate, particularly where project costs are highest. In some cases, the outlook improves if the costs of the project are financed over a long duration with low- to no-cost interest. If bringing deep residential retrofits to scale is truly to be a piece of the puzzle to reach decarbonization goals, then program design must prioritize affordability and convenience for homeowners, contactors, and capital providers.

A current example of this type of program is Vermont's Zero Energy Now (ZEN) Pilot, a comprehensive energy support program that includes weatherization, efficient heating solutions, and solar PV and results in drastic energy and greenhouse gas reductions for the homeowner. The pilot study concludes that the success of a ZEN-type retrofit rests on the following factors:

- the potential energy upgrades inherent in an existing building,
- the homeowner's ability and willingness to invest time and money in a project of this magnitude,
- the incentives and financing products available to the homeowner, and
- the contractor's ability not only to communicate the value and benefits of these projects, but also to assist in guiding the homeowner along the project pathway (Stebbins, Perry, and Faesy 2020).

Further information on this program can be found in a text box on page 52 of this report. Other good program models are also discussed in text boxes later in this report.

As utility bill savings alone do not cover the full cost of the energy efficiency investments described in this research, for most households some form of incentive will be required to cover the costs that exceed utility bill savings. This means that building decarbonization upgrades will require a combination of financing for the portion of the upgrade costs that can be recovered from bill savings, and other co-funding associated with the following additional value streams:

- **Customer co-benefits**—the gains that accrue to the homeowner beyond utility bill savings (e.g., health benefits and increased comfort)
- **Societal benefits**—the positive effects that decarbonization has on society that are not reflected in retail energy prices
- **Grid operator benefits**—benefits such as lower utility delivery costs, improved grid flexibility to balance intermittent generation sources, and others that arise, as a result of large-scale decarbonization efforts
- **Landlord–tenant equity**—potential copayments by landlords for a portion of the costs to replace essential HVAC equipment (Mast, Hummel, and Clinton 2020)

It is plausible to assume that homeowners with ready access to capital can largely finance their building decarbonization upgrades with conventional consumer savings, credit cards, or loan mechanisms. However, prior experience from energy efficiency programs over the past few decades has shown that the economic capacity to finance upgrades has not in itself been sufficient to mobilize most households to undertake them voluntarily, even with incentives (Mast, Hummel, and Clinton 2020).

At a minimum, the types of upgrades needed to achieve residential deep savings and electrification at scale require an approach that combines accessible and affordable financing products alongside incentives to cover the upfront capital required. A public–private investment partnership, whether formal or informal, will likely be necessary to fund efforts to achieve aggressive goals in this market. Short-term performance indicators must be adjusted to support, rather than undermine, the long-term goal of achieving a high level of market penetration of deep retrofits (Neme, Gottstein, and Hamilton 2011).

Design of a financing program necessary to scale deep residential energy retrofits will need to incorporate many elements including, but not limited to, inclusivity, attractive financing terms (rates, duration), a simple application process, convenience, contractor friendliness, scalability, and strategic public–private partnerships. Below, we summarize several current programs and market offerings that exemplify one or more of these design elements.

California's Residential Energy Efficiency Loan Assistance Program: Scalability

The Residential Energy Efficiency Loan Assistance Program (REEL) is designed to help Californians save energy at home by making attractive financing more widely available for home energy efficiency improvements. As of the end of 2020, REEL had granted 1,059 loans, 57% of them issued for properties in low/moderate-income census tracts, at an average value of $16,603. For terms up to 60 months, REEL participants have averaged an interest rate of 5.4%, versus 11.7% for borrowers not participating in REEL. For every $1 of credit enhancement allocated through REEL, an average of $6.61 in private capital has been leveraged through REEL's network of statewide and regional lenders, highlighting a successful public–private partnership. Moreover, 99.6% of Californians live in a county served by a REEL-approved contractor (CAEATFA 2020).

Sealed Home Advantage: Convenience, innovative financing

Sealed, a New York–based energy service company, offers energy service agreements (ESAs) for single-family homes to cover multiple retrofit packages. Customers are qualified via a virtual process that includes the development of a nonbinding proposal. After a customer is qualified and verbally commits to move forward, Sealed works with local contractor partners who conduct a home assessment, finalize a contract, and install the improvement packages. Common efficiency measures installed include air sealing, insulation, and smart thermostats. Customers receive a Sealed bill each month that replaces their utility bill, enabling ongoing engagement. Sealed has found that 68% of homeowners would want an energy retrofit if costs were not a factor; that households have less than a $3,000 budget for home improvements; and that less than 10% of U.S. homeowners expect to pay for home improvements with an unsecured loan. Sealed has been able to work around these issues, as well as traditional aversion to conventional financing, by covering a majority of the upfront costs, and homeowners pay Sealed on the basis of their actual monthly energy savings, unlike a fixed-rate monthly loan where preset payments are expected regardless of actual energy savings. Sealed's project close rate per customer proposal is 25%, compared with 16% for traditional energy improvement models, evidence of the market interest in their product and the potential of residential ESA to advance energy retrofits (Sealed 2021).

Mass Save HEAT Loan: Attractive rates

The Mass Save® HEAT Loan offers interest-free financing for eligible Mass Save customers for home energy efficiency upgrades like heating and water heating equipment, central A/C and heat pumps, insulation, and more. Loans can vary between $500 and $25,000 with terms of up to seven years. The HEAT Loan program is a collaboration among Massachusetts's utilities (Berkshire Gas, Cape Light Compact, Eversource, Liberty Utilities, National Grid, and Unitil), the Massachusetts Department of Energy Resources, and 100 lending institutions. The funding, which subsidizes the 0% interest rate, is supported by a charge on customers' energy bills (Mass Save 2021). The HEAT Loan program is the largest ratepayer-funded utility energy efficiency lending program in the country, by volume, issuing 13,443 loans at an average amount of $11,675 in 2019 alone (Mass Save 2019).

National Energy Improvement Fund EnergyPlus Improvement Loan: Efficiency, convenient platform

The EnergyPlus Improvement Loan program from the National Energy Improvement Fund (NEIF) is a monthly payment plan designed specifically for energy-related home improvements. EnergyPlus loans are simple-interest, fixed-rate installment loans with no fees to the borrower and no prepayment penalties. The program provides 100% financing, instant credit decisions, a paperless process, and responsive communication with customers and contractors to ensure that work is properly completed. All loans are made directly to the consumer by the National Energy Improvement Fund, LLC with fixed interest rates ranging from 7.99% to 12.99% and a duration of up to 10 years (NEIF 2021).

Michigan Saves Home Energy Loan: Public–private partnership

The Michigan Saves Home Energy Loan program offers unsecured loans for energy improvement projects; the most common residential improvements include insulation, air sealing, furnace or boiler replacement, windows, energy-efficient roofs, and appliances. Homeowners are eligible for rates ranging from 4.44% to 7.90% APR, though most finance at 5.50% APR. Terms of up to 15 years are available, with loan amounts ranging from $1,000 to $50,000 (Michigan Saves 2021). Michigan Saves is a green bank model made possible by partnerships with private-sector lenders, energy providers, a vast network of contractors, and credit enhancements via a loan-loss reserve that reduces the default risk for capital providers.

Ouachita Electric's HELP PAYS: Inclusivity

Ouachita Electric's HELP PAYS® utilizes a pay-as-you-save investment model to fund energy efficiency upgrades for its customers. Customers receive a no-cost energy assessment to identify and recommend efficiency upgrades for the home. If a customer elects to proceed with the energy upgrade, Ouachita provides the upfront capital and is paid back by the customer each month on the electric bill when energy savings are applied to the cost of the retrofit project. To participate in the program, no credit checks or debt-to-income thresholds are imposed, but customers must be in good standing with the utility with a good payment history (Ouachita Electric Cooperative Corporation).

Challenges and Barriers to Deep Energy Reductions and Decarbonization

Home retrofits offer many benefits, yet consumer investment and program participation remain low despite decades of promotion and incentives. The barriers to greater adoption of home retrofits are well documented (Cluett and Amann 2016; Hoffmeyer 2016; Fuller et al. 2010). In this section, we discuss the particular challenges facing deep retrofit and decarbonization projects.

TECHNICAL CHALLENGES

The catalog of successful deep retrofit projects demonstrates a variety of approaches for achieving significant energy use reductions—and increasingly decarbonization—in homes (Amann 2017). While the technology for deep savings exists, technical challenges to scaling up the number of projects remain. Experience to date shows that retrofit approaches requiring extensive disruption to occupants or focusing on envelope and major systems alone will not increase adoption or result in savings of 50% or more on a routine basis.

Research and development of advanced retrofit methods is very promising and has the potential to transform the retrofit market, but we are still years away from widespread deployment (Egerter and Campbell 2020). In the meantime, technical challenges include:

- Expanding the range of heat pump products that deliver high efficiency at a lower cost, including smaller-capacity equipment designed to meet reduced loads. Improving access to products offered in Europe and Japan could rapidly ensure a greater diversity of choices for the U.S. market.

- Developing standardized insulation packages to reduce installation time and error. Experience to date has informed creative strategies that eliminate the need for disruptive building shell modifications and reduce costs while improving air sealing, moisture management, and insulation performance.

- Advancing passive technologies to reduce load. Our analysis demonstrates savings from passive technologies like drain water heat recovery and cool roof coatings. A broader suite of cost-effective passive technologies suitable for retrofit applications can provide near-term savings and reduce the overall cost and uncertainties associated with decarbonization of buildings and the grid.

HIGH PROJECT COSTS

The cost of deep retrofit projects remains prohibitive. In our modeling analysis, project costs ranged from about $42,000 to $57,000. Data from actual projects generally align with these estimates (Less and Walker 2015; Neuhauser 2012). The cost of necessary repairs or related renovations that often must be completed before efficiency measures are installed can add significantly to project costs, creating an additional hurdle. For example, homeowners may need to upgrade the electrical panel in their home to meet the added load as fossil fuel equipment is replaced with electric models. One California estimate of the cost to upgrade to a 200-amp panel is $2,000–4,000 (E3 2019). The introduction of lower-cost panel upgrade packages would help address this barrier. More data are needed on the cost of this work.

Further research and development of retrofit-ready equipment designed to work on 110V outlets and low amperage or to fit in smaller spaces would reduce the cost and inconvenience associated with adoption of electric appliances and equipment. In the spring of 2021, the first retrofit-ready heat pump water heaters for the U.S. market were publicly introduced (Gibson 2021). These products serve as a model for the type of innovation that can accelerate high-efficiency equipment and building electrification.

Financing and incentives can help reduce the cost barrier, but limits to current financing products and their availability must be addressed. Staged retrofits can also make the investment more manageable and provide an option to incorporate efficiency measures into other home improvement projects, such as siding or roof replacement, basement renovation, or kitchen and bathroom remodeling. Implementing efficiency measures as part of these projects may be more cost effective than completing them in separate efficiency retrofits, but more data are needed.

WORKFORCE CAPACITY AND SEGMENTATION

The most successful retrofit programs in the country rely on a relatively small pool of contractors for the majority of completed projects. This pool typically represents the subset of contractors who have developed a business model to deliver complex projects by hiring (or subcontracting) technicians to perform the diverse set of services typically provided by different businesses and trades (e.g., insulation and air sealing, HVAC installation, window installation, plumbing) as well as the diagnostic testing, reporting, and quality assurance required for participation in most home performance programs. Many contracting businesses are daunted by the added complexity of selling and delivering these projects while also meeting program requirements and decide to forgo participation or have limited involvement. In one of the longest-running home performance programs in the country, New York Home Performance with ENERGY STAR, roughly 15% of the program's 200 participating contractors are responsible for the majority of completed projects (Schreyer et al. 2020).

Designing Retrofit Programs to Drive Decarbonization and Better Meet Customer Needs

A number of residential retrofit programs have incorporated one or more of the strategies examined in our analysis—staged retrofit options, defined retrofit packages, electrification, and financing—in an effort to address the persistent barriers to deeper savings and greater program participation. Examples are discussed below. While many of these programs have adopted these strategies relatively recently, early experience provides some indication of how these strategies can be effective, the potential limitations, and opportunities for further refinement or adjustments that could improve outcomes.

STANDARDIZED RETROFIT PACKAGES

Standardized retrofit packages can reduce barriers to greater contractor and customer participation in retrofit programs by decreasing the time, cost, and inconvenience associated with the typical highly customized approach to whole-home retrofits. Program administrators develop a set of standard measure packages designed to address common needs and opportunities in the local housing stock and ensure that all packages, even the most basic, achieve their minimum threshold for energy savings. Packages also offer a mechanism to combine more visible (and desirable) measures with required weatherization measures that can be difficult to sell to customers who do not understand their value (Perry and Young 2020). While the specific details of any given project must be tailored to each home, robust planning and analysis during design of the packages can eliminate the need for detailed pre-retrofit diagnostics in many homes. And regional characteristics can be incorporated. For example, standard packages in northern New England could account for supplemental heating from wood- or pellet-burning stoves common to homes in the region; in hot-humid climates there could be greater emphasis on moisture control and on duct sealing relative to insulation.

This approach benefits customers; the transaction process is less confusing because measures are combined into a few packages for their consideration. By focusing on the measures that have proved most effective in their region, the overall project can be completed with fewer contractor visits, thereby reducing the time customers spend to schedule and accommodate the work.

City of Fort Collins Utilities Efficiency Works Program

In 2015, Fort Collins (Colorado) Utilities launched the Efficiency Works Neighborhoods pilot program. The program aimed to increase the rates of participation, realize higher energy savings, and simplify the upgrade process for homeowners. Efficiency Works offers a streamlined service to overcome barriers such as the lack of time to select and meet with contractors, challenges in identifying the scope of work, distrust of contractor proposals, and lack of affordable ways to pay for projects. To recruit participants, the program uses targeted and tailored communications including brochures and digital ads.

Once the homeowner agrees to participate, a home efficiency assessment is performed and the customer receives a package of recommendations with standardized pricing for whole-home energy efficiency measures. The homeowner can choose from only three packages: Good, Better, and Best. The Good package, which is the base package, includes comprehensive envelope upgrades like insulation and air sealing. The Better package consists of the base package plus an upgrade to the HVAC system (e.g., furnace or boiler replacement) or windows. The Best package includes all the above plus rooftop solar. Participants have the option of implementing the recommended measures or customizing the package and then claiming the available rebates. The program selects a qualified contractor to complete the project, eliminating the time customers spend on meeting and receiving proposals from contractors. After the work begins, a manager reviews the work as part of the quality assurance process. Customers have the choice to use low-cost financing offered through the program to fund their projects. They can finance up to 100% of the project costs, at rates of 2.4% to 4% for up to 20 years.

Program data from 2018 show a total savings of 9,543 kWh per year per household. The average savings per home that completed a project was 750 kWh of electricity and 300 therms of natural gas (Kassirer 2018).

STAGED RETROFITS

Offering customers the option to split a deep retrofit project into two or more stages can make the process (and the investment) less daunting and allow them to tackle immediate needs first while providing a mechanism for ongoing engagement to support completion of the full retrofit over time. Staging can help programs and contractors scale up retrofit and electrification projects to meet energy and climate goals.

From a building science perspective, the optimal staging of a retrofit would start with envelope and duct improvements to reduce air (and moisture) infiltration, improve comfort, and reduce overall heating and cooling load. Equipment replacement in a subsequent stage or stages could then be properly sized for the new load with the benefits of better performance and, potentially, reduced equipment costs. The New York State Energy Research and Development Authority (NYSERDA) developed the Comfort Home Program to encourage homeowners to invest in envelope and duct improvements prior to replacement of fossil fuel heating systems with high-efficiency cold climate heat pumps (Schryer et al. 2020). This approach aligns with the state’s decarbonization goals by capturing near-term gas and oil savings, preparing homes for successful heat pump installation and operation, and reducing the magnitude of future winter peak electricity demand.

While this may be the preferred staging approach and a good option for many homes, additional staging options are needed to accommodate the realities of the marketplace and homeowner decision making. Our analysis demonstrates that retrofit projects following a different sequence for staging of measures can be effective when tailored to the local climate and housing stock. Further research and analysis on any additional transaction costs associated with staged projects would be useful for program design and development of incentive and financing options.

New York State Energy Research and Development Authority Comfort Home Pilot Project

In 2019, to meet its electrification policy goals, NYSERDA launched the Comfort Home pilot in select markets across New York State. The program supports three objectives: improving envelope performance of existing single-family homes through packages of measures in preparation for widespread heat pump conversions, streamlining the sales process, and establishing a savings calculation methodology. To recruit participants, NYSERDA uses geo-targeting analysis and a network of local contractors. The agency uses its market and segmentation tool and public data sets to identify potential customers with the relevant home characteristics, demographics, and heating fuel. This information guides the contractor outreach.

After homeowners agree to participate, a trained, qualified contractor helps them select the improvement package and available rebates and financing. To simplify the sales process, NYSERDA offers four standard load-reduction packages. The Basic package includes air leakage improvement measures, while the Good package specifies air sealing and insulating the attic and rim joists. The Better package adds insulation of the walls and floors. Last, the Best package incorporates all measures from the Good and Better packages and adds window replacement.

The packages streamline customer decision making and the contractor bidding process and help predict impacts. Incentives range from $500 for the Basic package to $4,000 for the Best (NYSERDA 2020).

Customers can claim an additional incentive for a heat pump if they install one within 12 months of completing a home load-reduction package. A participating contractor completes the work using rebates and financing to cover the project costs. The program team reviews the final project for inconsistencies and to ensure high-quality work.

The program utilizes a strategy to seal and insulate the home first, before investing in new HVAC equipment; this element of the program is similar to the staged approaches detailed in this report.

ELECTRIFICATION

As more states adopt aggressive clean energy goals, electrification is becoming an important focus for residential retrofit programs. Coupling electrification with deep retrofit projects can address some of the challenges of electrification and facilitate the transition to a decarbonized building stock. And at the project level, electrification can increase cost effectiveness and emissions reductions and improve overall home performance.

More broadly, reducing demand will offset near-term emissions associated with electrification while the grid transitions to cleaner power sources. It will also mitigate longer-term grid capacity and reliability issues associated with higher winter peaks (Specian, Cohn, and York 2021).

Zero Energy Now (ZEN) pilot program, Vermont

In 2016 the Building Performance Professionals Association of Vermont launched the ZEN pilot program for residential retrofits, funded through the state's largest utility, Green Mountain Power. The program offers a combination of weatherization measures, heat pumps, and rooftop solar to achieve deep savings and minimize greenhouse gas emissions. The pilot integrates several components, including custom solutions and financing, to meet specific goals of a 10% reduction in home energy use, a 50% reduction in fossil fuel and grid electricity, and an increase in on-site renewables.

To reduce customer confusion, a dedicated ZEN contractor guides the homeowner on which efficiency measures to implement. Customers then have access to affordable financing to help reduce the upfront costs. The program design encourages bundling of efficiency measures with renewables, which helps reduce the overall project costs. ZEN also offers a savings guarantee to increase homeowners' confidence in investing in large projects with significant costs. Customers are offered a refund of up to $1,000 if the actual energy use after one year is higher than the projected usage.

A total of 35 projects in the pilot have been completed. Data from 24 homes reveals average home energy savings of 39% and fossil fuel and grid electric savings averaging 64% (Stebbins, Perry, and Faesy 2020).

FINANCING AND INCENTIVES

Financing approaches for comprehensive packages and staged retrofits can help lock in the full project and encourage homeowners who decide to split the deep retrofit project into phases to follow through with the later stages. Customers opting for a staged retrofit get upfront savings in the first phase, either from implementing the envelope package or the combined equipment replacement and envelope measures. These savings can be substantial, and some customers may decide to drop out and not implement the remaining measures if they do not see the full value of additional savings. Aligning financing and incentive tools with each phase of the retrofit project can help encourage customers to continue on the path and engage them to complete the full retrofit over time.

ADDITIONAL PROGRAM CONSIDERATIONS

A number of other strategies have the potential to increase program participation, improve customer satisfaction, and increase savings while reducing program administrative costs. Promising strategies include:

- Establishing a single program/project point of contact for the customer
- Providing post-project follow-up with the customer
- Leveraging remodeling and other projects/transactions
- Marketing the multiple benefits of efficiency and decarbonization
- Updating and expanding direct-install measure offerings
- Incorporating smart features to improve project outcomes
- Integrating with other program offerings including marketplace and behavior program offerings

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Appendix A. Methodology for Modeling Retrofit Scenarios

In this project we developed decarbonization packages for residential retrofits along with recommendations for program design and retrofit approaches to scale customer adoption. We analyzed the energy savings and reductions in carbon emissions from three comprehensive retrofit scenarios that save close to 50% of home energy in each of the five Building America climates. Our retrofit packages were based on findings from the literature, experience from deep energy retrofit programs and initiatives, and case studies of individual projects that highlight technologies and approaches that have been successful.

To identify and prioritize the measures to be bundled in the retrofit packages and estimate the savings from different retrofit approaches (e.g., comprehensive and staged), we reviewed existing literature, interviewed experts, and conducted building energy modeling. Figure A1 describes the process. The remainder of this appendix describes the methodology for the modeling and energy savings analysis.

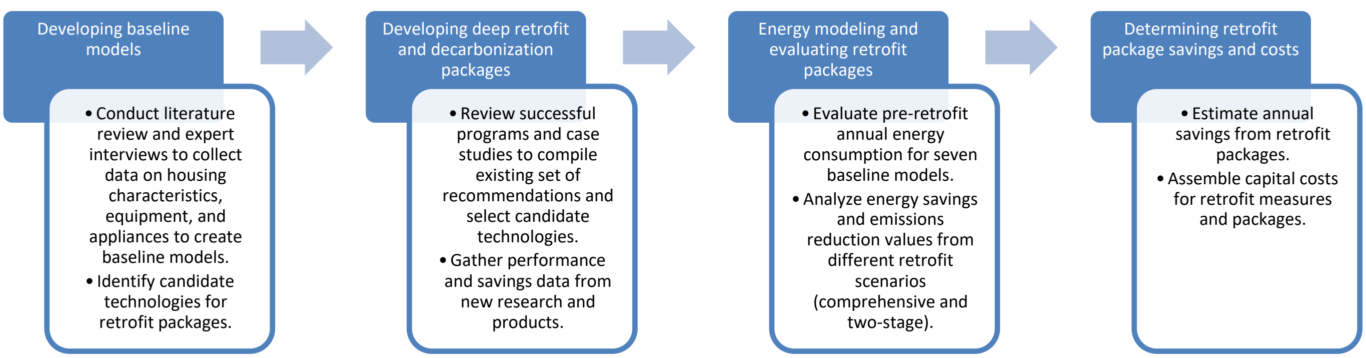

Figure A1. Study method overview

DEVELOPING BASELINE MODELS

To evaluate retrofit and decarbonization packages in each of the major U.S. climates, we selected a representative city in each of the five Building America climate regions. Using data from the 2015 Energy Information Administration's Residential Energy Consumption Survey, we identified the most common pre-2000 housing vintages in each climate region (EIA 2018). Table A1 shows the breakdown of single-family homes by vintage for each climate region. The seven climate-vintage combinations included in our analysis are shown in bold.

Table A1. Percentage of homes by vintage for each climate region

Climate zone and representative city	Cold/very cold: (Albany, NY)	Mixed-humid: (Baltimore, MD)	Hot-humid: (Houston, TX)	Hot-dry/ mixed-dry: (Sacramento, CA)	Marine: (Salem, OR)
Pre-1950s	**25.6%**	**17.3%**	6.6%	7.1%	**25.4%**

1950s	12.0%	10.4%	8.3%	10.2%	11.9%
1960s	10.6%	10.7%	11.0%	11.8%	11.9%
1970s	**14.8%**	**15.8%**	14.0%	17.3%	19.4%
1980s	9.4%	14.6%	**18.4%**	18.9%	7.5%
1990s	12.7%	14.0%	17.1%	**17.3%**	10.4%
2000s	11.8%	14.0%	20.2%	16.5%	10.4%
2010–2015	2.8%	3.0%	5.3%	1.6%	3.0%

Source: 2015 RECS

We developed seven baseline models, each with a 2,000-square-foot floor area. Our literature review was a starting point to identify the residential building characteristics, primary fuel use, typical heating and cooling equipment, and household appliances in single-family homes. We compiled this information from publicly available data sets including the National Renewable Energy Laboratory's (NREL) ResStock Analysis tool, the EIA Residential Energy Consumption Survey (RECS), the National Residential Efficiency Measures Database, and the Building America Research Benchmark Definition (Hendron and Engebrecht 2010). ResStock and RECS include details on housing stock characteristics and practices from a national representative sample of residential buildings. Table A2 shows the pre-retrofit building characteristics; enclosure details; typical heating, cooling, and ventilation equipment; water heating equipment; and lighting in each of the climate-vintage combinations we examined. We used this information to establish the baseline condition for our analyses and assess the impacts of deep energy retrofits in the energy modeling software.

Table A2. Pre-retrofit building characteristics and details of equipment used for heating, cooling, ventilation, and water heating by climate zone and vintage.

	Cold		Mixed-humid		Hot-humid	Hot-dry	Marine
	Pre-1950s	1970	Pre-1950s	1970	1980	1990	Pre-1950s
House size (s.f.)	2,000						
Ceiling height	8 feet						
Direction faced by front of the house	North						
Stories	2	1	2	1	1	1	1
Foundation/Basement	Uninsulated basement	Uninsulated basement	Crawl space, vented	Uninsulated basement	Uninsulated slab	Uninsulated slab	Crawl space, vented
Wall	R-7	R-7	R-7	R-7	R-11	R-11	R-7
Attic type	Unfinished, vented						
Attic insulation	R-19	R-38	R-19	R-38	R-30	R-30	R-13
Window to wall ratio	20%, same on all sides						
Window type	Clear, double, nonmetal						
Estimated infiltration	20 ACH50	15 ACH50	25 ACH50	20 ACH50	15 ACH50	15 ACH50	20 ACH50
Mechanical ventilation	Exhaust fans	Exhaust fans	Exhaust fans	Exhaust fans	Exhaust fans	Whole-house fans	Whole-house fans
HVAC system - cooling	Room air conditioners EER 10.7	Central air conditioner, 10 SEER	Central air conditioner, 10 SEER	Central air conditioner, 10 SEER	Central air conditioner, 10 SEER	Central air conditioner, 10 SEER	Room air conditioners EER 10.7
HVAC system - heating	Gas boiler	Gas furnace	Gas furnace	Gas furnace	Gas furnace	Gas furnace	Gas furnace

	Cold		Mixed-humid		Hot-humid	Hot-dry	Marine
Ducts	None	20% leakage, uninsulated	20% leakage, uninsulated	20% leakage, uninsulated	20% leakage, R-4	20% leakage, R-4	20% leakage, uninsulated
Ceiling fans per home	2	2	4+	4+	4+	4+	1
Cooling set point	72 °F, 2 °F offset	72 °F, 2 °F offset	72 °F, 2 °F offset	72 °F, 5 °F offset	75 °F, 2 °F offset	75 °F, 2 °F offset	72 °F, 2 °F offset
Heating set point	68 °F, 3 °F offset	68 °F, 3 °F offset	70 °F, 3 °F offset	70 °F, 3 °F offset	70 °F, 3 °F offset	70 °F, 6 °F offset	70 °F, 3 °F offset
Water heating	40 gallon, tank type, gas storage, EF 0.59						
Lighting	60% sockets efficient (LED)						

DEVELOPING DEEP RETROFIT AND DECARBONIZATION PACKAGES

We used findings from the literature and experience with deep retrofit projects to develop our comprehensive retrofit packages. We reviewed more than 50 published reports and peer-reviewed articles on deep energy retrofit programs and initiatives, case studies of individual projects, and recent literature on alternative technologies and approaches that have proved successful in delivering deeper energy reductions. This research informed the selection of appropriate measures, including several core, alternative, and supplemental technologies.

Our retrofit packages are based on the LBNL (2015) published recommendations for deep retrofits in each of the five Building America climate regions. We made some modifications to reflect more recent research findings and most efficient product models available in the market. Details of the retrofit measures modeled in our analyses are presented in table A3. Deviations from the LBNL packages are shown in italics in the table.

Table A3. Comprehensive deep energy retrofit packages

	Cold	Mixed-humid	Hot-humid	Hot-dry	Marine
Walls	R-30 assembly	R-20 assembly	*R-13 cavity*	*R-13 cavity*	R-30 assembly
Attic	R-60 insulation	R-49 insulation	R-38 insulation	R-38 insulation	R-38 insulation
	All climates: Convert to unvented attic, if feasible. If not, seal to ensure continuous air barrier at attic floor.				
Roof	No treatment	Reflective roof coating or membrane	Reflective roof coating or membrane	Reflective roof coating or membrane	No treatment
Founda-tion/ basement	Basement: R-20 continuous	Basement: R-10 continuous	Slab foundation: no treatment	Slab foundation: no treatment	Crawl space: R-15 continuous
	Basement/crawl spaces: Seal walls and vents, seal and insulate rim joists, install continuous vapor barrier in all exposed crawl spaces.				
Windows[a]	*ENERGY STAR Northern*	*ENERGY STAR North–Central*	*ENERGY STAR Southern*	*ENERGY STAR South–Central*	*ENERGY STAR Northern*
Air leakage	All climates: air sealing to ACH ≤ 7.0 (measured at 50 pascals of pressure)				
Mechanical ventilation	HRV/ERV: >75% heat recovery	None	None	None	HRV/ERV: 70% heat recovery

	Cold	Mixed-humid	Hot-humid	Hot-dry	Marine
(whole house)	All climates: ASHRAE 62.2 compliant ventilation				
Space conditioning	*NEEP cold climate or better*	*NEEP cold climate*	*ENERGY STAR Most Efficient*	*ENERGY STAR Most Efficient*	*NEEP cold climate*
(air source heat pump)[b]	All climates: Ducts insulated and sealed; smart thermostats installed				
Water heating	All climates: Install heat pump water heater *EF 3.45*; insulate pipes; repair all leaks; install low-flow fixtures (1.5 gpm or less)				
Lighting	All climates: 100% LED—*focus on specialty bulb types*				

Source: Less and Walker 2015 (LBNL) and ACEEE analysis. Variations from LBNL recommendations are in italics. *HPWH modeled in BEopt was 2.35EF (the highest efficiency available in the model). Savings were then adjusted to reflect performance of 3.45EF model.

[a] **ENERGY STAR Residential Windows, Doors, and Skylights V6.0:** www.energystar.gov/sites/default/files/asset/document/Windows_Doors_and_Skylights_Program_Requirements%20v6.pdf.

[b] **ENERGY STAR Most Efficient 2021:** www.energystar.gov/sites/default/files/CAC_ASHP_GHP%20ENERGY%20STAR%20Most%20Efficient%202021%20Final%20Criteria.pdf

We developed three deep retrofit and decarbonization packages for each of our seven homes. The first scenario is a single, comprehensive project in which all measures are implemented together. In the second and third scenarios, the retrofit projects are completed in stages, and we vary the sequencing of packages in two phases. The simulated retrofit scenarios include:

Retrofit A: comprehensive deep energy retrofit with deep decarbonization measures at one time

Retrofit B: staged retrofit with full shell measures in the first phase and equipment upgrades in second phase, and

Retrofit C: staged retrofit with a combination of shell and equipment upgrades in each phase.

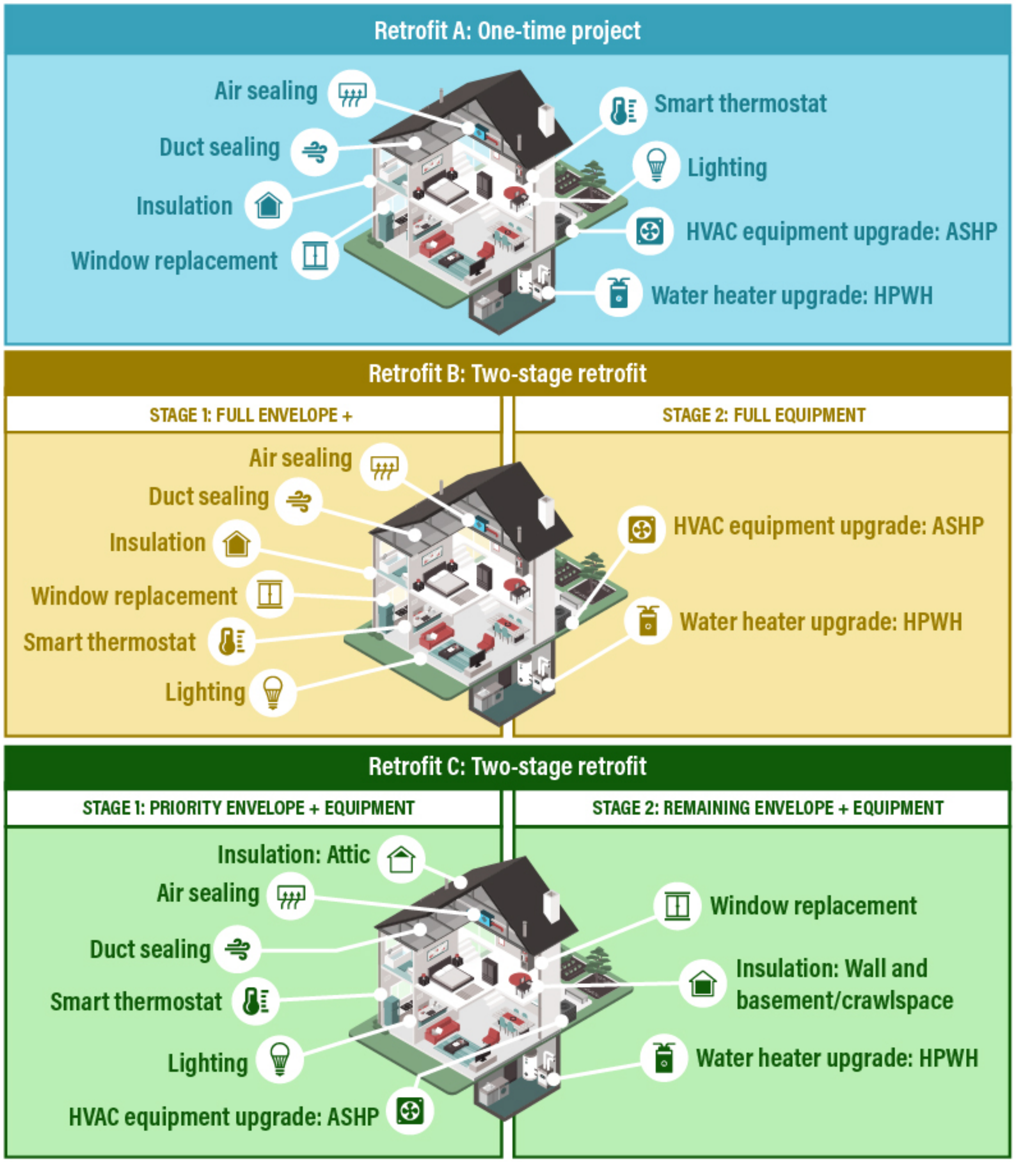

Figure A2. Details of retrofit scenarios modeled

BUILDING ENERGY MODELING

To evaluate the impact of deep energy retrofit packages and the project delivery approaches, we modeled the three retrofit scenarios relative to the seven baseline homes in the Building Energy Optimization Tool (BEopt), a residential building energy simulation software tool developed by National Renewable Energy Laboratory (NREL). BEopt uses the EnergyPlus simulation engine, with assumptions based on the Building America Housing Simulation Protocol. The simulation of the individual baseline models in BEopt with the appropriate representative city weather file allowed us to estimate the annual baseline energy use and carbon emissions. Additionally, the simulation of deep-retrofit scenarios enabled us to evaluate the impact of different project delivery approaches and to see how sequencing of measures in a retrofit package could yield energy savings while meeting customer needs. Figure A3 shows the BEopt geometry, input, and output screens.

To model and evaluate our retrofit packages in BEopt, we completed a sequential two-step study that included an incremental analysis and a combination analysis. The incremental analysis selected the best measure or equipment within a given category (e.g., heating, cooling). A number of measure or equipment options representing different levels of efficiency were simulated and evaluated relative to one another. We used the results and findings from the literature to assemble a package of measures that we modeled in the second analysis. The combination analysis helped estimate the changes in energy use and carbon emissions from implementing the deep retrofits with multiple measures. We used the analyses to evaluate the individual impact of measures and how the collections, or packages, of measures impacted energy use. This also helped us refine the three retrofit packages for the given climate-vintage combination.

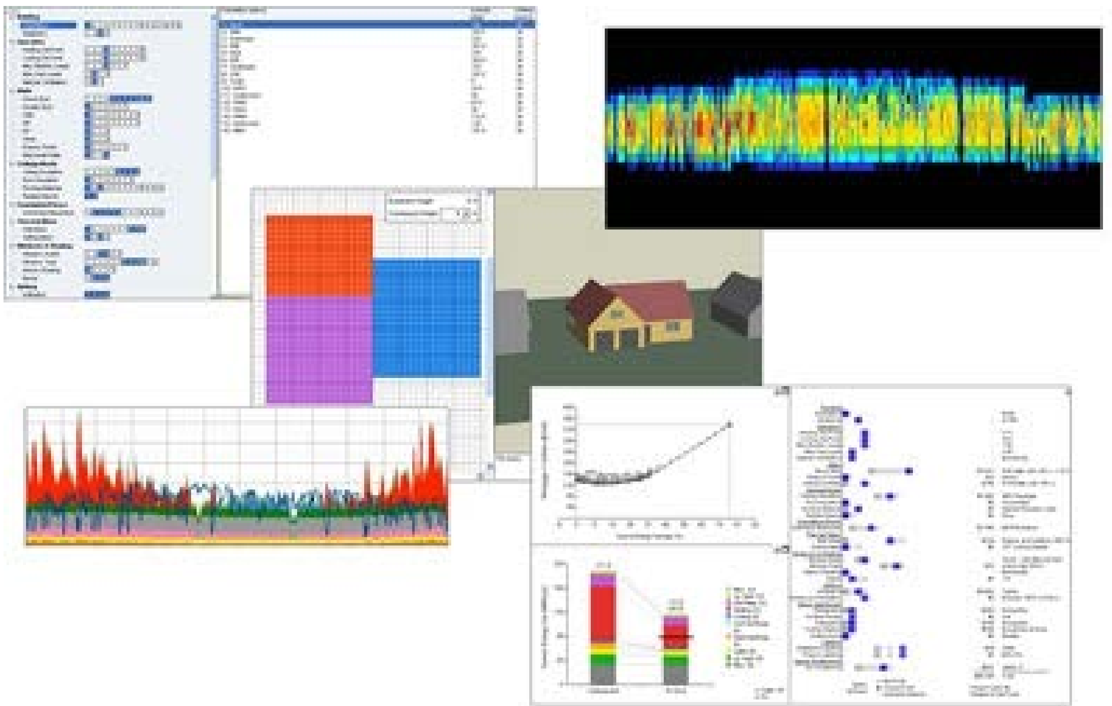

Figure A3. Input and output details from BEopt. Source: DOE.

To model the different project delivery approaches in BEopt, we used the tool feature that allows users to vary the time of replacement for certain measures. This was critical for simulating our two-stage retrofit scenarios, as we had different time horizons for implementing the efficiency measures. BEopt allows envelope upgrades (e.g., wall insulation) to occur only at the beginning of an analysis period (year 1), but it does let users specify the time when an equipment or system is replaced. This ability to vary the time for implementing certain measures helped us conduct the analysis in two stages and sequence the measures in phases. The analysis period for the first phase of the retrofit was set at five years, as that is the time span in which we would expect the next phase of retrofits to be implemented. This time horizon can be modified depending on program goals and customer needs.

RETROFIT PACKAGE SAVINGS AND COSTS

We estimated the energy savings and emissions reductions from the different retrofit packages by comparing the simulation results for the pre-retrofit building model with the results for the improved building model to which a combination of measures has been applied. This provided us with the source and site energy savings and the reduction in carbon emissions. The energy modeling tool also provided a breakdown of electricity and gas use, which helped us analyze the potential for achieving near-term savings and electrification.

We used the project costs from BEopt for the three retrofit scenarios that include the measures described in table A3. BEopt is integrated with NREL's National Residential Efficiency Measures Database, which provides costs for residential building measures, including labor and materials costs. BEopt provides a total project cost and the cost breakdown for implementing each of the individual measures. This allowed us to adjust costs for various retrofit scenarios. Figure A4 shows the BEopt graphic output screen with the total project cost and the cost breakdown for individual measures.

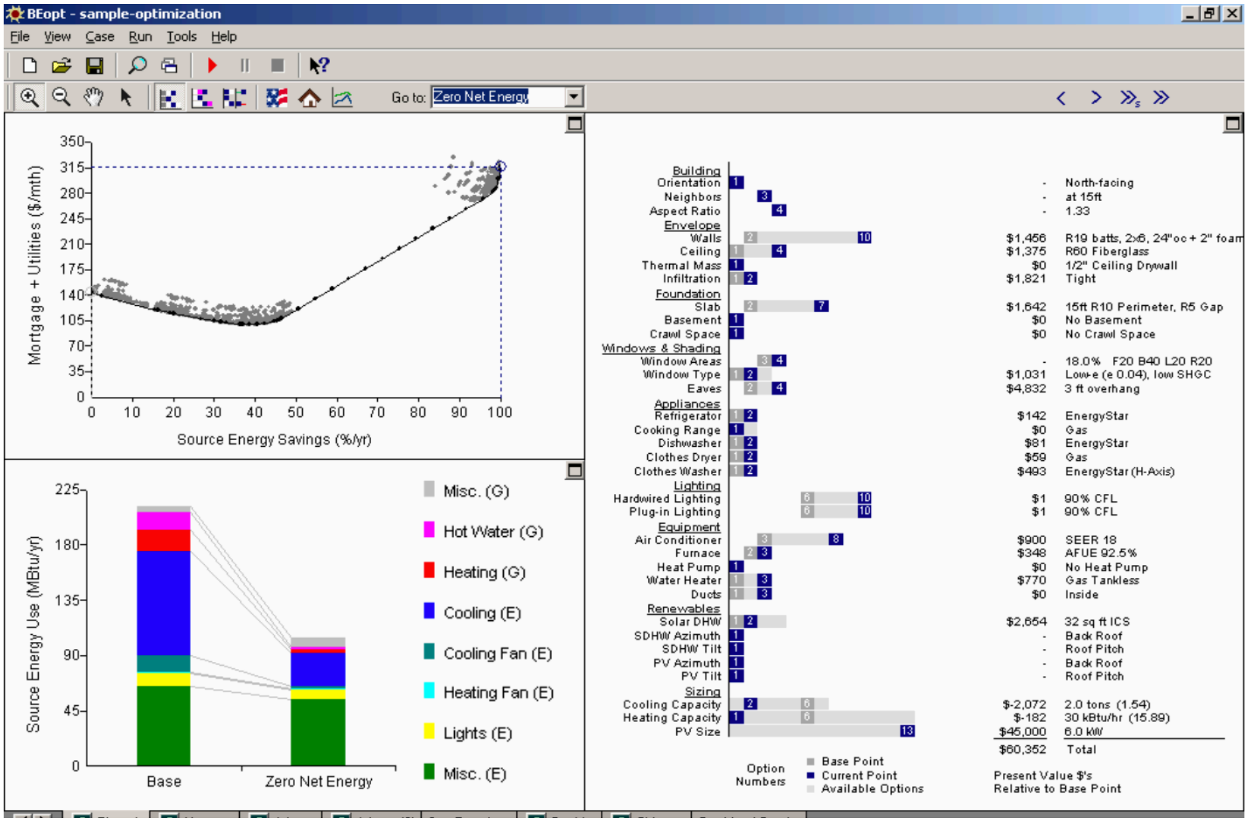

Figure A4. BEopt graphic output screen with the total project cost and the breakdown for individual measures

LIMITATIONS

Our analysis is based on a number of assumptions. The baseline data were created for selected building vintages using information from publicly available sources and may not account for individual building variations. For example, in our cold climate pre-1950s baseline home, we modeled a gas boiler, but some of these homes may have already upgraded to a furnace. This may impact the baseline energy use and the potential savings from the combination of different retrofit measures.

For some homes, there may be other upgrade options that could yield more savings than we modeled using measures and technologies available in the BEopt library. For example, there are more efficient heat pump water heaters available on the market (with energy factor= 3.25), but it is difficult to modify the existing model components in BEopt, which is currently using 2012 market products. Creating a new product in BEopt would require product details that we cannot obtain; therefore, we decided to model a lower-efficiency heat pump water heater.

Another modeling limitation is that BEopt allows only one heating or cooling system. Our baseline models have natural gas heating and a central or in-room air conditioner. In our retrofit scenarios, we had to assume that both the gas heating equipment and the electric cooling system were being replaced simultaneously with a single heat pump that would meet all heating and cooling needs.

The total retrofit package costs in our analysis also have limitations. For example, when we modeled a mini-split in the cold climate pre-1950s home, we specified no ducts. However, the simulation results from BEopt included costs for duct insulations. We decided to exclude this cost from the total retrofit package cost.