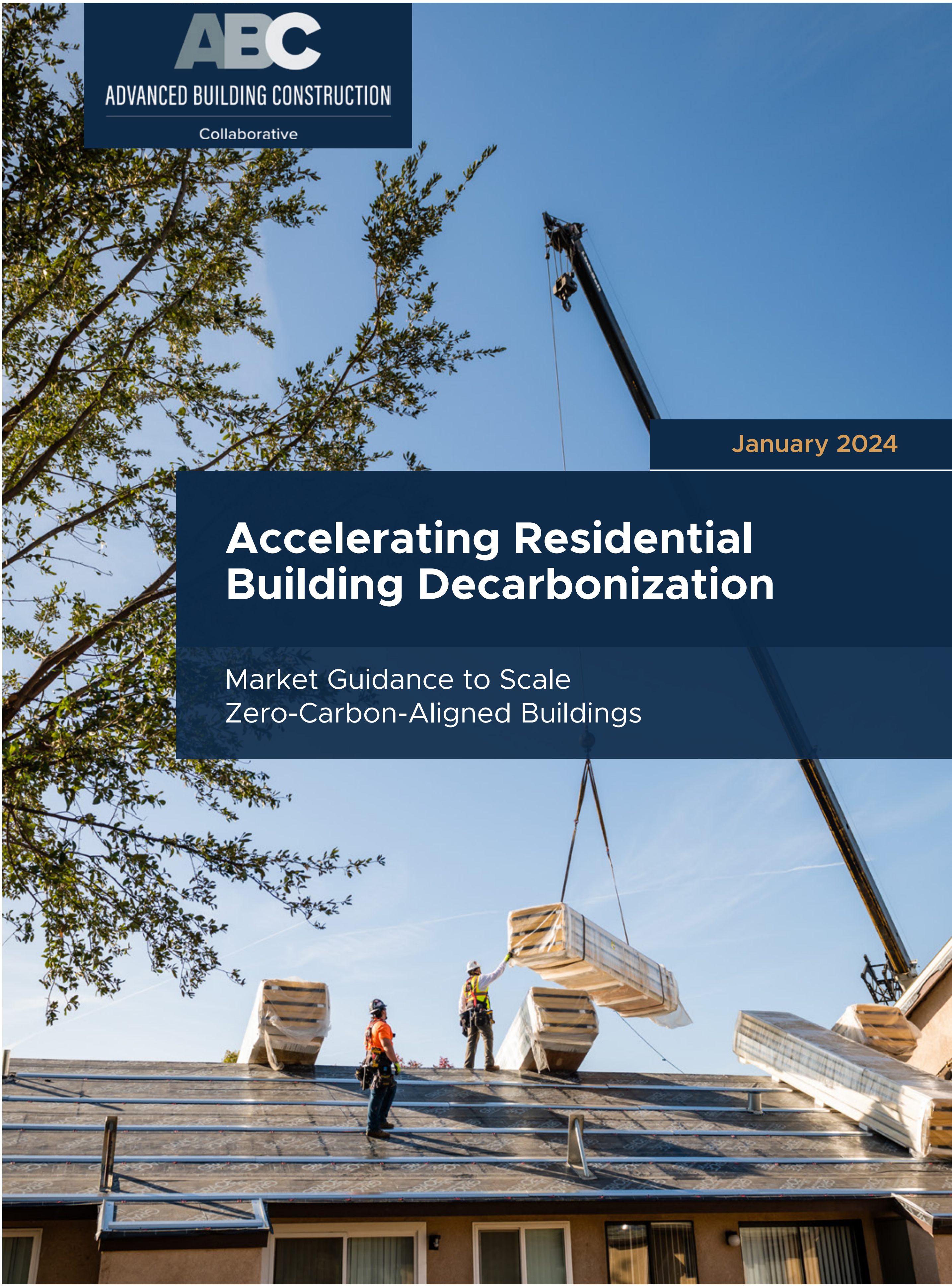
ADVANCED BUILDING CONSTRUCTION
Collaborative

January 2024

Accelerating Residential Building Decarbonization

Market Guidance to Scale Zero-Carbon-Aligned Buildings



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About Us

ADVANCED BUILDING CONSTRUCTION COLLABORATIVE

The Advanced Building Construction Collaborative is a market facilitation hub that brings together a diverse network of incumbent and emergent buildings sector actors — across construction, manufacturing, real estate, development, and related areas. It works to accelerate the uptake, scaling, and mainstream adoption of advanced building construction (ABC) — technologies and other innovations for new construction and building retrofits that combine energy-efficient building decarbonization with streamlined, scalable, industrialized construction methods — while supporting and leveraging modernization of the US construction industry. Its mission is to drive ABC in service of decarbonizing the US buildings sector before 2050 while improving affordability, resilience, and equity.

LAWRENCE BERKELEY NATIONAL LABORATORY

Founded in 1931 on the belief that the biggest scientific challenges are best addressed by teams, Lawrence Berkeley National Laboratory (LBNL) and its scientists have been recognized with 14 Nobel Prizes. Today, LBNL researchers develop sustainable energy and environmental solutions, create useful new materials, advance the frontiers of computing, and probe the mysteries of life, matter, and the universe. Scientists from around the world rely on the Lab's facilities for their own discovery science. LBNL is a multiprogram national laboratory, managed by the University of California for the US Department of Energy's (DOE) Office of Science. LBNL supports the Advanced Building Construction Initiative at DOE through leadership in the energy modeling and analysis space.

NATIONAL RENEWABLE ENERGY LABORATORY

The National Renewable Energy Laboratory (NREL) is the US Department of Energy's primary national laboratory for renewable energy and energy efficiency research and development. NREL's buildings research is transforming energy through building science and integration. Our research significantly enhances the resiliency, efficiency, and affordability of energy systems across the United States and the world. NREL is operated for the Department of Energy by the Alliance for Sustainable Energy, LLC.

PACIFIC NORTHWEST NATIONAL LABORATORY

The Pacific Northwest National Laboratory (PNNL), founded in 1965, is a national lab with Pacific Northwest roots and global reach. With more than three decades of experience in building energy research, PNNL is central to the nation's efforts to improve the energy efficiency of homes and buildings while making them more comfortable. PNNL is working with the US Department of Energy's Building Technologies Office, other national laboratories, and industry to limit rising energy consumption and costs in buildings. PNNL supports the Department of Energy's Advanced Building Construction Initiative through leadership in the research, development, and demonstration space.

RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. RMI works in the world's most critical geographies and engages businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

VEIC

VEIC is a sustainable energy organization on a mission to generate the energy solutions the world needs. For over 35 years, VEIC has been working with governments, utilities, foundations, and businesses across North America to develop and deploy clean energy services that provide immediate and lasting change. VEIC has expertise in energy efficiency, building decarbonization, transportation electrification, and demand management for a clean and flexible grid. We design innovative solutions that meet clients' goals, while reducing greenhouse gas emissions. VEIC is nationally recognized for programs and pilots that optimize energy use, reduce energy burdens for low-income customers, and advance emerging technologies and innovative program models. In addition to our full-service consulting business, VEIC administers three large-scale sustainable energy programs — Efficiency Vermont, Efficiency Smart, and the DC Sustainable Energy Utility (DCSEU) — and serves on the program administration teams for Focus on Energy (Wisconsin) and Hawaii Energy.

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Abstract

The US buildings sector faces a confluence of challenges, including a clear necessity to decarbonize the built environment to mitigate climate change, a need for greater resilience in the face of more frequent extreme weather events, a dearth of affordable housing, and flat or declining construction productivity that hinders the sector's ability to adapt. Better data and guidance on new and existing residential buildings can outline paths forward for the market. These can help clarify stakeholder priorities and highlight applications for new (or newly relevant) technologies and approaches that have the potential to break traditional barriers, bridge technical gaps, reduce costs, create added value, and enable decarbonization of the national residential building stock.

Decarbonizing the national building stock before 2050 will require massive increases in zero-carbon retrofits and new construction in this decade. By 2030, whole-home retrofit activity must increase severalfold, and virtually all new construction will need to be zero carbon. It is difficult to imagine achieving this transformation without substantial changes in how buildings are constructed and retrofitted. By employing innovative building technologies and modernized construction techniques, while leveraging novel business models and aggregated demand, the residential construction industry has the opportunity to deliver energy-efficient, zero-carbon-aligned, and ultimately cost-effective new and retrofitted homes at scale, with streamlined delivery and consistent quality.

This report provides product manufacturers, fabricators, contractors and installers, design professionals, owners, and real estate developers with technical performance and cost guidance for scalable zero-carbon-aligned new construction pathways and retrofit packages across the nation's climate regions. The report builds on market research, stakeholder engagement, and modeling and analysis by the Advanced Building Construction Collaborative and its national laboratory partners. Market stakeholders can use this information to focus their strategic and project-level decision-making to drive zero-carbon-aligned buildings within the limited time frame for decarbonization. Though the report does not provide policy recommendations, public-sector stakeholders may also see it as a useful input into their decision-making.

The information in this report can serve as a springboard for further development and refinement of specific physical solutions — such as construction products and assemblies — that can achieve necessary performance levels to meet climate goals. It can also inform business models that can deploy these physical solutions at scale and enabling financial and technical tools. In particular, it can be relevant to stakeholders in the emergent advanced building construction (ABC) market.

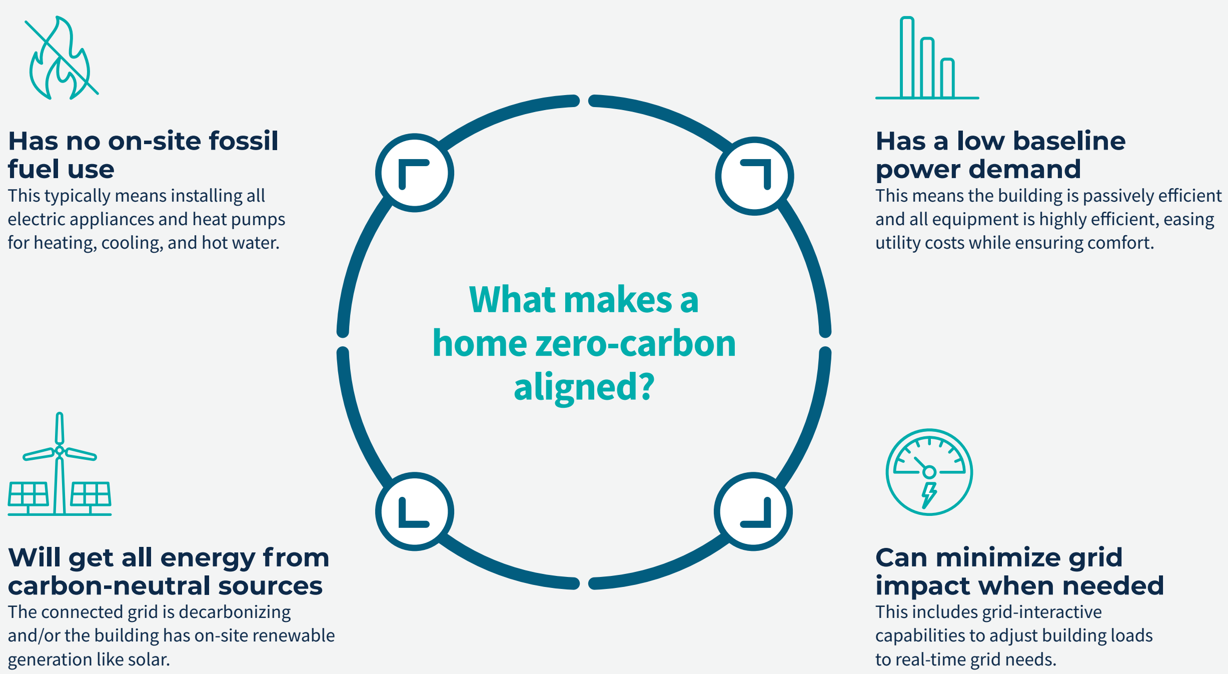
Executive Summary

This report provides the market with technical information and guidance on how to achieve zero-carbon new and existing residential buildings at scale. The report is designed to inform a wide range of building industry stakeholders, including integrated solution providers, industrialized fabricators of building assemblies, design professionals, building owners, and real estate developers. It can also support decision-making by public officials.

This work is motivated by the confluence of challenges facing the US buildings sector, including a clear necessity to decarbonize the built environment to mitigate climate change, a need for greater resilience in the face of more frequent extreme weather events, a dearth of affordable housing, and flat or declining construction productivity. The Advanced Building Construction Collaborative has identified a distinct need for accessible guidance that supports the scaling of zero-carbon retrofit and new construction solutions in housing.

Avoiding the worst effects of climate change will require rapid transformations in the way new buildings are constructed and existing buildings are retrofitted. In both cases, the objective must be “zero-carbon-aligned” (ZCA) buildings — a term that encompasses energy efficiency and a concerted phaseout of all fossil fuel appliances and equipment, among other measures (see Exhibit ES1). To get the United States on track to decarbonize the building stock before 2050, in line with global climate goals, virtually all new construction must be ZCA by 2030. At the same time, the United States has a shortage of an estimated 3.8 million homes today and may need in excess of 14 million new homes over the next 10 years while contending with a challenging labor market.

Exhibit ES1. Attributes of zero-carbon-aligned (ZCA) buildings



Among existing residential buildings in the continental United States, representing some 125 million housing units, our analysis shows that around 40 million units — about a third of the existing residential building stock — will require only an appliance and mechanical system swap-out to become ZCA. Around 42 million — roughly another third of the stock — will require a modest level of envelope improvement in addition to equipment swap-outs. Around 32 million units — roughly a quarter of the stock — will require deeper envelope interventions in addition to equipment swap-outs to be ZCA. (About 10 million units, or some 8% of the stock, is sufficiently ZCA that it need not be prioritized for retrofit.) The retrofit interventions suggested here can be considered minimum levels necessary to reach zero-carbon alignment. Deeper energy retrofits beyond the retrofit intervention assignments outlined in this report may offer additional benefits in terms of resilience, reduced burden to the electrical grid, and other non-energy benefits. Given current rates of whole-building ZCA retrofits (likely well below 1% of the total stock per year[i]) and the finding that nearly 60% of the stock will need to undergo a retrofit that includes envelope upgrades, industry must increase the annual volume of these retrofits at least severalfold, reaching annual rates of around 3% by the end of the decade to deliver a decarbonized residential building stock by 2050.

Meeting this unprecedented challenge will therefore require massive increases in ZCA retrofits and new construction in this decade. It is difficult to imagine achieving this transformation without substantial changes in how buildings are constructed and retrofitted, especially given labor availability, productivity trends in construction, and the necessary number and pace of projects.

Advanced building construction (ABC) can accelerate the deployment of ZCA retrofits and new construction to help meet this challenge. Broadly, ABC refers to streamlined, scalable industrialized construction approaches to building decarbonization.[ii] ABC encompasses solutions achieving much-needed process efficiencies and rapid deployment speed at a reasonable cost, which can help scale ZCA new construction and retrofits to meet the challenge of decarbonizing the built environment before 2050. The concept of ABC stems from the thesis that effectively decarbonizing the existing and future US building stock will in part require systematically modernizing construction practices and technologies (as well as the business models that deploy them). This report posits that suitable guidance will drive increased development and deployment of innovative building decarbonization solutions, including ABC.

This report provides technical performance guidance and estimated cost targets for new construction and retrofit packages for a priority set of residential building segments, backed by research and analysis. For new construction, where many voluntary building performance programs exist, we identify market trends in terms of regulation, volume, and costs. For the retrofit market, we assign specific ZCA retrofit packages to existing building segments. We then prioritize segments by geography and building type to provide estimates of the market size for whole-building retrofits.

New Construction Market

The need for total building decarbonization requires that new construction quickly shift to designs, materials, equipment, and construction practices that support zero-carbon goals. Residential buildings are designed to have long life spans, and between 2023 and 2050, 32 million new homes are projected to be built. More than 9 million of those are expected by 2030 — a substantial demand that could be met with ZCA construction (Exhibit ES3).

Building energy codes are moving toward zero-carbon alignment. For example, the 2021 International Energy Conservation Code (IECC) includes Solar-Ready and Zero Energy provisions that may be adopted by states or local jurisdictions. In California, all new single-family and small multifamily construction since 2020 must have solar and be designed to achieve net-zero energy (with solar plus storage required for commercial buildings since 2023), and Washington State passed the first state-level mandate requiring heat pumps for space heating/cooling and water heating in residential buildings. However, at a national level, the market is not yet moving at the necessary pace.

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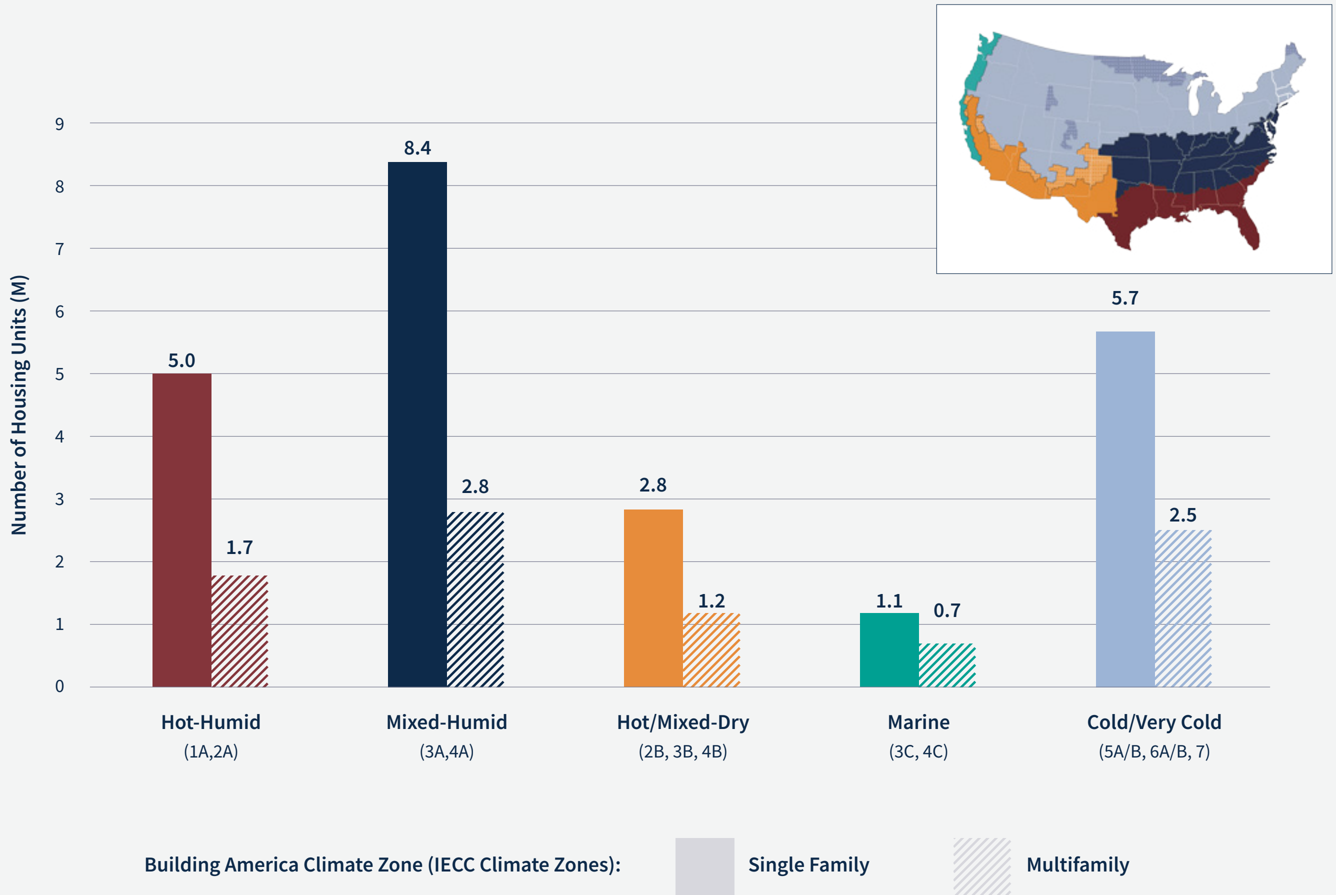
i. Reasonable estimates provide an annual rate of less than 1% for energy retrofits — a figure not limited to decarbonization or whole-building retrofits, which therefore may have an even lower rate. See for instance the Buildings section of the IEA's *Sustainable Recovery* report at **https://www.iea.org/reports/sustainable-recovery/buildings** and the *Global Alliance for Buildings and Construction's Global Roadmap towards Low-GHG and Resilient Buildings* at **https://globalabc.org/sites/default/files/2020-03/GABC_Global_Roadmap_Website.pdf**.

ii. "Industrialized construction" refers to the application of modern manufacturing and installation practices to optimize construction. These practices can include prefabrication, standardized or repeatable elements, automation, digital tools, and integrated workflows.

Exhibit ES2. Projected Residential New Construction (New and Replacement), 2023–2050



Source: Annual Energy Outlook 2022 projections distributed using Pacific Northwest National Laboratory weighting factors

Several voluntary building performance programs and standards — including ENERGY STAR, Zero Energy Ready Homes (ZERH), and Phius — support ZCA new construction with cost-effectiveness in mind (Exhibit ES3). These programs have provided builders with targets and technical assistance to construct energy-efficient homes and achieve certifications that help consumers easily identify more efficient homes. In addition, several state and utility efficiency programs provide monetary incentives to offset incremental costs of construction, and the Inflation Reduction Act of 2022 (IRA) provides for incentives in the form of rebates and tax credits for new homes certified to meet ENERGY STAR (a $2,500 credit for single-family homes and $500 credit per multifamily unit) and ZERH (up to a $5,000 credit for single-family homes and per multifamily unit) efficiency levels.

Industrialized construction approaches, though used in a small percentage of the new construction market today, can help accelerate the pace of new ZCA construction while reducing construction waste and deployment timelines.

Homes built following passive house principles typically reduce energy use by 40%–60% compared with baseline construction. A growing body of industry data suggests that, in some multifamily markets, buildings built to related standards, such as Phius and PHI, can be consistently completed at or near cost levels of equivalent code-minimum buildings. For example, 2018 cost data from affordable multifamily housing projects in Pennsylvania shows that, with experience and good design, new buildings meeting passive house standards can even be built at lower cost than conventional construction (Exhibit ES4). Similarly, average incremental costs from 2017–2018 for high-performance construction through the Massachusetts Clean Energy Center Passive House Design Challenge were minimal (2.3% before incentives) compared with building to code.

Exhibit ES3. Voluntary Building Performance Certification Programs Overview

The Path to Zero-Carbon Aligned* (ZCA) New Buildings

START +	CHOOSE +	CONSIDER	VERIFY
with high-performance building design and construction	high-efficiency electric equipment over on-site combustion	decarbonization of other elements (note: ZCA buildings have future carbon-neutral energy supply)[a]	

Voluntary Programs	Minimum Technical Requirements					Offsets		Compliance Verification	
	Co-Requisite Certifications	Above Code Design & Construction	Ultra-Low Load Design & Construction	Electric Ready	No On-Site Combustion	Renewable Energy Offsets[b]	Value Chain Carbon Emissions Offsets[c]	On-Site Inspection	Performance Verification
ENERGY STAR v3.2	-	✓○	●	○	○			✓	●
ENERGY STAR Next Gen	ENERGY STAR v3.2	✓○	●	✓○[d]	○			✓	●
DOE ZERH v2.0	ENERGY STAR v3.2 Indoor airPLUS	✓○	●	✓○[e]	○			✓	●
PHIUS CORE	ENERGY STAR v3.2 ZERH v2.0 Indoor airPLUS	✓○	✓	✓○	✓○[f]			✓	●
PHIUS ZERO	ENERGY STAR v3.2 ZERH v2.0 Indoor airPLUS	✓○	✓	✓○	✓○	✓[g]		✓	●
LEED Zero Energy	ENERGY STAR v3.2 LEED BD+C	✓○	●	○	○	✓		✓	✓
LEED Zero Carbon	ENERGY STAR v3.2 LEED BD+C	✓○	●	○	○	✓	✓	✓	✓
ILFI Zero Energy	-	✓○	●	✓○	✓○	✓		●	✓
ILFI Zero Carbon	-	✓○	●	✓○	✓○	✓	✓	●	✓

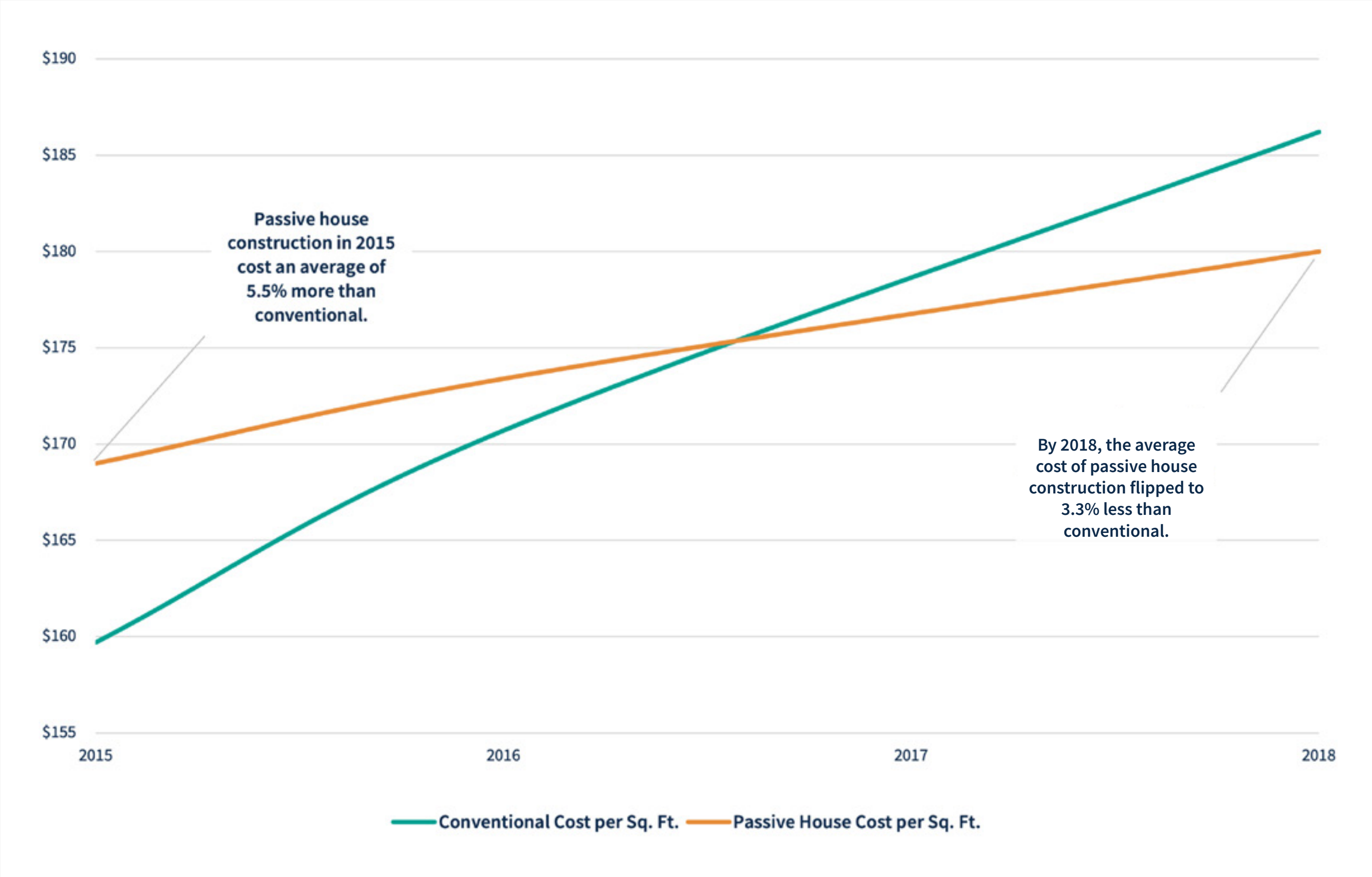
Table Legend ✓ Required for program certification ○ Element of zero-carbon alignment ● Additional industry best practice

***Zero-Carbon Aligned (ZCA):** No on-site fossil fuel use, low power and thermal loads, obtains all energy from a carbon-neutral grid and/or carbon-neutral local resources currently or before 2050 under a planned scenario, and reduces impact on the grid through peak and general demand reduction and grid interactivity (or, alternatively, through off-grid operation), with the aim of a decarbonized US building stock before 2050.

a) Zero-carbon alignment includes energy supply coming from a carbon-neutral source currently or before 2050 under a planned scenario. If energy supply is not carbon-neutral currently, building may consider offsets to mitigate impact while supply decarbonizes.
b) Renewable energy offsets - program requirements vary with respect to on-site energy generation vs. allowances for off-site generation or credits.
c) Value chain (Scope 3) carbon emissions offsets - LEED requires offsets for transportation emissions, ILFI requires offsets for embodied carbon emissions (A1-A5).
d) ENERGY STAR Next Gen requires: all primary heating, cooling and water heating be supplied by heat pump technology; induction cooking; and EV charging infrastructure.
e) ZERH requires solar readiness.
f) On-site combustion only allowable under PHIUS CORE Performance compliance path.
g) Renewable energy can be used to meet the net source energy criterion but is not required.

Exhibit ES4.

Comparative Cost of Low-Income Affordable Multifamily Passive House and Conventional Construction in Pennsylvania



Note: Data represents multifamily construction that qualified for Low-Income Housing Tax Credits (LIHTC); Pennsylvania did not award the LIHTC in 2017.

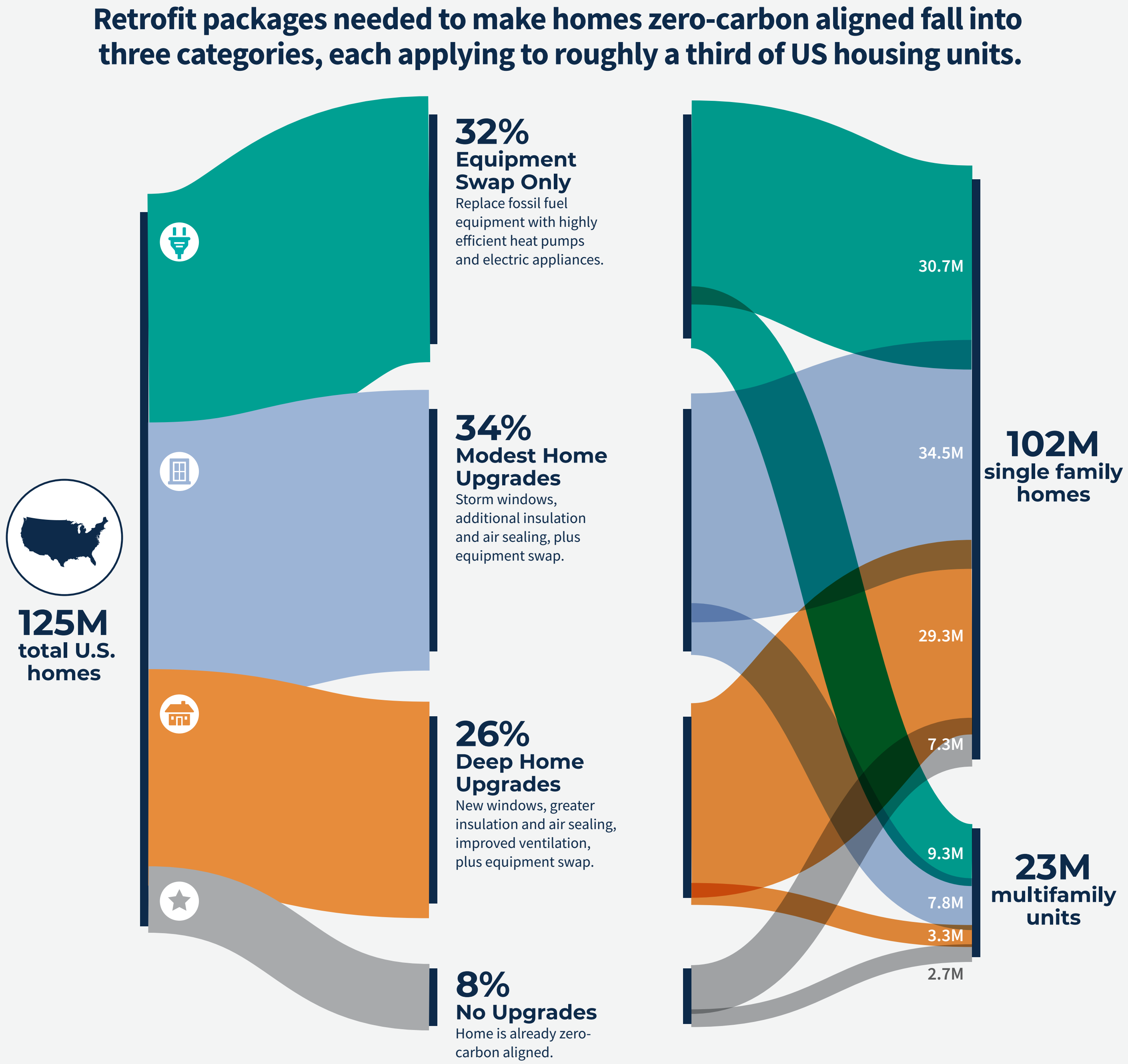
Source: "How a PA Affordable Housing Agency Is Making Ultra-Efficient Buildings Mainstream," Pittsburgh Post-Gazette, December 31, 2018; Pennsylvania Housing Finance Agency

Retrofit Market

This report incorporates several data sources from both existing, published reports as well as from original analyses to develop retrofit guidance for the residential building stock. This report includes suggested upgrade packages and performance levels, in addition to estimated cost targets for priority market segments. Together, these results aim to inform the building retrofit industry of the types of building retrofits that are projected to make homes ZCA across different geographies and building types. They also aim to provide highly granular data that can assist industry actors in developing replicable retrofit solutions at costs that ensure broad uptake in the market.

For each single-family and multifamily housing segment across the US building stock, we assign a retrofit performance level that our analysis indicates is the necessary minimum for a building in that segment to become ZCA. Exhibits ES4 and ES5 presents the results of our upgrade package assignment analysis.

Exhibit ES5. Summary of distribution of residential retrofit packages for zero-carbon alignment



We estimate that a sizable share of the existing US housing stock can become ZCA without the need for extensive envelope upgrades. Around 40 million housing units (about 32% of the residential building stock) can become ZCA by swapping out appliances for more efficient versions and replacing building mechanical systems with best-in-class, high-performance heat pumps — full electrification without parallel envelope improvements. A further 10 million units (8% of the stock) are already at a performance level consistent with zero-carbon alignment as defined in this report. However, it is worth noting that additional efficiency beyond these levels can provide a range of benefits to both the building and the electrical grid in terms of resilience and reduced electrical loads.

Around 42 million housing units (about 34% of the stock) can become ZCA if they also undertake modest wall and window improvements (what we refer to as "conventional" envelope upgrades in this report). The remaining 35 million or so housing units (about 26% of the residential building stock) require a deeper or higher-performance retrofit to become ZCA, according to our analysis (i.e., retrofits aligned with current model code or beyond-code performance levels). Of these segments of the stock requiring deeper retrofits, the vast majority are single-family or smaller multifamily homes (totaling around 29 million housing units); a much smaller share are larger multifamily buildings (totaling around 3.3 million housing units), although this latter segment may be well suited for the early deployment and scaling of industrialized retrofits.

In total, we estimate about 60% of the housing stock (around 75 million housing units covering more than 125 billion square feet of building floor area) requires upgrades to building envelope components in addition to replacing equipment and major appliances. As ABC innovations are particularly suited to improving the speed and scale of deploying these types of whole-building retrofits — for which current approaches are overly complex, disruptive, lengthy, and costly — these 75 million housing units represent a massive market opportunity for ABC innovations to improve the design and delivery of such retrofits.

Exhibit ES6. Total Number of Housing Units and Percentage of Stock Assigned Each Upgrade Package by Building Type

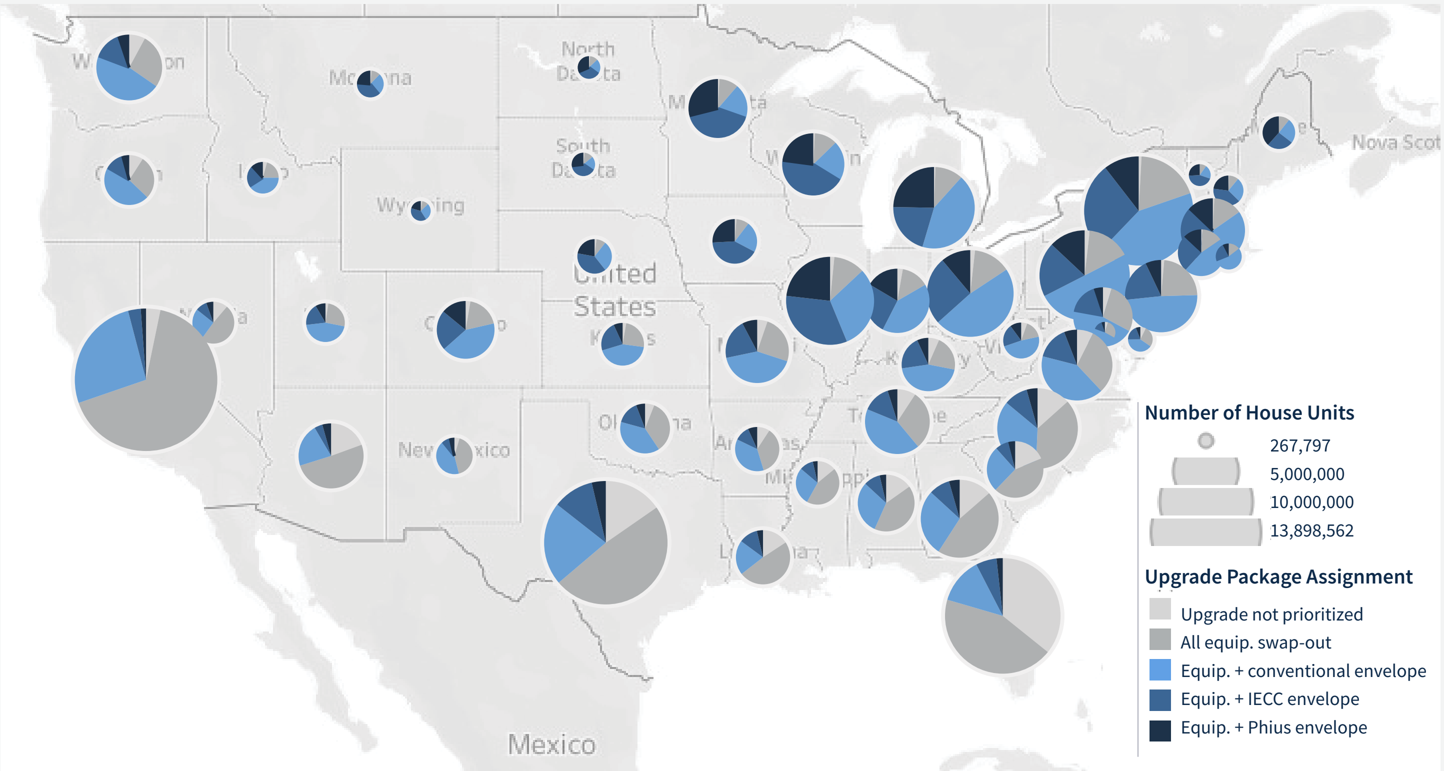
Building Type	Prioritized Upgrade Package	Number of Housing Units (million)	Share of Stock
Single-family/small multifamily • Single-family detached • Single-family attached • Multifamily, 2–4 units	Upgrade not prioritized	7.3	7%
	All equipment swap-out	30.7	30%
	Equipment + conventional envelope	34.4	34%
	Equipment + IECC envelope	18.8	19%
	Equipment + Phius envelope	10.4	10%
Large multifamily housing • Multifamily, 5+ units, 1–3 stories • Multifamily, 5+ units, 4–7 stories • Multifamily, 5+ units, 8+ stories	Upgrade not prioritized	2.7	12%
	All equipment swap-out	9.3	40%
	Equipment + conventional envelope	7.8	34%
	Equipment + IECC envelope	2.6	11%
	Equipment + Phius envelope	0.7	3%

Note: See Exhibit XX for the assumed performance parameters and equipment upgrades that define each upgrade package.

To assist industry in meeting this enormous and challenging opportunity, the retrofit guidance in this report further identifies building upgrade needs by state and climate region while also aggregating buildings across similar types and characteristics. This data can facilitate the development of replicable retrofit solutions meeting given performance levels to scale the use of ABC approaches in delivering whole-building retrofits.

Exhibit ES7 presents a state-by-state breakdown of retrofit package assignments, indicating both the size of the existing building stock across states as well as highlighting the regional markets where a larger proportion of deeper building retrofits inclusive of envelope upgrades is necessary to achieve zero-carbon alignment. The state map can provide insight into regional trends in retrofit needs, such as the finding that cold climate regions covering the Midwest and Northeast regions of the United States represent a market that is especially in need of the types of building retrofits that ABC approaches can help deliver less disruptively at greater speed and reduced costs.

Exhibit ES7. Upgrade Package Assignment for All Residential Buildings by State



Source: **ABC Market Guidance for Zero-carbon Aligned Residential Buildings** by NREL Building Stock Analysis.

To provide more granular information to industry actors, the retrofit section of the report aggregates buildings by key characteristics that will influence the design and replicability of whole-building retrofit solutions and then ranks these by climate region. For example, our analysis identifies mid-century (1940–1979) single-family detached homes that heat with natural gas and are located in cold climates as one such high-priority market for retrofit packages meeting the "conventional envelope" performance specifications (totaling around 1.5 million housing units). Similarly, we find that newer, mid-rise (one- to three-story) multifamily buildings that heat with electricity are another high-priority market for "conventional envelope" packages (with around 290,000 housing units meeting these characteristics). We provide similar statistics for all climate regions (while also identifying priority segments that are assigned the higher "IECC" or "Phius" performance levels).

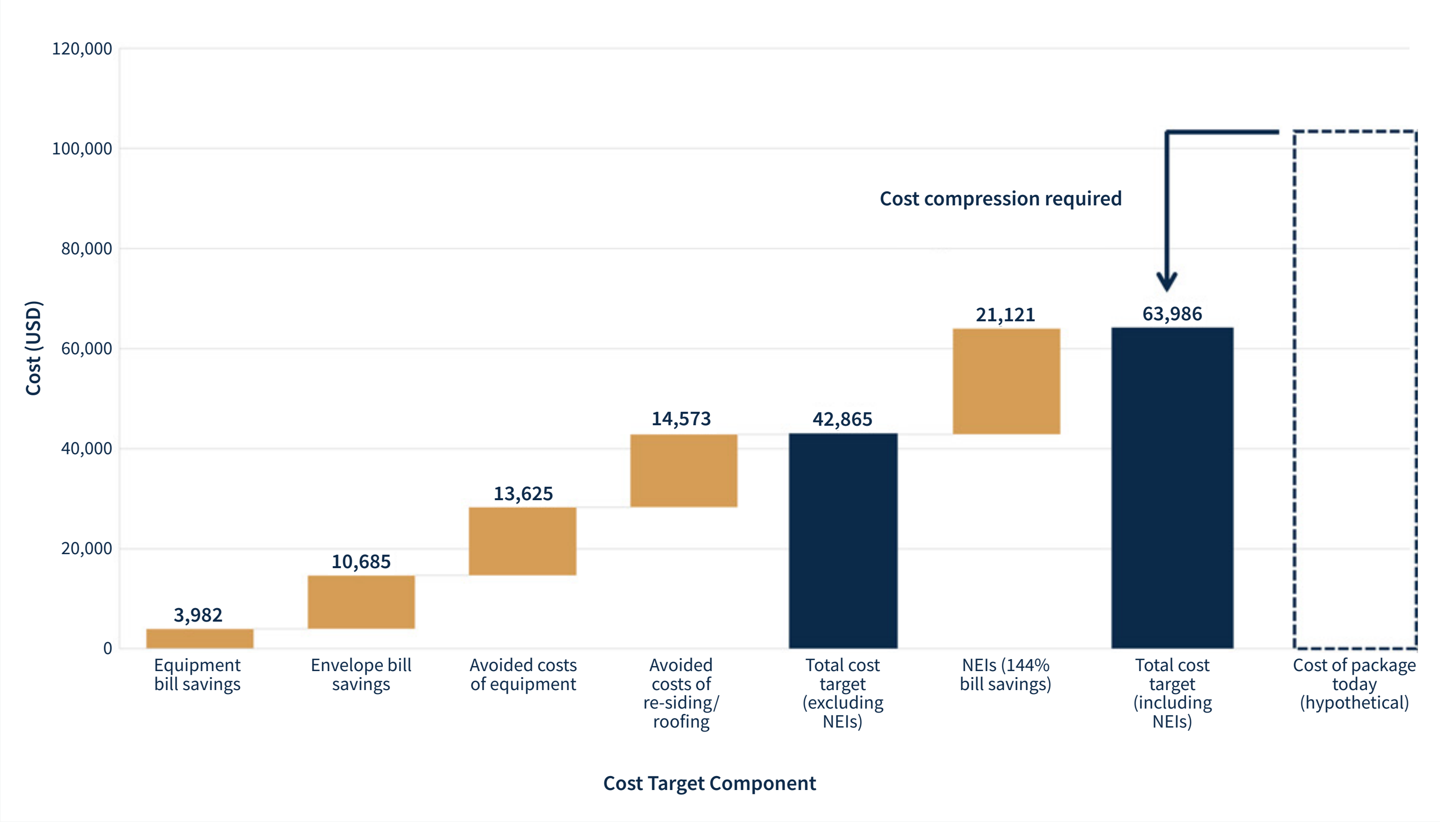
A key takeaway from our analysis is that, in most regions, the largest segments of the building stock can achieve zero-carbon alignment without retrofitting to the highest performance levels we assessed (though higher efficiency may provide additional benefits). This finding should guide industry to focus on innovations that can accelerate deployment of market-ready technologies to those segments of the building stock in the near term. This can provide opportunities to test and scale ABC approaches to delivering these types of retrofits while also providing more time for research, development, and demonstration of solutions conforming to the highest-performance upgrade packages, which may not be cost-effective or, in some cases, practical today.

A final contribution of the retrofit section of this report is the development of cost targets for the priority market segments and performance upgrades in our analysis. These aggressive but realistic installed cost targets are calculated such that the entire retrofit package is cost-neutral over its lifetime on a present-value basis. The cost targets incorporate estimated values of utility bill savings, approximate values of non-energy impacts (NEIs), and avoided business-as-usual building renovation costs. Exhibit ES7 shows an illustrative diagram that breaks down the cost target for the "equipment + IECC envelope" package, inclusive of these elements.

While energy savings resulting from equipment replacements and envelope upgrades will generate real savings for building owners, other value streams, such as those resulting from NEIs, are less often measured or accurately monetized in building retrofit projects. NEIs include factors such as occupant health and safety, reductions in building maintenance needs, and other related benefits to participants. Our approach to including NEIs in the estimated cost targets is conservative in that we only include the value of NEIs to building owners or occupants rather than those that accrue to other energy system actors (e.g., utilities) or to society more broadly. Even when taking this conservative approach, it is clear that the value of these benefits is substantial; finding real ways to monetize this value stream is essential for broad deployment of high-performance retrofits.

Very little data is available today on the costs of the deepest retrofit packages, given how rarely these types of projects have been undertaken historically, but what limited cost data is available suggests these retrofit projects will require substantial cost compression in addition to effective monetization of additional value streams from NEIs in order to be cost-neutral over their lifetimes. In the retrofit section of the report, we identify and describe several levers for cost compression, including technology and process improvements, policy mechanisms, learning or experience among solutions providers, and business model innovation. Preliminary evidence from the industrialized construction industry shows promise for reducing costs along many of these lines; furthermore, the history-making IRA provides for a substantial influx of capital for whole-building retrofits, as does the Bipartisan Infrastructure Law (BIL). In the retrofit section of the report, we discuss the most promising cost compression opportunities across these categories and indicate how ABC approaches can help realize them in the retrofit market.

Exhibit ES8. Illustrative Cost Targets for the “Equipment + IECC Envelope” Package for Single-Family Homes



Note: NEIs, or non-energy impacts, are discussed in the body of the report and discussed in Appendix A2.

Conclusion

This report offers information on priority markets, performance levels, and target costs for ZCA new construction and retrofits. But there is still a great need for broader availability of specific physical solutions — such as construction products and assemblies — that can achieve ZCA performance levels or higher. Similarly, there is a need for innovations beyond the immediate scope of this report: business models that can deploy these physical solutions at scale and enabling financial and technical tools. Industry must play an important role in filling these needs.

With the market opportunity increasingly clear, existing and emergent manufacturers, fabricators, and other supply-side actors can apply and build on the guidance in this report to develop, refine, or further invest in much-needed repeatable ZCA physical solutions appropriate for key market segments and major typological tranches.

Providers that deliver these physical solutions — whether vertically integrated or separate contractors — can use insights from this report to prioritize their creation or acquisition of project pipelines. Taking this view, providers have an opportunity to deploy innovative business models that capitalize on the shortcomings of traditional approaches to construction, which deal with individual projects in isolation and take a narrow treatment of benefits and risks. Business models built on expanded concepts of value, repeatability in procuring both projects and the products used in them, and continuous improvement of execution processes are key to scaling ZCA new construction and retrofits.

These physical solutions and business models will benefit from enabling tools such as financial, insurance, and software products that are built for integrative projects at speed and scale and eschew arbitrary barriers born of convention — too often a challenge in these areas.

Any market will develop more robustly with clear demand signals. It is incumbent upon demand-side stakeholders like real estate owners, operators, and developers to recognize and act on the fact that the future of the buildings sector necessarily lies in zero-carbon alignment — and that this shift will yield benefits beyond utility savings and even emissions reductions. In residential buildings, many of these benefits can especially improve the lives of disadvantaged or vulnerable community members. This future must be embraced broadly and rapidly, with ABC as part of the way forward. Demand-side stakeholders have a critical role to play in bringing a holistic lens to their construction pipelines and building portfolios — something this report seeks to support — and cooperatively engaging with forward-looking supply-side providers to apply ZCA solutions.

Beyond industry, public-sector stakeholders can consider using the technical information in this report to inform decision-making around building performance requirements and the allocation of resources relating to the building stock.

Given the magnitude of the task ahead, there is an opportunity for virtually all types of buildings sector stakeholders to participate in and prosper as part of a suitably rapid transition toward zero-carbon alignment, but an uncommon degree of foresight, innovation, and collaboration will be essential to success.


Photo credit: Module Housing

1. Introduction

1.1 Motivation

The US buildings sector faces a confluence of challenges, including a clear necessity to decarbonize the built environment to mitigate climate change,[1] a need for greater resilience in the face of more frequent extreme weather events, a dearth of affordable housing, and flat or declining construction productivity that hinders the sector's ability to adapt.[2] Better data and guidance on new and existing residential buildings can outline paths forward for the market. These can help clarify stakeholder priorities and highlight applications for new (or newly relevant) technologies and approaches that have the potential to break traditional barriers, bridge technical gaps, reduce costs, create added value, and enable decarbonization of the national building stock.

Decarbonizing the national building stock before 2050 will require massive increases in zero-carbon retrofits and new construction in this decade. By 2030, the rate of residential net-zero carbon retrofits must likely reach more than 3 million units[i] annually (a severalfold escalation in retrofit activity), and virtually all new construction will need to be zero carbon.[3] It is difficult to imagine achieving this transformation without substantial changes in how buildings are constructed and retrofitted.

Whether the necessary market transformation occurs depends on the constructive participation of a wide range of emergent and incumbent organizations in the private and public spheres. The Advanced Building Construction Collaborative has identified a distinct need for accessible guidance on zero-carbon retrofit and new construction solutions in housing. This need comes from stakeholders' desire to ease their initial decision-making and prioritization in the context of high-performance new construction and retrofits.

This desire for clear guidance stems in part from jurisdictional actions that have increased demand for decarbonized buildings. Jurisdictions in many parts of the country are adopting goals and policies aimed at supporting electrification, high-efficiency building technologies, renewable energy generation, and energy storage. In some cases, jurisdictions have mandated that building owners and developers reduce carbon emissions, creating additional motivation for stakeholders to seek out or provide building decarbonization solutions.[ii]

This report provides technical guidance, backed by research and analysis, on new construction and retrofit approaches for supply-side and demand-side stakeholders. (Public-sector stakeholders may find the information useful, as well.) The guidance also covers segment prioritization to help stakeholders optimize where concerted innovation is supported and deployed. This report posits that suitable guidance will drive increased development and deployment of innovative building decarbonization solutions.

i. This estimate is calculated by taking our finding that about 115 million existing units require a retrofit to become ZCA, minus some allowance for units retrofitted before 2030 or taken out of service before 2050, and spreading this across the 20 years from 2030 to 2050.

ii. For example, the City of New York's Local Law 97 places a progressively stringent limit on carbon emissions for large buildings (greater than 25,000 square feet). See: https://www1.nyc.gov/site/sustainablebuildings/ll97/local-law-97.page. Similarly, the City of Boston's Building Energy Disclosure Ordinance (BERDO) requires residential buildings with 15 or more units to disclose and reduce energy and water usage over time; BERDO will hold them to emissions standards beginning in 2031. See: https://www.boston.gov/departments/environment/building-emissions-reduction-and-disclosure. In Washington State, policymakers adopted a revised energy code that requires electric heat pump heating, cooling, and water heating technologies in most new commercial, multifamily, and residential buildings; originally slated to go into effect in July 2023, the revised building energy codes will go into effect in March 2024. See: https://sbcc.wa.gov/state-codes-regulations-guidelines/state-building-code/energy-code.

1.2 Industrialized Construction and the ABC Thesis for Residential Decarbonization

The United States has a shortage of an estimated 3.8 million homes,[i] and it may need in excess of 14 million new homes over the next 10 years.[4] This new construction activity will contend with a challenging labor market and must avoid exacerbating the climate impact of buildings. Moreover, the United States has around 144 million existing dwelling units,[5,ii] most of which will require some retrofit intervention to meet climate targets. This monumental volume of work could effectively support a substantial retrofit subindustry within construction.

Advanced building construction (ABC) can deliver much-needed improvements to the US housing market. ABC refers to technologies, packages, and techniques for new construction or retrofits that support energy-efficient building decarbonization and that employ (or are compatible with) streamlined industrialized construction methods.[iii] By employing high-performance building technologies and industrialized construction techniques, while leveraging novel business models and aggregated demand, the residential construction industry can deliver high-efficiency, cost-effective, all-electric, and zero-carbon new and retrofitted homes. What is more, the industry can deliver these results across housing segments, at scale, with streamlined delivery and consistent quality. (See the Zero-Carbon-Aligned (ZCA) Buildings section for a discussion of the zero-carbon concept used here.)

The concept of ABC stems from the thesis that — given labor availability, productivity trends in construction, and the necessary number and pace of projects — decarbonizing the existing and future US building stock will require modernizing the construction industry with industrialized construction approaches that incorporate energy-efficient decarbonization.[iiii] Further, industrialized construction methods have shown the potential to lower costs, shorten schedules, improve budget and schedule certainty, increase quality, reduce waste and embodied carbon, improve worker safety, and reduce disruption around the construction site.[6]

Industrialized construction may be particularly well suited to residential buildings. Residential configurations and uses of space are often broadly similar within building typologies, allowing for the consistent designs, components, and practices that make industrialized construction most effective.[7] Given the great need for capacity to deliver both new construction and retrofit projects — while acknowledging that the demand for each can fluctuate — manufacturers of industrialized construction components and assemblies may consider establishing flexible designs and lines. Although manufacturers typically seek the efficiencies afforded by long production runs of fairly consistent outputs, this flexibility could allow manufacturers to switch between new construction and retrofit products as demand for each shifts on a longer timescale with macroeconomic (or local and regional market) trends, drawing additional benefit from up-front investments and reducing volatility in their business.

In short, ABC can clearly be part of the answer to the manifold problems facing the buildings sector. This change in paradigm represents an opportunity to apply integrative design not only to new construction and retrofit projects,[iv] but also to holistic ABC-supportive market interventions. These interventions can stimulate a vibrant, modernized construction industry and buildings sector that delivers broad benefits for the domestic economy and many of the nation's 130 million households.

1.3 Zero-Carbon-Aligned (ZCA) Buildings

Various terms describe high-performance buildings, including net-zero energy and net-zero carbon, and each of these various terms can be useful in different contexts. This report's guidance specifically supports the concept of "zero-carbon-aligned" (ZCA) buildings.[v] This term is intended to be both technology- and standard-agnostic, indicating that a building is compatible with a decarbonized building stock. A ZCA building:

- Has no on-site fossil fuel use (generally meaning all end uses are electrified[vi])
- Eases the decarbonization of its end uses by having low power and thermal loads that do not require substantial electrical or mechanical infrastructure, while considering added benefits, such as comfort and resilience

i. The situation is even more dire for extremely low-income renters, who face a shortage of some 7 million affordable and available homes. See: **https://nlihc.org/sites/default/files/gap/Gap-Report_2022.pdf**.

ii. This total, somewhat larger than the total number of units covered in our retrofit analysis dataset, represents the 50 US states plus the District of Columbia and includes nonpermanent housing, such as "mobile home[s]." See: **https://www.census.gov/quickfacts/fact/note/US/HSG010222**.

iii. "Industrialized construction" refers to the application of modern manufacturing and installation practices to optimize construction. These practices often include prefabrication, standardized or repeatable elements, automation, digital tools, and integrated workflows.

iiii. Note that there is a risk in pursuing maximized performance of individual projects at the expense of pace and scalability (resulting in very high-performance buildings but at insufficient volumes) or in pursuing industrialization of the construction industry without intentionally including energy-efficient decarbonization (resulting in accelerated construction activity that worsens the climate impact of the buildings sector).

iv. For a primer on integrative design, see RMI's report *Integrative Design: A Disruptive Source of Expanding Returns to Investments in Energy Efficiency*, **https://rmi.org/insight/integrative-design-a-disruptive-source-of-expanding-returns-to-investments-in-energy-efficiency/**.

v. The concept of ZCA buildings is similar to "zero-carbon-ready buildings" (ZCRB) as described by the IEA in *Technology and Innovation Pathways for Zero-Carbon-Ready Buildings* by 2030, h**ttps://www.iea.org/reports/technology-and-innovation-pathways-for-zero-carbon-ready-buildings-by-2030**. The federal government's forthcoming definition of "zero-emissions" buildings as announced on September 28, 2023, is largely consistent in principle with the ZCA concept described here, but it requires that a building use carbon-neutral electricity currently (rather than under an expected future scenario). Zero-carbon alignment can be seen as a precursor to becoming a zero-emissions building, with the transition happening automatically as the grid (or other energy supply) that serves a ZCA building decarbonizes.

vi. Narrow exceptions to the typical case of electrification could include, for example, the use of responsibly sourced renewable biomass as fuel.

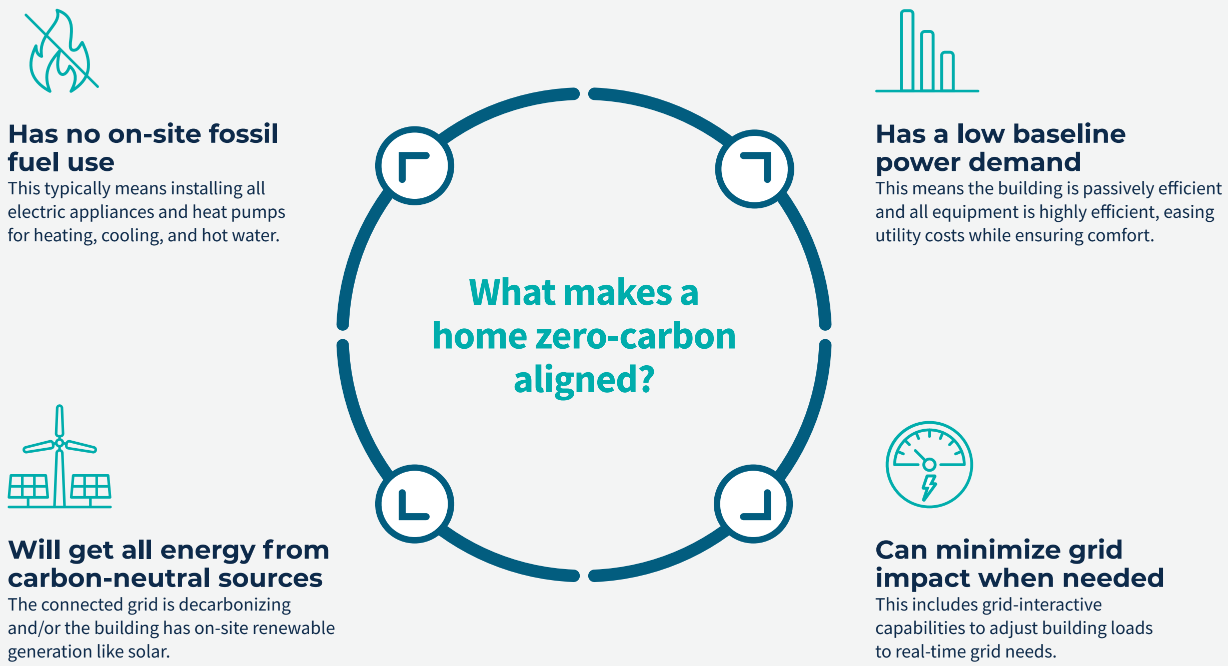
- Sources — or will source before 2050 under a reasonable targeted scenario[i]— all energy from a carbon-neutral grid and/or carbon-neutral local resources (such as roof-mounted solar photovoltaics or other on-site renewable energy generation)
- Supports decarbonization of the grid by minimizing its grid impact through peak and general demand reduction and grid interactivity or, alternatively, through off-grid operation

In short, if all US buildings are built or retrofitted to be ZCA before 2050 and the assumed grid scenario is achieved, the US building stock can be considered decarbonized in terms of operational emissions (Scope 1 and 2, as defined by the US Environmental Protection Agency, or EPA).[ii]

Embodied and supply chain carbon emissions (Scope 3, per the EPA) associated with buildings must be considered in parallel with operational emissions and minimized. In new construction especially, the embodied carbon footprint can represent a substantial portion of a building's lifetime emissions. In retrofits, specific measures and designs that decrease the operational carbon emissions of a building can be evaluated for their combined (net) embodied and operational carbon contribution. Such changes should not be implemented if their overall emissions profile is unfavorable (i.e., if operational savings do not significantly outweigh embodied carbon). Given the typical embodied carbon penalty of replacing existing buildings rather than retrofitting them, retrofitting structurally sound buildings may often be preferable, especially if the most carbon-intensive materials are avoided in the retrofit.

The performance guidance in this report does not prescribe the use of specific materials. However, materials and technologies with a lower embodied carbon profile that offer suitable performance should be considered when such alternatives are available. The *Embodied Carbon* section of this report and *Appendix D* provide further discussion on embodied carbon and a review of some common materials.[iii]

Exhibit 1. Attributes of zero-carbon-aligned (ZCA) buildings



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i. Perhaps the most salient of these scenarios is the Biden administration's goal of carbon pollution–free electricity by 2035, as outlined in Executive Order 14057 and the accompanying Federal Sustainability Plan. See: **https://www.sustainability.gov/federalsustainabilityplan/carbon.html**.

ii. See the EPA's "Scope 1 and Scope 2 Inventory Guidance" for a description of the scopes and a list of related guidance documents: **https://www.epa.gov/climateleadership/scope-1-and-scope-2-inventory-guidance**.

iii. Additional guidance on embodied carbon is available from a range of sources, including RMI's 2021 report *Reducing Embodied Carbon in Buildings* (**https://rmi.org/insight/reducing-embodied-carbon-in-buildings/**) and its 2023 report *Transforming Existing Buildings from Climate Liabilities to Climate Assets* (**https://rmi.org/insight/transforming-existing-buildings-from-climate-liabilities-to-climate-assets/**).

1.4 Purpose of This Report

This report builds on prior analytical work on ABC by the ABC Collaborative and national laboratories and synthesizes it for broader industry use. The intent of this research is to support industry actors in capitalizing on opportunities for innovative, scalable retrofits and new construction (including using ABC approaches) and in moving the market toward building decarbonization at the necessary pace and at reasonable cost. By employing innovative building technologies and industrialized construction methods while leveraging novel business models and aggregated demand among similar projects, ZCA buildings can become more compelling and attainable to pursue at scale.

Establishing clearly defined outcomes — like those presented in this report — can help the industry (and researchers) focus on what is needed to achieve those outcomes and develop technologies and services that deliver decarbonized buildings that are cost-effective and appealing.

The guidance in this report is intended to inform, simplify, and expedite early decision-making by industry stakeholders — both on the supply side (manufacturers, fabricators, contractors, and other providers) and the demand side (owners, developers, asset managers, and other real estate project sponsors). Further, it can serve as an informational input for public officials in policymaking, program development, planning, and prioritization, though it does not provide policy recommendations. This guidance is not meant to create additional standards for new construction, and it explicitly references and complements certain accepted standards (such as Phius and the US Department of Energy's Zero Energy Ready Homes Program).

For manufacturers, contractors, and other providers and building industry professionals (i.e., the "supply side"), this report provides data on the market opportunity for innovative products and services that can deliver ZCA buildings. The data is provided for the United States as a whole and for individual building-type segments and geographies, and it includes guidance on indicative performance levels. Potential supply-side use cases for this guidance include:[i]

- **Creating and justifying a product development and investment strategy** for specific building decarbonization innovations or whole-building packages, including ABC technologies and approaches[ii]
- **Making the business case** for aggressive participation in early projects to become established in a high-potential space and compete for a defined addressable market
- **Expanding beyond an existing focus** on a particular geography, market segment or building type, or technology area or technical innovation
- **Broadly laying out what will be required** to create competitive innovative building decarbonization solutions (with regard to performance and price) within a chosen building typology and climate region

For building owners, operators, and developers (i.e., the "demand side"), the guidance in this report can provide a ready understanding of performance levels prior to or as a starting point for predevelopment activities. This can build confidence in early decision-making without the need for express engineering or consulting. It can also allow for consideration of ABC or other innovations at the beginning of the design process, when it is easier and less costly to incorporate changes.[iii]

Potential demand-side use cases for this guidance include:

- **Understanding what an optimized set of retrofit improvements could look like** for prospective acquisitions when limited building information is available
- **Sketching out and prioritizing building decarbonization** target performance levels across a portfolio of existing buildings
- **Estimating the measures and reasonable cost** required to build a net-zero building or pipeline of buildings
- **Determining the volume of buildings** within a portfolio (or across collaborating portfolios) that could use a common solution package

This guidance is likely to be most useful at the business, pipeline, or program planning level and at the early project stage. It is assumed that a given project — particularly one that is larger or more complex — will require some degree of engineering. Even so, it is reasonable to anticipate that project-level energy engineering requirements will be reduced as solutions for common building types are developed, validated, and scaled, and as the market gains experience with ZCA projects — especially those that use ABC.

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i. Similarly, it can also help answer questions such as: How many similar buildings of a certain type — and for which the same solution package would substantially apply — exist or are likely to be built in a given geography? What energy- and carbon-reduction measures might they need? Where should I focus investment — geographically or on certain segments or typologies — on replicable products or packages and capacity? What approximate performance levels should I target? What approximate costs should my packages target for a given segment?

ii. See the 2023 ABC *Research Opportunities Report* for examples of ABC innovations: **https://www.pnnl.gov/projects/industrialized-construction-opportunities**.

iii. Similarly, it can also help answer questions such as: What optimized performance level should I aim for in retrofits of my existing buildings? Which buildings should I prioritize, and in what way? What approximate performance levels should my new buildings target, and what is the reasoning behind those levels? What kind of work would a net-zero commitment for a future development or acquisition pipeline entail? What are the cost ranges for new ZCA buildings compared to what I am used to? What might be a justifiable cost for a ZCA building or a whole-building ZCA retrofit package?

1.5 Scope of This Report

This report covers retrofit and new construction applications for virtually all residential building types, aside from manufactured housing.[i] The technical information focuses mainly on envelope and HVAC measures, while also covering basic appliances and lighting. Due to differing methodologies and data availability, as well as the inherent differences between known existing buildings and hypothetical new buildings, the retrofit analysis uses a more granular segmentation of building types. The term "guidance" as it is used in this report refers to the general sense of the word, not to specific guidance issued by government agencies or offices pursuant to legislation or regulation.

1.6 Incentives Supporting Building Decarbonization and ABC

The landscape of incentives is moving rapidly for high-performance new construction and retrofits, as well as for the manufacturing of related components and equipment. Increasingly, federal, state, local, and utility programs are offering incentives and support (such as tax credits; upstream, midstream, and downstream rebates; technical assistance; and grants) that may be relevant to building decarbonization activities, including ABC projects. The landmark Inflation Reduction Act of 2022 (IRA) contains several tax credits and rebates that can support ABC and other building energy efficiency and/or electrification projects and products.[8] Additionally, the Database of State Incentives for Renewables and Efficiency (DSIRE) provides a regularly updated summary of policies and incentives by state.[ii] In many markets and building segments, available incentives increase the attractiveness of pursuing ABC and other high-performance projects or developing and manufacturing ABC technologies. Because the availability and specifics of relevant incentives change frequently, this report does not provide an extensive summary of ABC-relevant incentives.[iii]

1.7 General Considerations and Assumptions

In much of this report, we use site energy consumption and energy savings as primary metrics for determining the appropriate performance levels for certain buildings and for providing performance guidance. We decided to use energy as the primary metric — rather than, say, cost or carbon savings — for several reasons, which we discuss in detail in *Appendix A1*. For example, the currently available data on installed costs for retrofits, construction costs for new builds, energy costs, and carbon emissions is highly dependent on factors such as location, fuel prices, and the grid decarbonization timeline. Furthermore, the cost data available today does not typically represent the types of industrialized construction techniques that characterizes ABC.

We do present cost and carbon savings results for the various packages modeled in this report, and we explicitly define our assumptions for those calculations. We also use energy cost savings as one element in calculating indicative cost targets. However, we do not use these for the primary task of determining an appropriate level of energy performance for the building segments in our analysis.
The transition from fossil fuels to electricity will, in many cases, add load to the electrical grid. Weighing building-level versus power system investments is beyond the scope of this report, but the guidance presented here is grounded in the reality that building and electricity decarbonization are inextricably tied. For instance, energy efficiency and demand flexibility in buildings will both decrease power system costs and aid in electricity system decarbonization by minimizing grid peaks and matching electricity demand to the availability of renewable energy on the grid.[9]

Electrification and energy efficiency improvements often yield additional benefits beyond reducing energy use, referred to as non-energy benefits (NEBs) or the more neutral "non-energy impacts" (NEIs). These impacts are important to identify and quantify, in part because the up-front or installed costs of building efficiency and electrification technologies are not always offset by near-term utility bill savings. In *Appendix A2*, we review the evidence for several NEIs that we consider most relevant and promising in the context of this market guidance, including occupant factors (e.g., health, comfort, and productivity), building or dwelling factors (e.g., resilience, durability, reduced maintenance, and increased building equity value), and community-level benefits (e.g., pollution reduction, community-scale public health benefits, and economic factors related to job growth and development).

i. Manufactured housing was included in the analysis of the existing building stock underlying the retrofit guidance but is not part of the priority market segments for retrofits. New construction guidance is not provided for manufactured housing in this report. The existing building stock data covers the continental United States.

ii. DSIRE (https://www.dsireusa.org/) is one of the most comprehensive sources of information on incentives and policies that support renewables and energy efficiency in the United States.

iii. The ABC Collaborative may periodically provide its Collaborator and Supporter organizations with current general information on ABC-relevant incentives and funding opportunities or support subsets of these organizations in identifying incentives for specific projects or technologies.

1.8 Market Opportunities Identified in Prior ABC Collaborative Work

This market guidance report builds on the ABC Collaborative's market insights report, *Market Opportunities and Challenges for Decarbonizing US Buildings*. That 2021 report synthesized and interpreted findings from primary and secondary market research conducted by the ABC Collaborative spanning the entire construction and real estate development value chain and considering the landscape of external market factors.[10] The work investigated systemic problems across the buildings sector, examined critical technologies and approaches, analyzed market segments and geographies, and summarized interviews with key industry stakeholders.

The market opportunities and challenges report provided a summary of existing market approaches and innovative technologies that can offer streamlined, high-quality, low-carbon solutions for new construction and building retrofits, as well as an evaluation of the most opportune geographies and market sectors for those innovations. Finally, the report provided a stakeholder needs assessment for the buildings sector to outline how to best support industry players, and it clearly articulated institutional and market barriers that must be overcome.

A key section of the market opportunities and challenges report as it relates to this market guidance report is its analysis that assesses and compares market opportunities across geographies and segments in the United States to help prioritize initial market investment. Here, a geographical analysis ranks states based on five metrics relating to opportunities for scaling and early market penetration: 1) energy-related emissions; 2) energy cost; 3) economic environment; 4) construction and buildings sector needs; and 5) policy environment. As shown in Exhibit 2, this analysis ranks states by compiled scores across these five categories, with the top five states being California, New York, Texas, Massachusetts, and Pennsylvania, respectively. See *Appendix A3* for an overview of the main sections of the market opportunities and challenges report.

Exhibit 2. State Prioritization Analysis Results

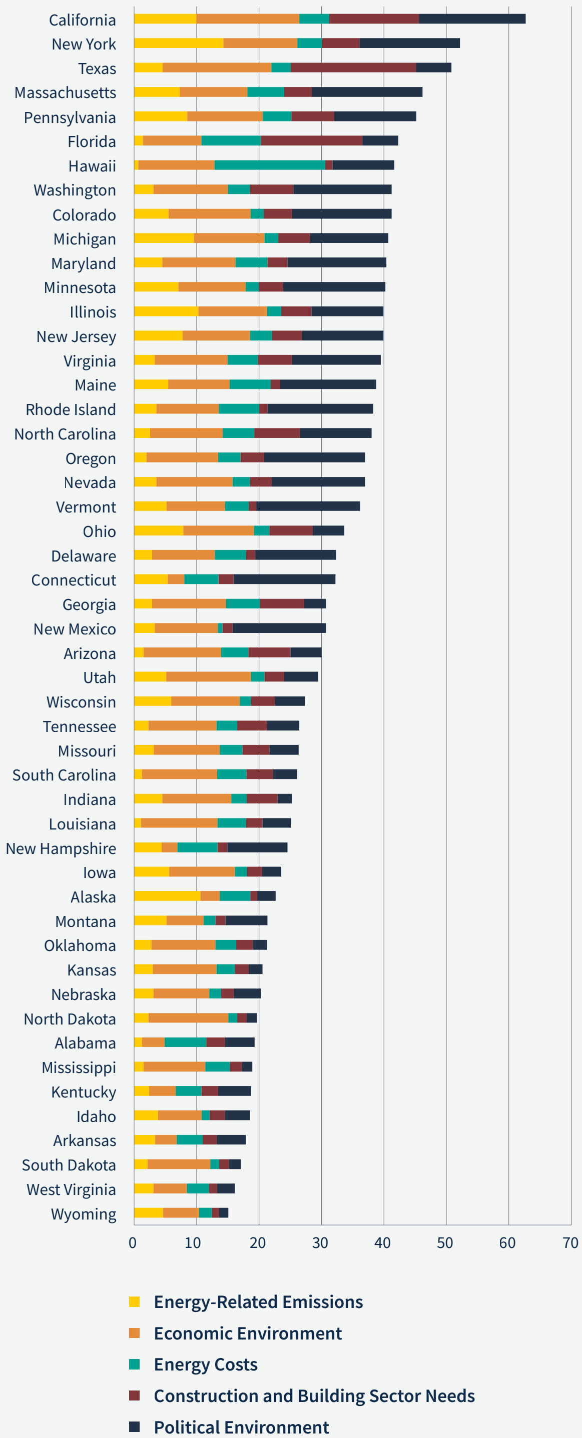



Photo credit: Onion Flats

2. New Construction

2.1 Introduction

The need for total building decarbonization requires that new construction quickly shift to designs, materials, equipment, and construction practices that support zero-carbon goals. Residential buildings are designed to have long life spans, with some buildings lasting for hundreds of years. ZCA design and construction should result in buildings that have low energy loads that can reasonably be offset with on- and/or off-site renewable energy generation and — until the grid becomes decarbonized — that can draw on grid energy at the times when it is cleanest.

As previously outlined, decarbonizing the future national residential building stock is only possible by modernizing the construction industry with ABC approaches that incorporate industrialized construction and energy-efficient decarbonization. Industrialized construction involves prefabricating components in a factory and assembling and installing them at a building site. Industrialized new construction includes volumetric modular construction, panelized construction, and additive manufacturing. Although there has been progress, ZCA new construction still only constitutes a small portion of new homes built, and an even smaller subset of those homes are built with industrialized ABC methods.

The new construction guidance in this report can help architects and builders transition from business-as-usual approaches to ZCA construction — and access existing programs that can support it. The case studies included in *Appendix B5* provide examples of pivoting business strategy from code-minimum construction to ZCA construction only, delivering ZCA buildings with little or no incremental cost, and projects that leverage ABC approaches. For business owners and entrepreneurs, the forecast for residential new construction by region indicates the scale of the emerging market opportunity for ZCA single-family and multifamily new construction. It also points to ways ABC can help meet the need and achieve climate goals.

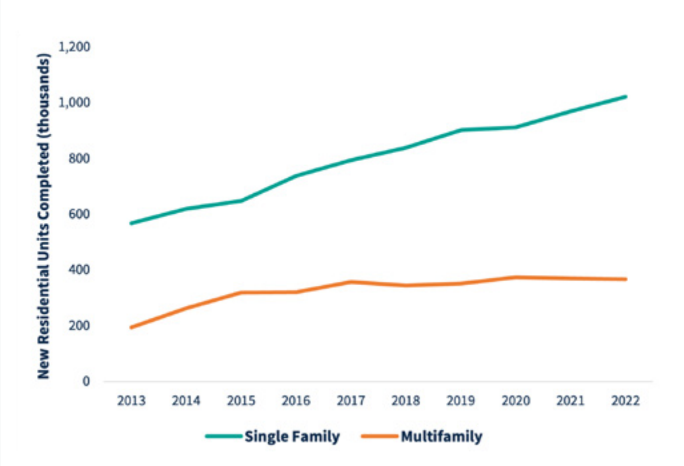
2.2 New Construction Market and Future Demand

Residential new construction includes single-family detached, duplexes, and townhomes, as well as low-rise and high-rise multifamily buildings. (Manufactured housing is not addressed here.) Over the previous decade, completion of new single-family homes has outpaced completion of new multifamily units by an increasing margin (Exhibit 3).

The rates of new construction for each housing type diverge noticeably after 2017. Since that time, a nearly constant number of multifamily housing units have been built each year, while more single-family homes have been built year after year. In 2022, over a million single-family homes were completed, which was more than double the number of multifamily units built.

The heating fuels and system types in those new homes are also changing. Exhibit 4 shows that electric heat pumps and, to a lesser extent, electric furnaces have taken almost half the market share that gas furnaces held in 1999.

Exhibit 3.
New Residential Construction Units Completed, 2013–2022



Source: US Census Survey of Construction, "Square Feet," https://www.census.gov/construction/chars/

The trends in Exhibit 4 show shifting market preferences and acknowledge the expense of installing infrastructure for a second fuel in homes that will already have electricity.[i] However, this trend toward electricity does not mean the market will deliver decarbonization, resilience, and affordability without further intervention. More than 40% of new homes are still being connected to gas or relying on propane/LPG, locking in decades of dependence on fossil fuels, despite the sometimes higher costs. Exhibit 5 shows that in 2022, new single-family home completions still saw a predominance of fossil fuel heating systems, especially in the Northeast, Midwest, and West. Exhibit 6 shows that, while electricity-based heating systems are more common nationally in new multifamily unit completions, fossil fuel heating systems are predominant in the Northeast and Midwest. Coupled with the strong market for electric furnaces and heat pumps in the South, there is a significant opportunity to shift toward high-efficiency heat pump equipment across the United States.

In addition, the electric heating systems shown are likely to have high operating costs due to code-minimum equipment and envelope efficiency — a missed opportunity for affordability and resilience. In all but the mildest climates, homes need more efficient electric heating equipment and will also benefit from higher-performance envelopes. Electric furnaces that use resistance heat, as well as the single-speed, low-efficiency units that make up the majority of heat pumps in this data, have higher operating costs for occupants and higher peak impacts on the grid,[ii] leading to higher costs for utilities and ratepayers.

While the number of multifamily units completed annually is roughly flat, the size of the buildings containing those units is changing. Large buildings (those with 50 or more units) constitute a growing portion of new multifamily construction (Exhibit 7). The shift toward larger buildings is present in major metro areas, like Philadelphia and New York, as well as smaller cities, including Napa, California; Madison, Wisconsin; and Missoula, Montana.[11]

At the historical US peak of off-site construction in 1997, 11% of single-family new construction nationwide was primarily built using off-site construction methods, including modular and panelized approaches. Since that time, the reported share of homes delivered mainly with off-site construction has declined. In 2022, approximately 2% of single-family homes (26,000 homes) and approximately 2% of multifamily buildings were built primarily with off-site construction methods.[12] Even so, as the need for housing grows and construction labor challenges continue, there is renewed interest in employing off-site construction — and, increasingly, more deliberately industrialized approaches — for housing to achieve the previously noted benefits, including shortened schedules, improved budget and schedule certainty, worker and productivity advantages, and potentially lower costs and increased quality.

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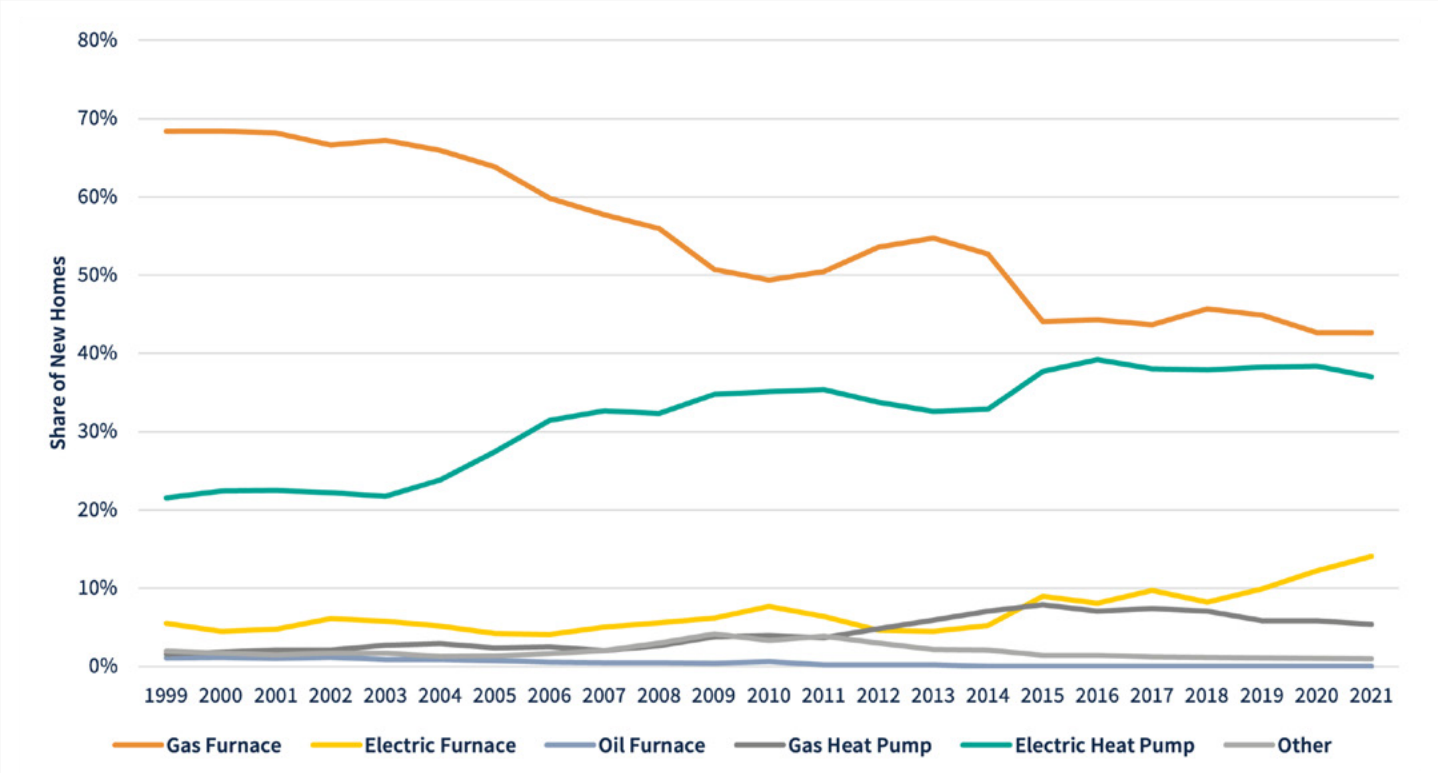
i. As described in the *Case for Industrialized ZCA Homes* section, recent studies from RMI (https://rmi.org/insight/the-economics-of-electrifying-buildings/) and NBI (https://newbuildings.org/new-study-on-electrification-costs-shows-benefits-to-building-owners-and-society/) have shown that building new homes as all-electric with heat pumps results in lower net present cost over the lifetime of the equipment compared with fossil fuel furnaces.

ii. Studies from NREL (https://www.nrel.gov/docs/fy21osti/78027.pdf, figure 5) and Oak Ridge National Laboratory (https://www.energy.gov/sites/default/files/2021-12/bbrn-peer-120921.pdf, slide 41) both show that variable-speed heat pumps cause about half the increase (over baseline equipment) in peak demand compared with single-speed heat pumps.

Exhibit 4. Heating Fuel and System Type in New Single-Family and Multifamily Units



Source: US Census Survey of Construction, "Heating Fuel by Heating System," **https://www.census.gov/construction/chars/**

The United States is in the midst of a widely acknowledged housing shortage, but there is little publicly available data that forecasts how much new housing will be built, or where. To examine the market potential for ZCA new construction, we used projections from the US Energy Information Administration (EIA) *Annual Energy Outlook* and Pacific Northwest National Laboratory (PNNL) weighting factors. The *Annual Energy Outlook* (AEO) includes projections of the number of households nationwide by housing type.[i] The number of households residing in both single-family and multifamily homes is expected to grow, but the AEO projects faster growth in single-family homes, as shown in Exhibit 9 (and continuing the trend noted in Exhibit 8).

Between 2023 and 2050, the AEO projects that 28 million residential buildings will be constructed (including both new and replacement homes). More than 9 million of those are expected by 2030.[ii] This equates to around 17 billion square feet: 15 billion square feet in 6.7 million single-family homes, and 2.2 billion square feet in 2.6 million multifamily homes.[iii] Exhibit 9 indicates how this opportunity is distributed across building types and climate zones.

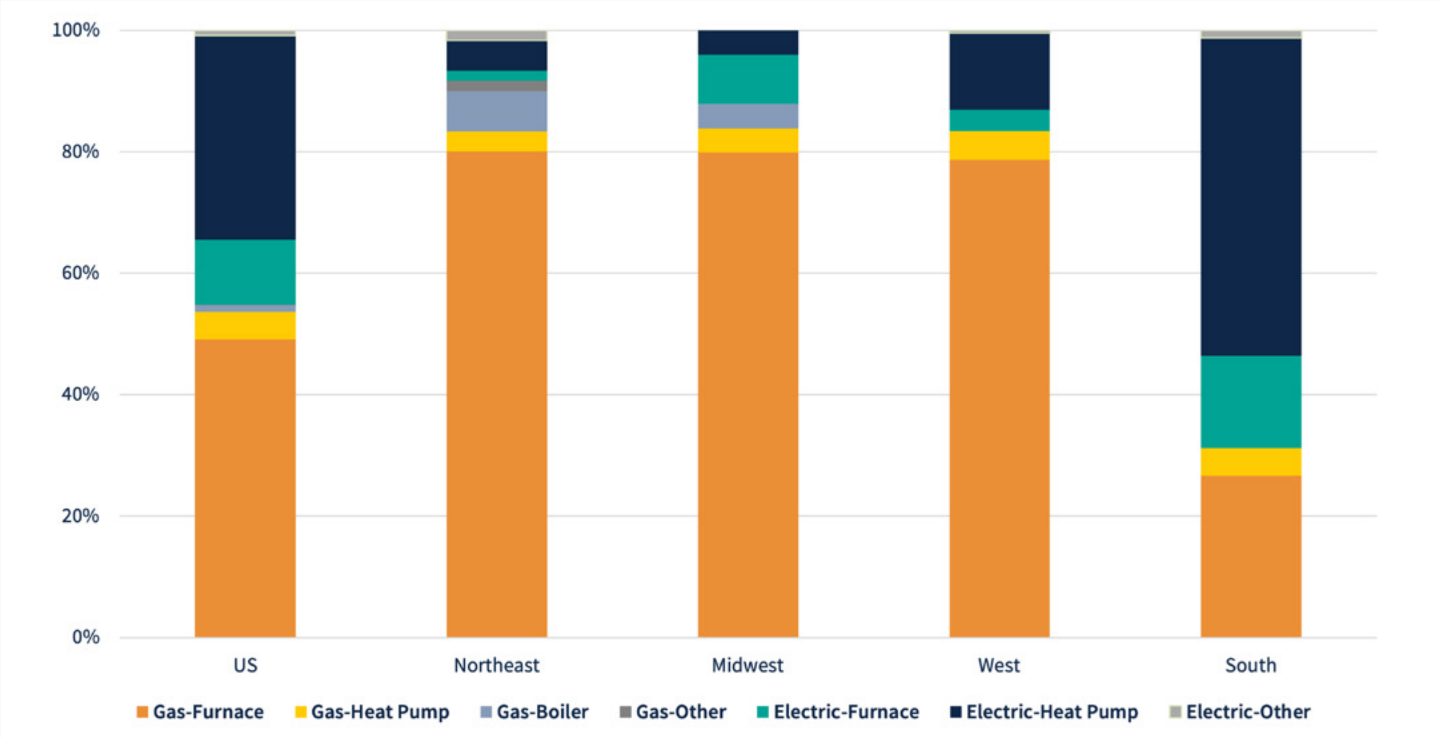
The AEO projections assume a slight growth in the share of single-family homes, but if a greater share of new homes were in multifamily buildings, zero-carbon alignment could be achieved at lower cost, as shown in the *Case for Industrialized ZCA Homes* section. Also, this shift could reduce emissions from both housing and transportation by housing more people closer to daily necessities, services, and amenities. These effects were quantified in the RMI-authored section within the 2022 *Housing Underproduction in the U.S.* report.[13] Families living in denser urban neighborhoods emit approximately 5 to 15 fewer tons of CO2 equivalent (CO2e) per year. This translates to a technical potential of approximately 100 million to 200 million tons of CO2e avoided after 10 years if housing is built in more optimized locations. At the upper end of this range, the avoided emissions would be roughly equivalent to phasing out all gas appliance sales by 2030 or all states adopting 100% zero-emissions passenger vehicles by 2035.

i. The AEO includes projections of households residing in single-family homes (attached and detached), multifamily homes (all sizes, from duplexes to 20-plus units), and mobile homes. This market guidance report only includes projections for single-family and multifamily homes.

ii. This estimate is based on AEO projections and assumptions. Replacement homes account for 25% of new construction during the period 2023–2030. Replaced homes and new construction account for 7% of total homes in 2030.

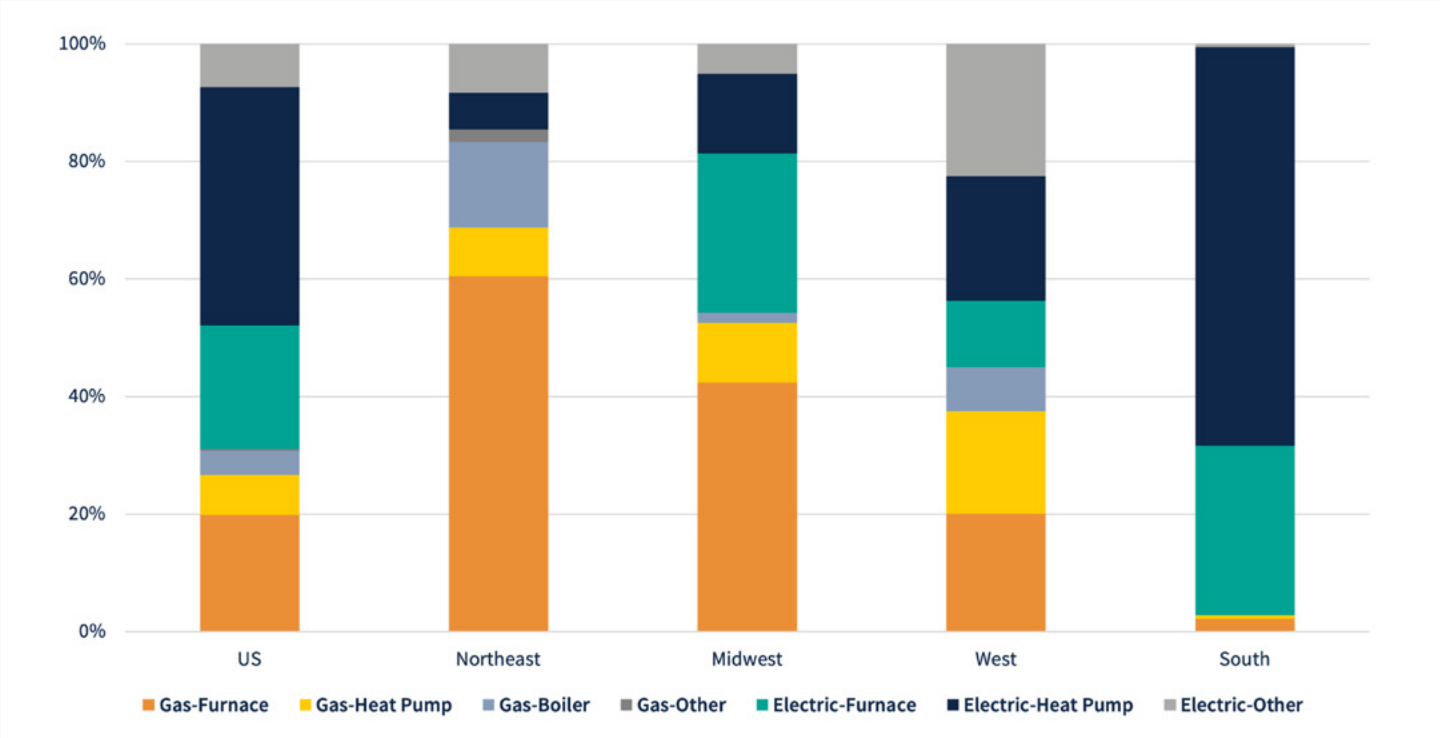
iii. These estimates are based on overall average square footage per household from AEO, adjusted for single-family and multifamily building types. The assumed average area is 2,250 square feet for single-family homes and 883 square feet for multifamily homes.

Exhibit 5. Primary Heating Fuel and System Type in New Single-Family Homes, 2022



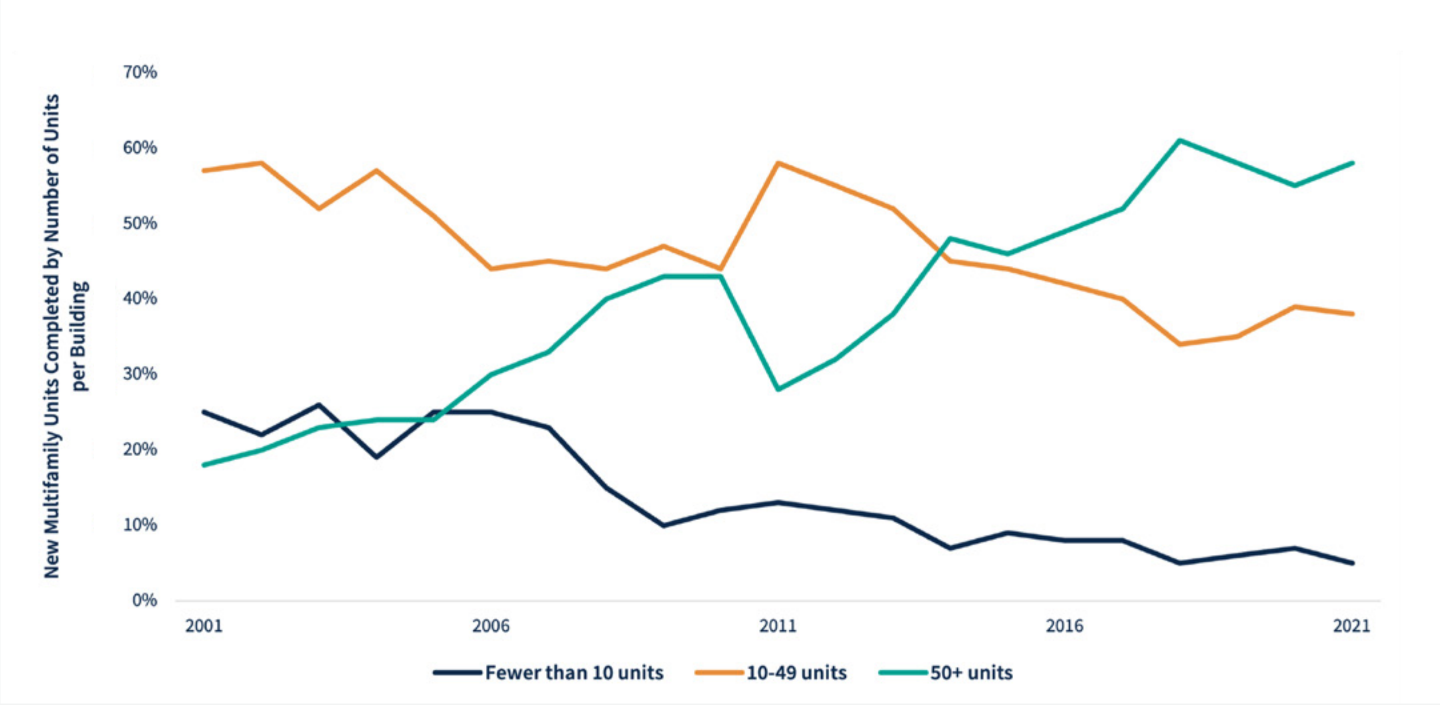
Source: US Census Survey of Construction, "Heating Fuel by Heating System," **https://www.census.gov/construction/chars/**

Exhibit 6. Primary Heating Fuel and System Type in New Multifamily Units, 2022



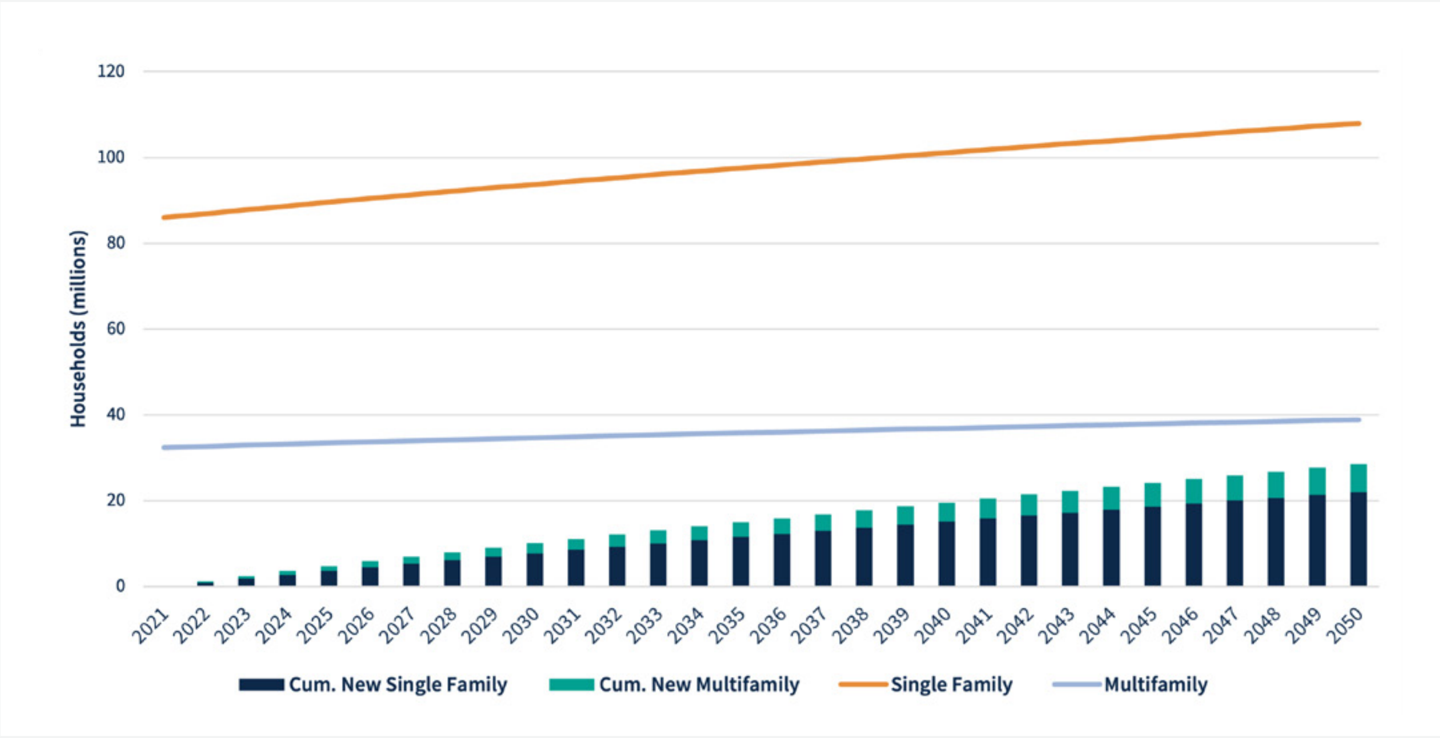
Source: US Census Survey of Construction, "Heating Fuel by Heating System," **https://www.census.gov/construction/chars/**

Exhibit 7. Share of Multifamily Units Completed by Building Size, 2002–2022



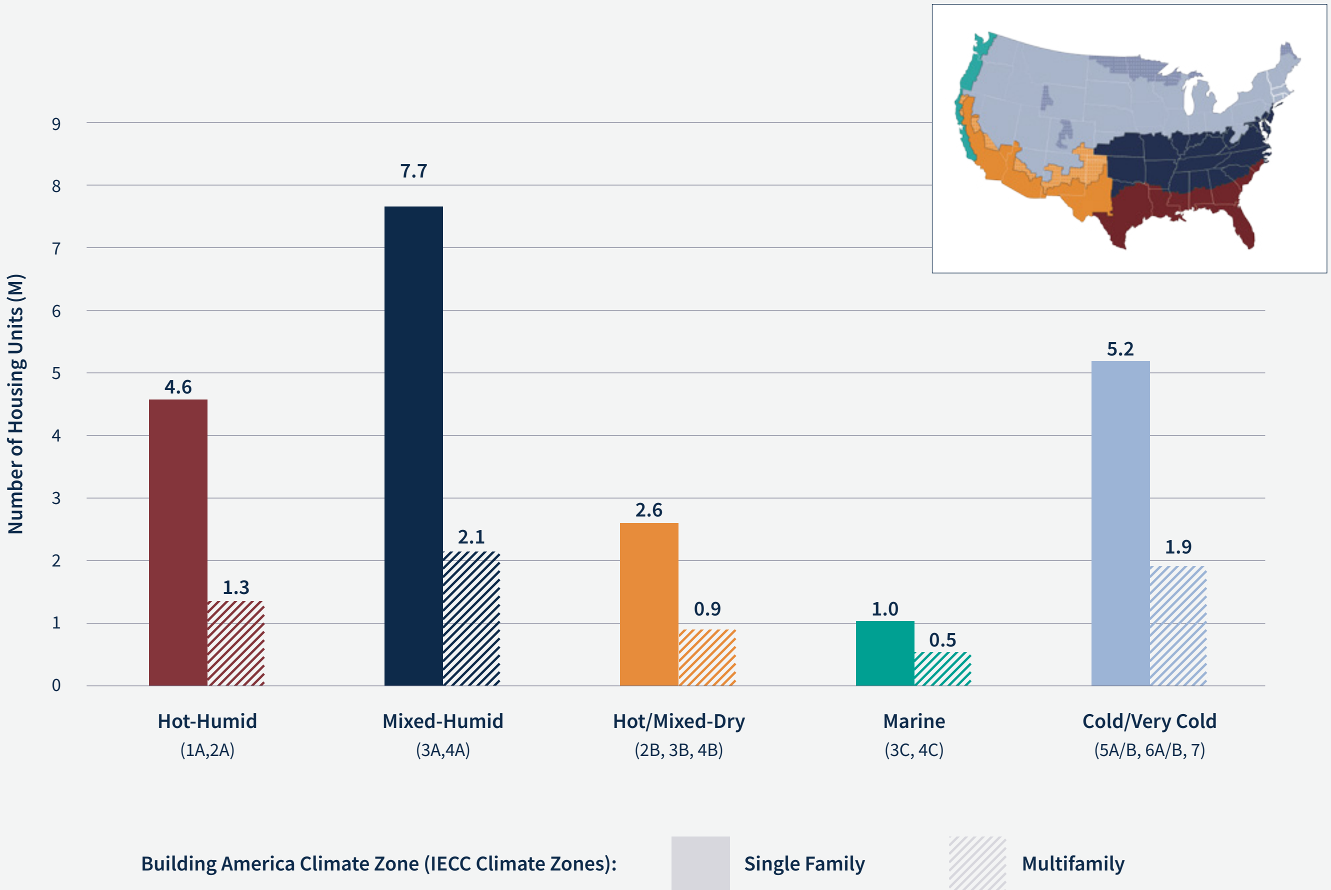
Source: US Census Survey of Construction, "Units per Building," https://www.census.gov/construction/chars/

Exhibit 8. Projected Number of Households by Housing Unit Type, 2021–2050



Source: US Energy Information Administration, Annual Energy Outlook 2022, Table 4

Exhibit 9. Projected Residential New Construction (New and Replacement), 2023–2050

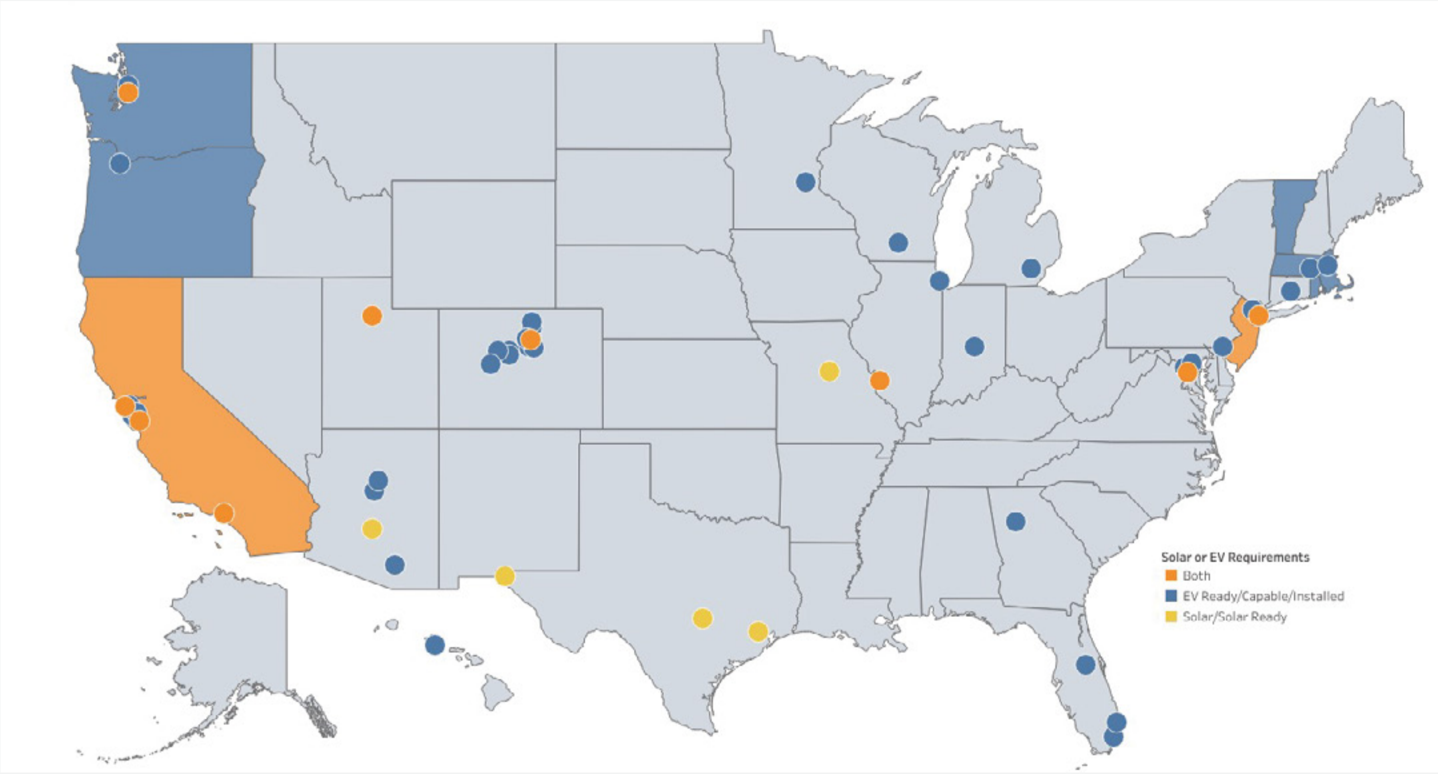


Source: *Annual Energy Outlook 2022* projections distributed using weighting factors from PNNL Report 30547: *Filling the Efficiency Gap to Achieve Zero-Energy Buildings with Energy Codes*

2.3 Trends in Energy Codes

Ongoing efforts around energy codes and standards are providing public-sector stakeholders with new tools to accelerate decarbonization in the built environment. The 2021 International Energy Conservation Code (IECC), which is the foundational energy code for single-family homes, two-family homes, and multifamily buildings of three stories or less, includes Solar-Ready and Zero Energy provisions that states or local jurisdictions can adopt. Several organizations have created additional frameworks or code language to assist policymakers in enacting local decarbonization codes and policies, including for larger buildings not covered by IECC. See *Appendix B1* for more on these efforts.

Exhibit 10. State and Local Electric Vehicle and Solar Requirements

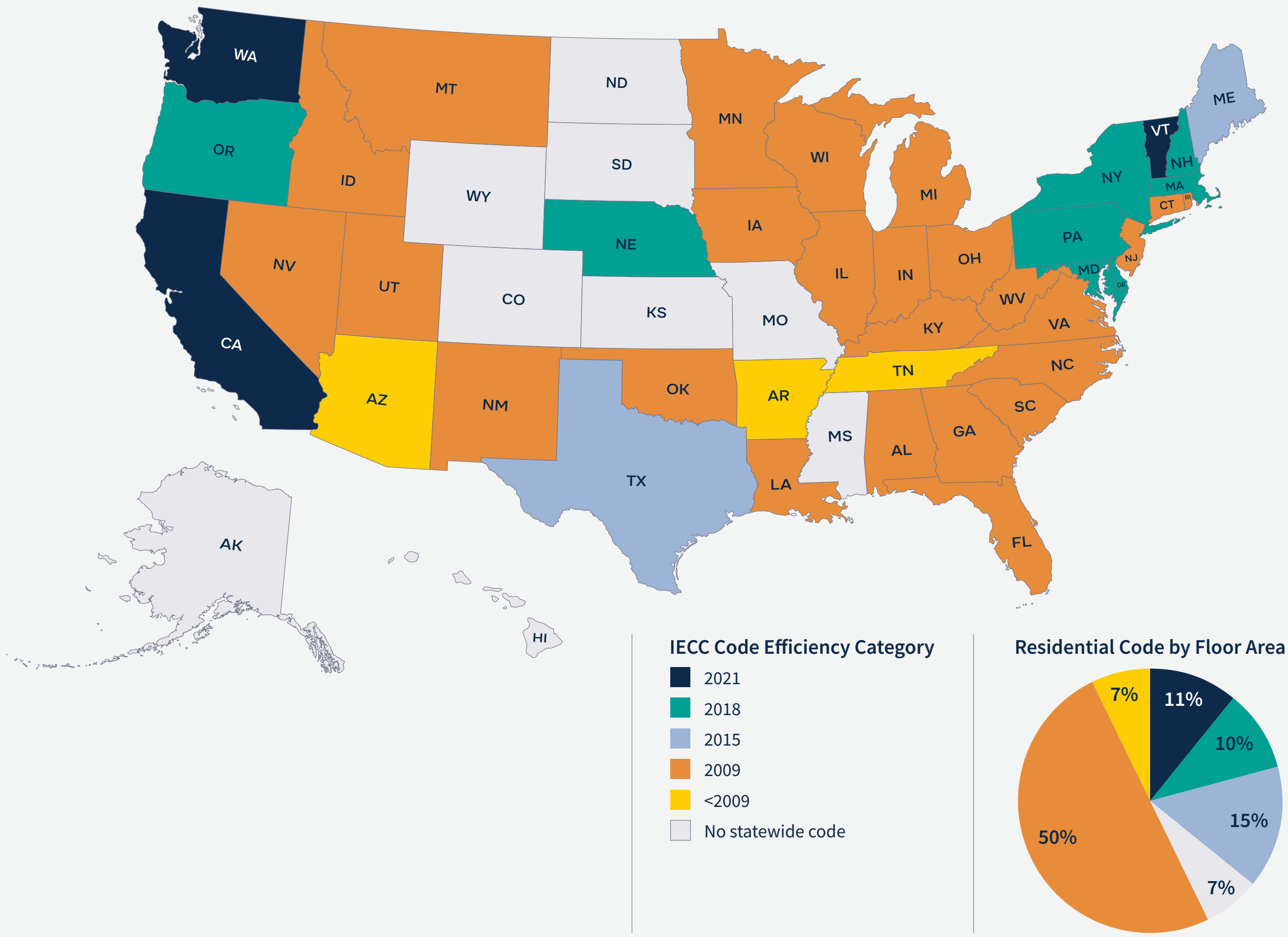


Source: US Department of Energy BECP, "Infographics," **https://www.energycodes.gov/infographics**

Some leading states and localities have already taken bold steps in advancing their building requirements. In California, all new residential buildings since 2020 must have solar and be designed to achieve net-zero energy.[14] Additionally, the state plans to ban most gas space and water heaters by 2030. Washington State approved new building codes in 2022 that would have required heat pumps for space heating/cooling and water heating in all new buildings.[15] Due to industry opposition, however, both California and Washington have experienced setbacks in establishing regulations that require electric equipment and appliances over combustion-based equipment. Officials in Washington are pursuing an alternative path to achieving large-scale adoption of highly efficient heat pumps in new construction building codes with less potential to trigger federal preemption rules.[16] In the vein of supporting decarbonization, several jurisdictions across the United States have implemented electric vehicle or solar requirements; Exhibit 10 shows jurisdictions with such requirements as of June 2023.

Voluntary stretch codes are another path jurisdictions are pursuing to advance electrification and net-zero buildings. Massachusetts has now also adopted a "Specialized" energy code — which goes beyond the Commonwealth's Stretch Code — to ensure new construction meets state emissions limits and aligns with a net-zero economy by 2050.[17] As of November 2023, more than 20 Massachusetts municipalities had already adopted the Specialized Code (with an overwhelming majority of Massachusetts municipalities having adopted at least its Stretch Code).[18]

Exhibit 11. Status of Residential Energy Code Adoption Relative to Model Energy Codes



Source: US Department of Energy BECP, "Status of State Energy Code Adoption: Residential," **https://public.tableau.com/app/profile/doebecp/viz/BECPStatusofStateEnergyCodeAdoption/ResidentialDashboard**

Although IECC is updated on a three-year cycle, not all states adopt the latest model energy code, and some states do not have a statewide energy code at all. Exhibit 11 shows the status of state-level code adoption. As of September 2023, only five states, representing 13% of total residential floor area, have codes that have been deemed equivalent to the current model energy code, 2021 IECC, which provides more than 25% energy savings over the 2009 IECC, according to US Department of Energy (DOE) estimates.[19]

More consistent standards for industrialized construction are now emerging, with the aim of facilitating broader adoption of advanced construction methods. The International Code Council (ICC) and the Modular Building Institute (MBI) have published two new standards to accelerate the off-site construction industry and promote consistency of regulatory requirements for off-site construction.[i] The ICC is also undertaking the development of a new standard that will include mechanical, electrical, and plumbing systems and how they incorporate into modular construction.

i. The 2021 ICC standard for inspection and regulatory compliance of off-site construction is available here: **https://codes.iccsafe.org/content/ICC12052021P1**. The 2021 ICC standard for planning, design, fabrication, and assembly is available here: **https://codes.iccsafe.org/content/ICC12002021P**1.

2.4 Voluntary Building Performance Programs

Overview

Several national program frameworks are available to support the industry in achieving ZCA single-family and multifamily new construction. These programs offer a variety of ways for buildings, builders, and design teams to pursue higher performance, demonstrate compliance, and earn nationally recognized certifications. Voluntary building performance programs provide pathways to reduce overall building energy consumption, ensure that buildings perform as designed, implement or prepare for electrification, and install on-site renewables or purchase renewables credits. The technical specifications of these programs are often developed using cost-effectiveness frameworks designed to deliver efficiency, durability, comfort, and resilience. Program considerations are explored in detail in *Appendix B2*.

Programs

For about 25 years, national building performance programs have provided builders with targets and technical assistance to construct energy-efficient homes and achieve certifications that help consumers easily identify more efficient homes. These programs leverage brands and frameworks to reduce confusion in the market and bolster consumer recognition. National tax credits and state or local energy efficiency incentive programs often leverage these national program standards. Over time, programs have developed in parallel using similar frameworks, benchmarks, and industry professions, providing flexibility for designers and builders to choose a program that best suits their needs as they strive for ZCA construction. Exhibit 12 illustrates the relationship between selected voluntary building performance programs and elements of zero-carbon alignment.

Various programs can result in ZCA buildings, provided that fossil fuel energy sources are excluded from on-site equipment and there is a reasonable expectation that the applicable grid (or distributed energy source) will become decarbonized if it is not already. Generally speaking, the programs shown in Exhibit 12 are designed to increase in stringency, start with low-energy design, and ideally include some level of post-occupancy monitoring to verify the design. While lower levels of efficiency may be sufficient to reach zero-carbon alignment, incorporating higher levels of energy efficiency can provide additional benefits such as resilience, comfort, and occupant health (as well as advantages for building- and grid-level electrical infrastructure). See *Appendix B4* for a brief summary of major building performance programs.

Photo credit: Mighty Buildings

Exhibit 12. Voluntary Building Performance Certification Programs Overview

The Path to Zero-Carbon Aligned* (ZCA) New Buildings

		START +		CHOOSE +		CONSIDER		VERIFY	
		with high-performance building design and construction		high-efficiency electric equipment over on-site combustion		decarbonization of other elements (note: ZCA buildings have future carbon-neutral energy supply)[a]			
Voluntary Programs	Minimum Technical Requirements					Offsets		Compliance Verification	
	Co-Requisite Certifications	Above Code Design & Construction	Ultra-Low Load Design & Construction	Electric Ready	No On-Site Combustion	Renewable Energy Offsets[b]	Value Chain Carbon Emissions Offsets[c]	On-Site Inspection	Performance Verification
ENERGY STAR v3.2	-	✓○	●	○	○			✓	●
ENERGY STAR Next Gen	ENERGY STAR v3.2	✓○	●	✓○[d]	○			✓	●
DOE ZERH v2.0	ENERGY STAR v3.2 Indoor airPLUS	✓○	●	✓○[e]	○			✓	●
PHIUS CORE	ENERGY STAR v3.2 ZERH v2.0 Indoor airPLUS	✓○	✓	✓○	✓○[f]			✓	●
PHIUS ZERO		✓○	✓	✓○	✓○	✓[g]		✓	●
LEED Zero Energy	ENERGY STAR v3.2 LEED BD+C	✓○	●	○	○	✓		✓	✓
LEED Zero Carbon		✓○	●	○	○	✓	✓	✓	✓
ILFI Zero Energy	-	✓○	●	✓○	✓○	✓		●	✓
ILFI Zero Carbon		✓○	●	✓○	✓○	✓	✓	●	✓

Table Legend ✓ Required for program certification ○ Element of zero-carbon alignment ● Additional industry best practice

***Zero-Carbon Aligned (ZCA):** No on-site fossil fuel use, low power and thermal loads, obtains all energy from a carbon-neutral grid and/or carbon-neutral local resources currently or before 2050 under a planned scenario, and reduces impact on the grid through peak and general demand reduction and grid interactivity (or, alternatively, through off-grid operation), with the aim of a decarbonized US building stock before 2050.

a) Zero-carbon alignment includes energy supply coming from a carbon-neutral source currently or before 2050 under a planned scenario. If energy supply is not carbon-neutral currently, building may consider offsets to mitigate impact while supply decarbonizes.
b) Renewable energy offsets - program requirements vary with respect to on-site energy generation vs. allowances for off-site generation or credits.
c) Value chain (Scope 3) carbon emissions offsets - LEED requires offsets for transportation emissions, ILFI requires offsets for embodied carbon emissions (A1-A5).
d) ENERGY STAR Next Gen requires: all primary heating, cooling and water heating be supplied by heat pump technology; induction cooking; and EV charging infrastructure.
e) ZERH requires solar readiness.
f) On-site combustion only allowable under PHIUS CORE Performance compliance path.
g) Renewable energy can be used to meet the net source energy criterion but is not required.

2.5 Funding to Support ZCA New Construction

It is most straightforward to implement new technologies and construction practices in new building construction (as compared with retrofits of existing buildings). Initially, these technologies and/or construction practices may be more expensive due to low demand or an implementation learning curve. However, costs come down as designers become more familiar with and craft workers become more skilled at the new practices. (Industrialized construction approaches have the potential for greater cost compression at scale through the efficiencies of replicability and continuous process improvement.) Additionally, when more efficient systems and construction practices are voluntary, the awareness and demand may not be sufficient to bring market costs down. Strong demand, obtained through enforcement, a favorable policy environment, or shifting market desires, can help reduce these incremental costs.

State and Utility Efficiency Programs

Several states offer above-code new construction programs that provide monetary incentives to encourage higher-performance buildings and offset incremental costs of construction, as well as technical training, marketing assistance, and program certification costs. A study conducted by the U.S. Green Building Council Massachusetts Chapter found that zero-energy building designs reduced energy use by 44%–56% relative to state building codes and decreased lifetime building costs by 0.3%–9.8%.[20] State and utility-administered programs across the country that offer incentives to meet zero-energy and zero-energy-ready standards have a median value of $3,000 per home or apartment (a number that may increase with the deployment of the IRA).[21] While program incentives can be a gauge of the incremental cost of implementing a more efficient product or construction practice, incentives may also act as drivers for meeting state and federal climate goals. As noted in the Introduction section, DSIRE maintains a list of current rebates and policies that encourage higher levels of efficiency.

In 2020, there were 13 residential efficiency programs with a total annual budget of $65 million to support the construction of zero-energy-ready and zero-energy homes across the country, and some were beginning to incorporate net-zero-carbon emissions.[22] Although most programs were less than five years old, they collectively completed approximately 200 single-family homes and 900 multifamily projects, many of which are affordable housing projects. In New York State alone, these efforts have led to nearly 5,000 apartments under construction. As of 2022, a total of 34 state and utility member organizations from the Consortium for Energy Efficiency (CEE) are partnered on new construction efforts with the ENERGY STAR program and seven are partnered with ZERH.[i] (As the IRA continues to roll out, including through state-administered programs, investment levels and project numbers will increase substantially.) Program implementers found that creating simple incentive structures and offering training helped builders, designers, and developers adopt higher-performance construction; this suggests such programs can be effective in pushing the industry toward zero-carbon alignment.

State Housing Finance Agencies

Low-Income Housing Tax Credits (LIHTC) are the largest source of funding for new or rehabilitated affordable rental housing. LIHTC is an indirect federal subsidy in which the IRS allocates tax credits to a state based on population. Every year, state housing finance agencies publish a Qualified Allocation Plan (QAP) outlining criteria and eligibility requirements for developers to receive LIHTC funding. LIHTC awards are competitive, and QAPs incentivize aspects of project applications using a points system. In 2023, 19 states allocated points for projects achieving passive house certification,[23] and 13 states allocated points for meeting the requirements of DOE's Zero Energy Ready Homes (ZERH) program.[24]

Inflation Reduction Act

The IRA will provide additional incentives in the form of rebates and tax credits for new homes certified to meet ENERGY STAR and ZERH efficiency levels.[ii] As Exhibit 12 in the Voluntary Building Performance Programs section illustrates, most programs incorporate ENERGY STAR and/or ZERH as a prerequisite for their own certification. This may make projects certified under these programs eligible for the 45L tax credit for energy-efficient homes, provided the tax credit applies to the version of ENERGY STAR and/or ZERH incorporated by the given program. There is some uncertainty in this area, given that ENERGY STAR and ZERH are both transitioning to new versions and the implementation specifics for the IRA are still being released.

Photo credit: B.PUBLIC Prefab

i. For information on CEE member organizations and available high-performance program offerings, see: **https://cee1.org/index.php/program-resources/**.

ii. The IRA updated and extended the Section 45L tax credit for energy-efficient new homes. As a result, new homes certified to ENERGY STAR standards are eligible for tax credits ranging from $500 per multifamily unit to $2,500 for a single-family home or a manufactured home. New homes certified to the ZERH standard will be eligible for a $5,000 tax credit. Additional rebates are available for electrification and energy efficiency. More information on the tax credit for ENERGY STAR new homes is available here:

2.6 The Case for ZCA Residential New Construction

The websites of voluntary building performance programs contain many case studies of ZCA buildings showcasing their technical specifications, construction methods, post-occupancy performance, and construction costs. Perceived increases in first cost are a common barrier to adoption of ZCA construction. First cost data is often difficult to obtain across projects, can vary considerably by region, and is impacted by a variety of factors such as volume. That said, there are many examples of ZCA construction with little or no incremental cost. Commonly accepted building standards such as Phius, PHI, and ZERH are largely consistent with and can result in ZCA construction, provided on-site end uses decarbonized.

Industrialized approaches can allow builders to deliver ZCA buildings with net cost advantages. The standardization and repetition of industrialized construction has allowed builders, such as Blokable, to leverage learnings through repeated design processes and production efficiencies to produce ZCA buildings with cost savings as compared to decarbonized traditional builds.[25] Research has found that industrialized construction processes, in combination with the use of low-carbon materials and systems, have allowed builders to achieve 60% lifecycle emissions reductions without incurring additional costs. The efficiencies of production at volume and the benefits of vertically integrated business models can allow buildings and developers to scale ZCA new construction cost competitively with traditional construction methods.[26]

Increasingly, it is reasonable for ZCA new construction to strive for close to cost parity with code-minimum construction costs, given the growing industry experience with ZCA construction, the rising floor for code-minimum construction in many jurisdictions, and the benefits that industrialized approaches can provide in reaching this goal (especially if the value of accelerated and less disruptive delivery is considered).

Multifamily

Phius maintains a database of resources for architects, builders, and developers seeking information on passive house construction, with information on how costs have changed over time and on state QAPs incorporating passive house standards, codes, and incentives.[27] At a high level, many Phius-certified buildings are now being completed at or near cost levels of equivalent conventional buildings. Multifamily Phius projects have proven to be the most cost-effective, with affordability increasing alongside the number of stories and units. (As detailed above in the New Construction Market and Future Demand section, well-sited multifamily housing can lower both costs and emissions.) Additionally, incremental costs have been trending lower as developers gain experience on Phius projects.[28] Buildings constructed to Phius standards tend to reduce energy use by 40%–60%, offering potentially significant operational cost savings.[29]

Pennsylvania was one of the first states to encourage passive house design for new multifamily construction. Beginning in 2015, the state housing finance authority altered the application for LIHTC so that 8% of points in the scoring matrix were allocated toward passive house design features. Given the competitive nature of the award process, developers were highly encouraged to voluntarily incorporate passive design into proposals without the need for additional state funding. In the years following this change, 20%–30% of awarded projects were constructed to meet passive house requirements. By 2018, the average incremental cost of passive house projects was 3.3% lower than traditional construction (Exhibit 13).[30]

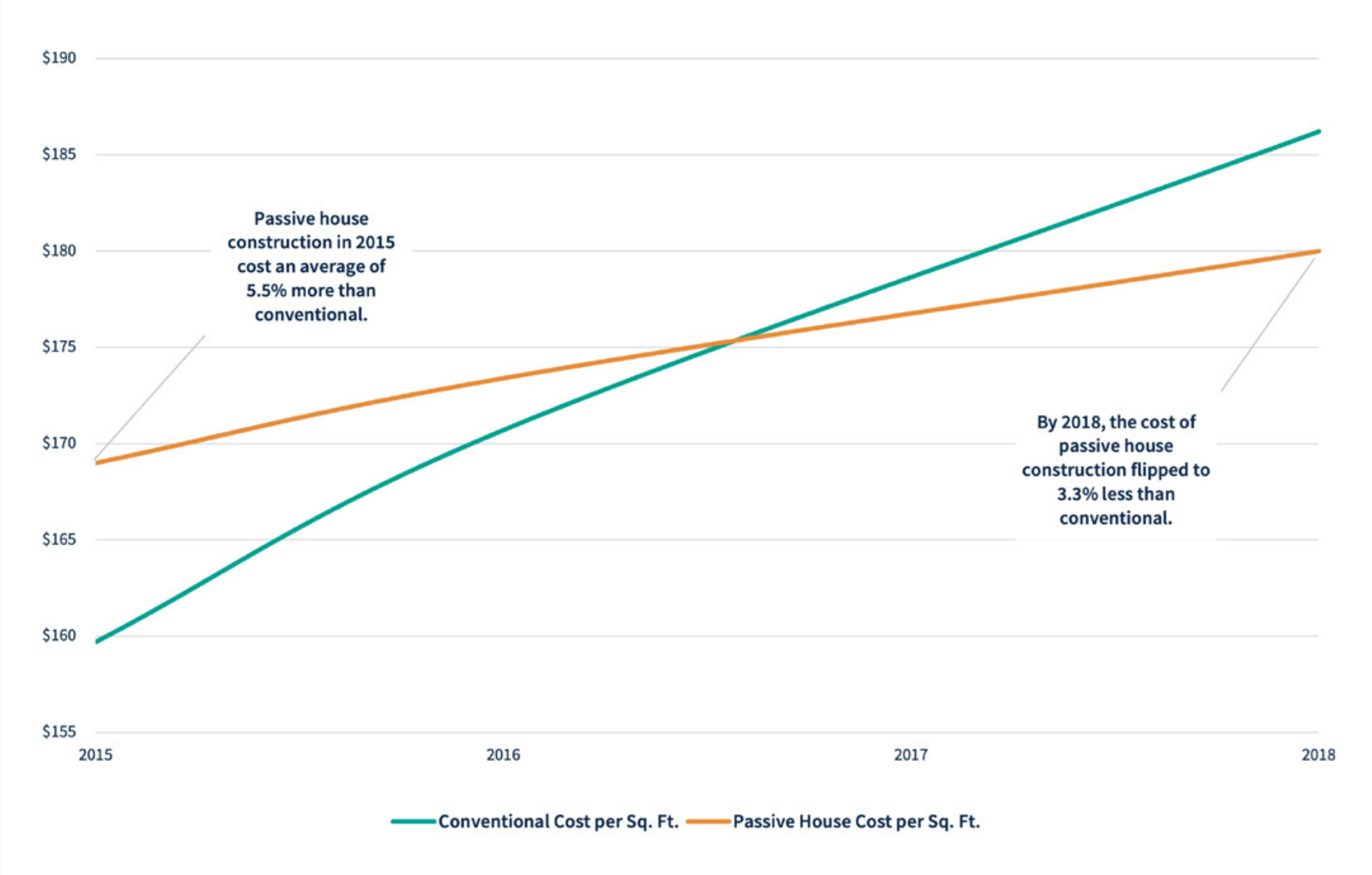
In 2017, the Massachusetts Clean Energy Center (MassCEC) launched the Passive House Design Challenge.[31] Rather than alter the LIHTC scoring, the state provided additional milestone-based incentives to incorporate design features from the onset of projects. This included up-front incentives covering design costs and per-unit incentives for precertification and certification. The system was created to eliminate up-front barriers to get developers on board and support the process along the way. Findings from the first seven projects funded through the program demonstrate an average incremental cost increase of just 2.3% before incentives, compared with project costs without passive house certification measures. In addition to the Design Challenge, Mass Save, a collaborative organization run by local utilities, offers incentives for all new multifamily construction projects of five units or more that meet certain performance requirements. As of December 2022, there were 152 multifamily buildings in Massachusetts with over 10,000 units on the path toward construction and certification to passive house standards.[32]

The New York State Energy Research and Development Authority (NYSERDA) recently established the Buildings of Excellence competition to encourage well-designed, high-performance multifamily buildings.[33] A passive house certification is not a requirement to receive funding, but proposals that seek such a certification are awarded funding at a high rate, given their cost-effective design relative to performance. Data from buildings that have completed construction or are under way shows an average incremental cost of 5% before incentives and credits and −1% after performance-based incentives have been applied. Developers can further reduce costs for projects eligible for the LIHTC, historic tax credits, property tax abatements, and other financial benefits not based on performance.

Each of these programs demonstrates different ways to encourage developers to seek out passive house design in their proposals. The programs indicate that simple incentive programs can offset much, even all, of the additional costs incurred building to passive house standards.

Exhibit 13.

Comparative Cost of Low-Income Affordable Multifamily Passive House and Conventional Construction in Pennsylvania Codes



Note: Data represents multifamily construction that qualified for the Low-Income Housing Tax Credit (LIHTC); Pennsylvania did not award the LIHTC in 2017.

Source: "How a PA Affordable Housing Agency Is Making Ultra-Efficient Buildings Mainstream," *Pittsburgh Post-Gazette*, December 31, 2018; Pennsylvania Housing Finance Agency

Single Family

Building all-electric new homes can have a lower net present cost than building homes that use fossil fuels. A 2022 RMI study found that estimated net present cost savings of all-electric new construction compared to mixed-fuel (gas and electric) new construction range from $1,950 to $10,775, depending on the climate and location-specific variability in heating and cooling equipment and avoided gas infrastructure costs.[34] A 2022 report by NBI and NRDC found that the first cost of constructing an all-electric single-family home is $7,500–$8,200 less than that of a mixed-fuel home meeting code, and an electrification-ready home has an incremental first cost of $1,000–$1,800.[35] Similar to the 2022 RMI study, avoiding the expansion of fossil fuel infrastructure is a key factor in the cost-effectiveness of all-electric homes, and it is important to consider how rate structures and avoided gas infrastructure costs vary locally when assessing the cost savings of all-electric new construction. Electrifying during new construction is far more cost-effective than electrification readiness, although electric-ready households still can save thousands of dollars compared with standard retrofits. Homes in warmer climates and areas with low electricity rates benefit more from going all-electric, as do those that can take advantage of time-of-use rates.

In the greater Austin, Texas, area, a group of industry professionals shared lessons learned from personal projects they designed and built to Phius standards (see case studies in *Appendix B5*). In addition to achieving substantial energy savings, the homes are notable for their resilience. They withstood the challenges posed by the Texas winter storm and power outage of 2021 and are poised to meet the extreme heat challenges of decades to come. Recommendations from the group include working with organizations like Phius to tap into their modeling and building science expertise; marketing the safety, comfort, and durability of above-code homes to clients; and ensuring that the entire team involved in design and construction has the skills and training necessary, particularly in adhering to building science principles.

In December 2021, the Marshall Fire destroyed over 1,000 homes in Boulder County, Colorado. In the wake of this tragedy, Xcel Energy announced a package of incentives designed to support the community's clean energy goals and rebuild to a range of above-code efficiency standards.[36] Through this program, homeowners impacted by the fire were given the option to build to code or receive higher incentives for building to ENERGY STAR, ZERH, and passive house standards.

Two companies involved in helping residents rebuild to these higher standards are Diverge Homes and B.PUBLIC Prefab. Diverge Homes has designed a series of model homes specifically for these rebuilding efforts to help the community recover quickly without sacrificing quality or performance.[37] Because of the knowledge and experience gained constructing high-performance, all-electric homes in these rebuilding efforts, the company has transformed its operations to deploy all-electric homes across all of its developments in Colorado and beyond. B.PUBLIC Prefab has partnered with local Colorado architects in designing custom homes, as well as offering standard home plans direct to homeowners working with local builders. The company has provided both the technical expertise and local workforce training necessary to build to these higher standards, as well as its "kit of parts" prefabricated panels to achieve required performance cost-effectively and with speed.

The ABC solutions offered by Diverge Homes and B.PUBLIC Prefab allowed for the Boulder area to rebuild faster following the Marshall Fire while also providing zero-carbon alignment — and associated energy efficiency and resilience in the face of future extreme weather.

Situated 30 miles inland of Fort Myers, Florida, the community of Babcock Ranch recently provided a testament to the value of building with resilience in mind. The community is host to 650,000 solar panels providing 150 MW of generation capacity alongside a 1-megawatt storage system capable of supplying power to the community's 5,000 residents on cloudy days and nights. Babcock Ranch's sustainability-centric design withstood the worst impacts of Hurricane Ian in 2022. While millions in the state suffered from flooding and power outages, especially in nearby Fort Myers, the damage to Babcock Ranch was relatively minor, and no homes lost power. Every home there must be certified at least Bronze "Florida Green" by the Florida Green Building Coalition, a standard of high-performing homes that are efficient users of energy and water, have good indoor air quality, utilize environmentally sustainable materials, and use the building site in a sustainable manner.[38] Homes must provide a certified Home Energy Rating System (HERS) Index, only scoring points for achieving an Index rating below 75. The certification process also goes beyond HERS to consider measures that generate energy savings from passive design and layouts of homes. These factors contributed to the success of the community in weathering the storm.

2.7 New Construction Market Conclusions

- There is a housing shortage, and a large amount of new residential construction is anticipated — and needed — in the coming years, providing an opportunity for ABC to meet the needs of the market with rapidly scalable ZCA construction. Between 2023 and 2030, more than 10 million new homes are projected to be built.[i] This equates to around 17 billion square feet, with 15 billion square feet in 6.7 million single-family homes, and 2.2 billion square feet in 2.6 million multifamily homes.
- Code is moving toward zero-carbon alignment, but the market is not yet moving at the necessary pace nationally. The IRA will allocate $1 billion through 2029 to help states and local governments adopt building energy codes. Codes and policies effectively requiring ZCA buildings are already in place in leading jurisdictions, with increasing adoption on the horizon.
- There are several voluntary building performance programs available that can yield ZCA single-family and multifamily new construction, provided that decarbonized (generally all-electric) equipment and appliances are used. Programs offer ways to reduce energy consumption, ensure buildings perform as designed, implement or prepare for electrification, and install on-site renewables or purchase renewables credits. The technical specifications of these programs are developed using cost-effectiveness frameworks designed to deliver efficiency, durability, comfort, and resilience.
- Experience shows it is possible to cost-competitively construct buildings that are ZCA for certain typologies, and incentives expand the range of cost-competitive building types. This suggests it is within reach for all new residential construction to be ZCA.
- Industrialized approaches are a good fit for high-performance new construction and can help accelerate the pace of new construction that is ZCA. As states, cities, and utilities continue to set climate goals, the ability of ABC approaches to reduce energy use, energy demand, construction waste, and deployment timelines is increasingly valuable.
- Electrification is already happening in the market. The total number of zero-energy homes in the United States has increased by 29% since 2015. Studies completed by RMI and NBI have concluded that all-electric homes can save thousands of dollars over the lifetime of the building and in up-front costs for some scenarios. Developers adopting advanced construction practices now will be best prepared for coming markets with zero-energy codes and federal funding support on the horizon.
- Some affordable housing policies and funding mechanisms already support high performance and zero-energy homes, which off-site construction methods can help deliver effectively. Implementing new technologies and construction practices in new construction reduces costs over the lifetime of the building. Federal, state, and utility programs offset much of the up-front costs to earn crucial buy-in from developers early on and spur opportunities for the necessary workforce training to scale these practices.
- ABC presents a business opportunity for the sector by accelerating pathways to cost-effective, zero-energy, and quickly deployable building construction using industrialized methods. Larger multifamily buildings in particular have demonstrated low-cost energy-efficient construction. Incremental costs also tend to decrease as developers gain experience in building to above-code standards.


Photo credit: RMI

i. Based on AEO projections and assumptions. Replacement homes account for 25% of new construction during the period 2023–2030. Replaced homes and new construction account for 7% of total homes in 2030.

3. Retrofit

3.1 Introduction

Approximately two-thirds of existing buildings in the United States today are expected to still be in operation in 2050,[39] so retrofitting existing buildings is an essential part of ensuring the entire building stock is ZCA and thus meets emissions targets consistent with achieving economy-wide decarbonization goals. Previous research estimates that, to achieve these goals, the pace of whole-building retrofits needs to increase from the current rate of well below 1% per year to around 3% per year by the end of the decade and must be sustained at this rate through mid-century.[40] Despite this clear need to rapidly scale up whole-building retrofits in the United States, these types of upgrades are still rare today due to challenges that include high up-front costs, long project installation times, occupant disruption and displacement, and the lack of a streamlined delivery model.

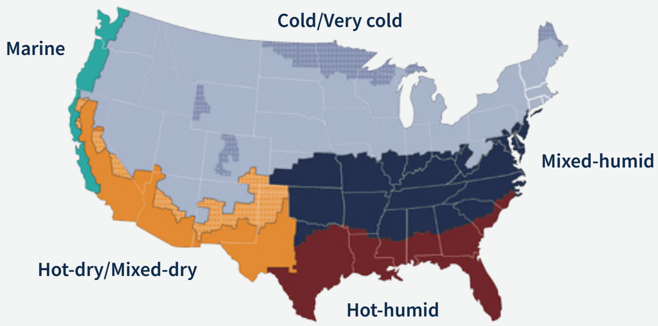
The DOE's ABC Initiative,[41] which provides funding for the ABC Collaborative, focuses on accelerating innovation in and deployment of solutions that achieve aggressive thermal energy use reductions on a whole-home basis.[42] As such, this retrofit guidance focuses on segments of the building stock that will likely require these types of solutions to become ZCA. We present recommended upgrade performance targets for all segments of the residential building stock and then prioritize those segments both nationally and regionally by the number of housing units that should receive a whole-building retrofit to provide a granular understanding of the market potential for ABC retrofit approaches. Next, we estimate installed cost targets for these retrofits based on their life-cycle value to signal to industry the costs that should be achieved for various segments of the residential building stock to accelerate broader adoption in the market.

Given the heterogeneity of the residential building stock in the United States, buildings vary considerably in how much energy they use and how this energy use is broken out across different fuels and end uses. As such, the pathway to achieving zero-carbon alignment for the existing building stock is also highly variable. For some building stock segments, becoming ZCA will require fewer upgrades (e.g., electrifying all building end uses without comprehensive envelope insulation upgrades). In other segments, especially those in climates with greater thermal demands, zero-carbon alignment will require higher-performance, whole-building upgrades. As described previously, these whole-home retrofits are a major focus of ABC innovation. Additionally, certain states have higher potential to adopt and support ABC solutions than others, given their regulatory and economic environments. In the sections that follow, we attempt to account for these many factors by first assigning all segments of the residential building stock a target upgrade package and then prioritizing those segments that offer the biggest opportunity for ABC innovation.

3.2 Market Segment Prioritization Inputs

We incorporated several data sources to select the priority residential market segments for ABC technology deployment and cost target analysis in this report. For existing buildings, these sources include the National Renewable Energy Laboratory (NREL) *U.S. Building Stock Characterization Study: A National Typology for Decarbonizing US Buildings*,[43] NREL's *Modeled Results of Four Residential Energy Efficiency Measure Packages for Deriving ABC Research Targets*,[44] and the ABC Collaborative's *Market Opportunities and Challenges for Decarbonizing US Buildings*.[45] These analytical products are all publicly available.

Exhibit 13. DOE Building America Program Climate Zones



Characterization of the Existing US Building Stock

The primary source used to characterize the existing residential building stock is DOE's ResStock software, which combines high-performance computing with open-source building energy models to conduct large-scale residential energy analysis.[46] In the *U.S. Building Stock Characterization Study*, ResStock is used to segment the US housing stock into 165 subgroups based on climate zone, wall structure, housing type, and year of construction. For each segment, the report authors quantify the thermal energy use (defined as energy used for heating, ventilating, cooling, and water heating) by end use to allow for prioritization of different building segments and technologies for targeted decarbonization upgrades. Thermal energy uses were selected as the primary focus for the ABC Initiative because these uses are the main driver of both residential energy use and emissions, and they are also the end uses most likely to be mitigated by ABC innovations.[47]

In addition, the report authors examine the heating and cooling component loads of each market segment and climate zone, identifying specific opportunities to achieve the greatest impact on thermal energy uses. This data is publicly available in an online dashboard.[i] Exhibit 14 presents a map of the Building America climate regions used in the building stock characterization study (and referenced below in the *Market Segment Prioritization Methodology and Results* section).[48]

Key takeaways from the *U.S. Building Stock Characterization Study* that are relevant to the guidance presented in this section include the following:

- **The majority of residential thermal load is in single-family detached homes.** The vast majority of residential buildings in the United States are single-family detached homes, which also have the highest thermal load intensity (with the exception of manufactured housing) and the largest amount of floor space per unit. This combination of factors means that any strategy looking to holistically reduce thermal loads in the residential sector must address single-family homes and the complexity of working in these segments, including ownership structures, small individual building sizes, and complex building shapes (challenges that were also identified in the ABC Collaborative's *Market Opportunities and Challenges for Decarbonizing US Buildings* report).
- **Infiltration drives heating. Infiltration is the component contributing most to heating loads in all climate regions studied.** In some segments — for example, in multifamily buildings in the cold/very cold climate region — infiltration contributes nearly double all other envelope heat transfer component loads combined. Retrofit strategies that deliver reductions in air infiltration, especially those that limit disruption to occupants from internal modifications, should be a priority for further research and development, considering the limited evidence base for how much infiltration can be reduced through panelized wall and window retrofits alone.
- **Electrification of space and water heating is necessary for decarbonization.** Fossil fuel–fired space and water heating are the largest contributors to thermal end-use intensity and total loads in climate regions covering most of the United States. Fossil fuel–based space and water heating are most prominent in cold and mixed climate regions, but they also represent a large share of thermal loads for single-family segments in hot and humid climate regions, where electric heating is more common.
- **Solutions are likely transferable between segments.** Packages developed for single-family detached, mid-century wood frame construction, which is the single-family segment with the highest thermal loads in each of the five climate regions, will likely be applicable to other segments, such as other wood frame single-family detached vintages, as well as low-rise wood frame multifamily buildings. Similarly, water heating retrofit upgrades developed for marine climate multifamily buildings that heat with electricity — over 95% of which use electric resistance technologies — could be applied to many different multifamily building segments, given that these upgrades are not dependent on exterior building features such as the wall structure type or materials.

i. See: https://resstock.nrel.gov/page/typology.

The primary pieces of information from the *U.S. Building Stock Characterization Study* that inform ABC market guidance are the identification of the top residential market segments in terms of number of units and total site energy use and the insights about the drivers of residential energy use. The top market segments for single-family and multifamily housing, ranked by number of housing units in each segment, are shown in the tables below.

Residential Retrofit Market Opportunities

The market segment analysis in the *Market Opportunities and Challenges for Decarbonizing US Buildings* report revealed important openings for ABC deployment with near-term opportunities in several subsegments, including the retrofit of the single-family and multifamily housing stock. The single-family segment of the housing market poses a massive addressable opportunity, with conservative estimates of 21 million single-family homes built prior to 1980 in need of retrofit. But the individualized ownership structure and potentially higher per-unit first costs create barriers to broad, near-term adoption of ABC retrofit solutions.[49] The high level of variability in the existing single-family housing stock is a significant barrier to standardized retrofits at a scale necessary to drive down costs.

This offers a clear need and opportunity for market innovation to address the very large single-family retrofit market. If a major player can overcome the existing barriers of high first cost to execute a single-family home retrofit across a fragmented ownership landscape, it could gain unconstrained early — even exclusive — access to an expansive market and a broad arena for product innovation. The market opportunities report suggests that "this segment could be made more attractive for ABC retrofits by streamlining financing and insurance considerations," and that securing commitments from owners of consolidated single-family rental housing portfolios could create a highly attractive opportunity for ABC in this subsegment.[50]

The multifamily residential market, while not as large as the single-family market, accounts for 25% of all US housing units. Multifamily buildings often have simpler layouts and geometries and therefore offer a promising opportunity and priority entry point for ABC retrofit technologies. Multifamily retrofits also represent a key market segment for near-term deployment activities due to the backlog of deferred maintenance in many multifamily buildings, particularly in affordable and workforce housing. This is especially true in the Northeastern United States, which includes nearly 30% of the country's multifamily residential buildings and where colder climates create greater energy and comfort burdens for tenants. ABC retrofits of existing multifamily buildings in the United States can help expand the availability of high-quality, low-carbon, healthy, and comfortable affordable housing.

Exhibit 14. Top Single-Family Market Segments by Number of Units

Climate Zone	Building Type	Wall Type	Vintage	Number of Housing Units (million)	Total Site Energy Use (TBtu)	Share of Total Site Energy Use across All Segments (%)
Cold & Very Cold	Single-family detached	Wood frame	1940–1979	9.8	1,393.3	14.7
Mixed-Humid	Single-family detached	Wood frame	1980-present	9.5	877.5	9.3
Mixed-Humid	Single-family detached	Wood frame	1940-1979	9.0	1,086.3	11.5
Cold & Very Cold	Single-family detached	Wood frame	1980-present	8.2	929.1	9.8
Cold & Very Cold	Single-family detached	Wood frame	Pre-1940	4.9	838.8	8.9
Hot-Dry & Mixed-Dry	Single-family detached	Wood frame	1940-1979	4.0	286.6	3.0
Hot-Humid	Single-family detached	Wood frame	1980-present	4.1	274.6	2.9
Hot-Dry & Mixed-Dry	Single-family detached	Wood rame	1940-1979	4.0	286.6	3.0
Cold & Very Cold	Single-family detached	Brick	1940-1979	3.6	501.0	5.3
Hot-Humid	Single-family detached	Brick	1980-present	3.6	238.1	2.5

Exhibit 15. Top Multifamily Market Segments by Number of Units

Climate Zone	Building Type	Wall Type	Vintage	Number of Housing Units (million)	Total Site Energy Use (TBtu)	Share of Total Site Energy Use across All Segments (%)
Mixed-Humid	Multifamily with 5+ units, 1–3 stories	Wood frame	1980-present	1.9	71.3	4.5
Cold & Very Cold	Multifamily with 5+ units, 1–3 stories	Wood frame	1980-present	1.8	78.0	4.9
Hot-Humid	Multifamily with 5+ units, 1–3 stories	Brick	1980-present	1.5	40.1	2.5
Hot-Dry & Mixed-Dry	Multifamily with 5+ units, 1–3 stories	Wood frame	1980-present	1.2	33.5	2.1
Cold & Very Cold	Multifamily with 2–4 units	Wood frame	Pre-1940	1.2	110.5	7.0
Cold & Very Cold	Multifamily with 2–4 units	Wood frame	1940-1979	1.1	84.8	5.3
Cold & Very Cold	Multifamily with 5+ units, 1–3 stories	Wood frame	1940-1979	1.1	58.8	3.7
Mixed-Humid	Multifamily with 2–4 units	Wood rame	1940-1979	1.0	71.2	4.5
Hot-Dry & Mixed-Dry	Multifamily with 5+ units, 1–3 stories	Wood rame	1940-1979	1.0	29.6	1.9
Mixed-Human	Multifamily with 5+ units, 1–3 stories	Brick	1940-1979	1.0	51.2	3.2

Modeled Upgrade Packages for Existing Buildings

Building on the work to characterize the residential building stock described above, NREL proceeded to evaluate the energy savings, utility bill impacts, and carbon emissions impacts of four simulated upgrade packages with specific target performance levels on a large representative sample of residential housing (approximately 550,000 dwelling units). This work is described in detail in the NREL report *Modeled Results of Four Residential Energy Efficiency Measure Packages for Deriving ABC Research Targets*.[51] The analysis was conducted using NREL's ResStock tool with input from the ABC Analysis Working Group, including representatives from RMI, the Association for Energy Affordability (AEA), VEIC, Phius, PNNL, LBNL, NREL, and DOE. The four upgrade packages considered were:

1. **All equipment swap-out:** Replacing all of the major end-use equipment with high-efficiency electric equipment.
2. **Equipment + conventional envelope:** Replacing end-use equipment as in package 1 and upgrading the building envelope with conventional, market-ready solutions such as low-emissivity storm windows and continuous exterior insulation at the time of re-siding.
3. **Equipment + IECC envelope:** Replacing end-use equipment as in package 1 and upgrading insulation, air leakage, and mechanical ventilation to levels consistent with the 2021 IECC residential prescriptive path building envelope requirements.
4. **Equipment + Phius envelope:** Replacing end-use equipment as in package 1 and upgrading insulation, air leakage, and mechanical ventilation to levels consistent with the 2018 Phius standard.

The target performance levels for each package are summarized below in Exhibit 16. The IECC and Phius performance levels are intended to inform research targets for ABC and do not necessarily represent upgrades that are practical or achievable in all situations.

A reference case for the upgrade packages was constructed by simulating the existing conditions and assuming that the equipment in the existing building is upgraded to federal minimum efficiency levels as of 2021, keeping the fuel type the same (to account for the fact that any equipment replacement would have to meet this minimum level). Utility bill savings estimates were calculated in reference to this case. Utility bills were calculated based on 2019 average fixed and variable charges for electricity, natural gas, and fuel oil by state.[52]

Exhibit 16. Upgrade Package Performance Assumptions

Building Component	All Equipment Swap-Out	Equipment + Conventional Envelope	Equipment + IECC Envelope	Equipment + Phius Envelope
Water Heater	Heat pump water heater; 80 gallons; UEF 2.4			
Heating and Cooling	• Air-source heat pump (homes with ducts): SEER 22; 10 HSPF (not cold-climate) • Mini-split heat pump (homes without ducts): SEER 29.3; 14 HSPF (cold-climate)			
Duct Sealing/ Insulation	All ducts in unconditioned spaces sealed to 10% and insulated to R-8			Ducts entirely within thermal envelope, no losses
Lighting	100% LED, 83 lumens/W			
Appliances	• ENERGY STAR (refrigerator and dishwasher) • ENERGY STAR Most Efficient (heat pump dryer and clothes washer) • Induction cooktop and electric resistance oven			
Window U-Value, Solar Heat Gain Coefficient (SHGC)	No upgrade	Low-e storm windows, U-value 0.29–0.69; SHGC 0.42–0.59	U-value 0.3–0.4; SHGC 0.25–0.4, by climate	U-value 0.12–0.5; SHGC 0.25–0.4, by climate
Wall/Floor R-Value	No upgrade	R-6.5 continuous if existing <R-19 and home older than 1990	R-13 to R-30, by climate	R-22 to R-51, by climate
Roof/Attic R-Value	No upgrade	R-29 to R-51, by climate	R-30 to R-60, by climate	R-51 to R-82, by climate
Foundation Wall R-Value	No upgrade	No upgrade	R-0 to R-15, by climate	R-7 to R-30, by climate
Slab Edge R-Value	No upgrade	No upgrade	No upgrade	2 ft, R-7 to R-30, by climate
Air Leakage	No upgrade	7%–62% reduction	3 ACH_{50}	1 ACH_{50}
Mechanical Ventilation	No upgrade	ERV/HRV if post-retrofit infiltration <7 ACH50	ERV/HRV	ERV/HRV

Note: The modeled ducted air-source heat pump retains about 50% of maximum heat output at 5°F and 25% at −15°F, so this is not considered a cold-climate heat pump. The modeled ductless mini-split heat pump retains about 85% of maximum heat output at 5°F and 80% at −15°F, so this is considered a cold-climate heat pump. Both heat pump models were autosized to have their nominal capacity sized based on the larger of heating/cooling design loads, while taking into account the heat pump's reduced capacity at the design temperature.

3.3 Market Segment Prioritization Methodology and Results

Overview

Exhibit 17 summarizes the market opportunity for ABC retrofit solutions, which is discussed in greater detail below and in *Appendices C1–C4*. The results from the building characterization study and modeled package upgrades analysis are segmented by several high-level variables, including building type, wall structure/type, and building vintage. The building type variable comprises six distinct building types that were identified in advance of the modeling work by the ABC Analysis Working Group:[i]

- Single-family detached
- Single-family attached
- Multifamily with 2–4 units
- Multifamily with 5+ units, 1–3 stories
- Multifamily with 5+ units, 4–7 stories
- Multifamily with 5+ units, 8+ stories

For the assignment logic steps outlined below, we determined that the following simplified building type grouping could facilitate a more straightforward application of assignment decision criteria:

- Single-family and small multifamily:
  - Single-family detached
  - Single-family attached
  - Multifamily with 2–4 units
- Large multifamily:
  - Multifamily with 5+ units, 1–3 stories
  - Multifamily with 5+ units, 4–7 stories
  - Multifamily with 5+ units, 8+ stories

The target package assignment method described below varies between these two groupings. Points of variation and the reasoning behind this grouping are discussed in *Appendix C1*.

Exhibit 17. Overview of Package Assignment Steps and Typology Segment Prioritization Criteria

Building type groupings:

Single-family & Small MF

- Single-family detached
- Single-family attached
- Multifamily 2-4 units

Large MF

- Multifamily 5+ units, 1-3 stories
- Multifamily 5+ units, 4-7 stories
- Multifamily 5+ units, 8+ stories

Performance level assignments

Step 01 Determine which building segments should not be prioritized for ABC guidance because they are already "on their way" to being ZCA

Step 02 Determine which buildings require envelope retrofits in addition to equipment replacement/ electrification to be ZCA

Step 03 Determine which envelope upgrade is needed to achieve zero-carbon alignment while also limiting HVAC capacity (i.e., to facilitate electrification while also mitigating grid impacts)

Typology segment prioritization criteria

Step 01 Prioritize building segments in states where ABC solutions can be adopted rapidly due to market and policy conditions

Step 02 Prioritize building segments that are assigned upgrade packages that the ABC initiative focuses on (i.e., those that include comprehensive envelope upgrades)

Step 03 Aggregate results across key building characteristics (e.g., building type, vintage, existing heating fuel, and wall structure) and rank segments by number of housing units

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i. A seventh building type not included below is manufactured housing. This building type is included in the *U.S. Building Stock Characterization Study* and the modeled package upgrades analysis, but we do not include manufactured housing in the priority markets for ABC. This is both because no manufactured housing segment is large enough to be included in the top segments and because manufactured homes are not the ABC Collaborative's primary focus.

Upgrade Package Assignment and Segment Prioritization

Methodology

Exhibit 17 provides a high-level overview of the package assignment and segment prioritization criteria. In order to determine which segments of the building stock should be targeted for ABC, we developed an approach to assign target upgrade packages to all segments of the residential building stock based on several decision criteria that were developed by the ABC Analysis Working Group and that rely on the analyses described in the previous sections, including the U.S. Building Stock Characterization Study and the modeled package upgrades analysis. Next, we selected the segments to which we assigned whole-home upgrades with more aggressive target performance levels as the target market for ABC. Finally, we aggregated segments based on geographic location and building characteristics such as number of housing units. At this stage, we also drew on the results presented in the Market Opportunities and Challenges for Decarbonizing US Buildings report to prioritize segments in states with high potential to support and benefit from adoption of ABC innovations.

The decision criteria in our package assignment rely on several key metrics, some of which are taken directly from the results of the building stock characterization study and modeled package upgrades analysis, and some of which require post-processing before they can be integrated into our assignment and prioritization approach. These include solar photovoltaic generation potential, building HVAC capacities for heating and cooling, and baseline building characteristics.

In general, the framework guiding the package assignment logic is the ZCA framing discussed previously. The first step in assigning packages is to identify which building segments are already ZCA or will not require much upgrade work to achieve this status (such as those with no on-site fossil fuel use and baseline electricity use low enough that it could be met by on-site renewables).[i] Next, for building segments that do not meet these conditions and are thus assigned an upgrade, the second step is to determine which target performance level is necessary to achieve zero-carbon alignment. Finally, several criteria are considered from an energy system perspective, such as limiting the size of building heating and cooling equipment by increasing the level of performance of building envelope upgrades. Resilience to winter and summer grid outages, though not a primary criterion for the core package assignment analysis, was investigated as a tertiary modifier of the upgrade package level. This part of the analysis is described in *Appendix C4*.

The typology segment prioritization steps follow the assignment of upgrade packages to all segments of the building stock. The first of these steps aims to prioritize segments in US states that can accelerate adoption of ABC innovations and will also benefit from the housing development and economic activity this adoption will generate. The second step prioritizes segments that are assigned an upgrade type and level that the ABC Collaborative and the ABC Initiative focus on (namely, comprehensive upgrades that include equipment replacements alongside envelope retrofits). The final step is to aggregate results across key characteristics of the existing building stock and rank segments by their size (in number of housing units). *Appendix C3* describes both the package assignment and segment prioritization steps in detail.

Results

Exhibit 18 shows the final package assignment results for the residential building stock by climate zone. This exhibit groups together all residential building types. In Exhibit 19, we return to the single-family versus multifamily categorizations described previously and show the total number of housing units and percentage of the stock assigned each upgrade package. To present finer geographic resolution for the package assignments, Exhibits XX and XX below show results at the state level for single-family/small multifamily and large multifamily, respectively.

The results of the package assignment show that most of the existing housing stock is not currently ZCA and thus requires an upgrade. Around 30% of the single-family/small multifamily stock and 40% of the large multifamily stock achieve zero-carbon alignment with the "all equipment swap-out" package that replaces existing heating and cooling equipment, as well as other major appliances, with highly efficient all-electric technologies. The remainder of the stock (around 60%) is assigned one of the packages that includes additional envelope upgrades, with the largest share assigned the "equipment + conventional envelope" package (34%), followed by "equipment + IECC envelope" (17%) and "equipment + Phius envelope" (9%).
Most of the housing units assigned an upgrade that includes exterior envelope measures are in either the "Cold & Very Cold" or "Mixed-Humid" climate regions, with cold climates having a proportionately larger share of those assigned these packages (85% of housing units in the "Cold & Very Cold" climate region and 63% of housing units in the "Mixed-Humid" climate region are assigned a package that includes an exterior envelope upgrade). This result is primarily driven by the large heating and cooling energy demands in these climates: in many of these housing units, electrifying thermal end uses even with highly efficient heat pump technologies does not sufficiently reduce site energy use or HVAC system capacity based on the criteria described in the previous section. Therefore, these housing units are assigned packages that include envelope upgrades, which then reduce site energy use and HVAC system capacities to levels that are ZCA. Future efforts to reduce the costs of high-performance envelope upgrades will help ensure homes in regions with high thermal demands can be ZCA at costs that are competitive in the market.

i. It is not necessarily envisioned that all buildings will have on-site renewables, but aiming to lower energy usage levels such that they can be fully met by on-site renewables is a useful proxy for limiting energy demand in the context of decarbonization.

Exhibit 18. ABC Upgrade Package Assignment for All Residential Buildings by Climate Zone

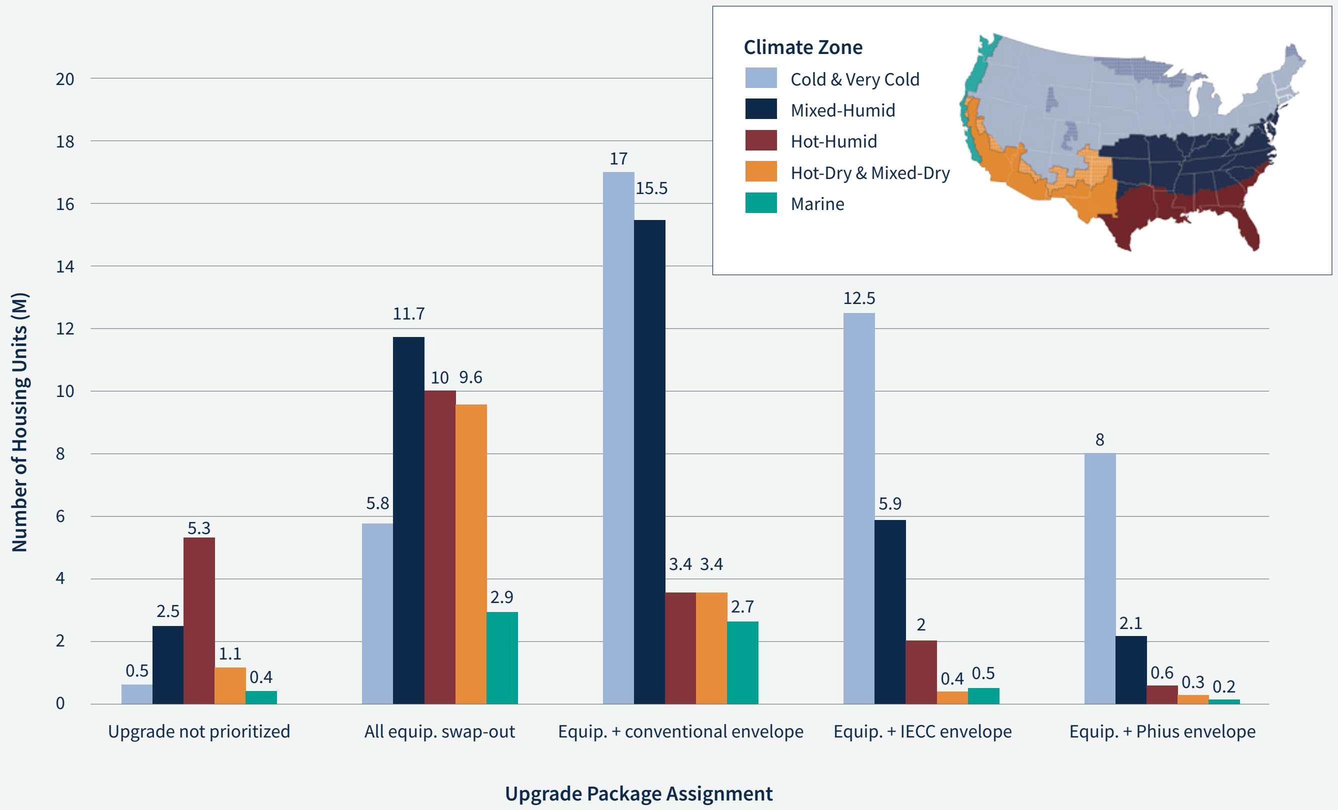
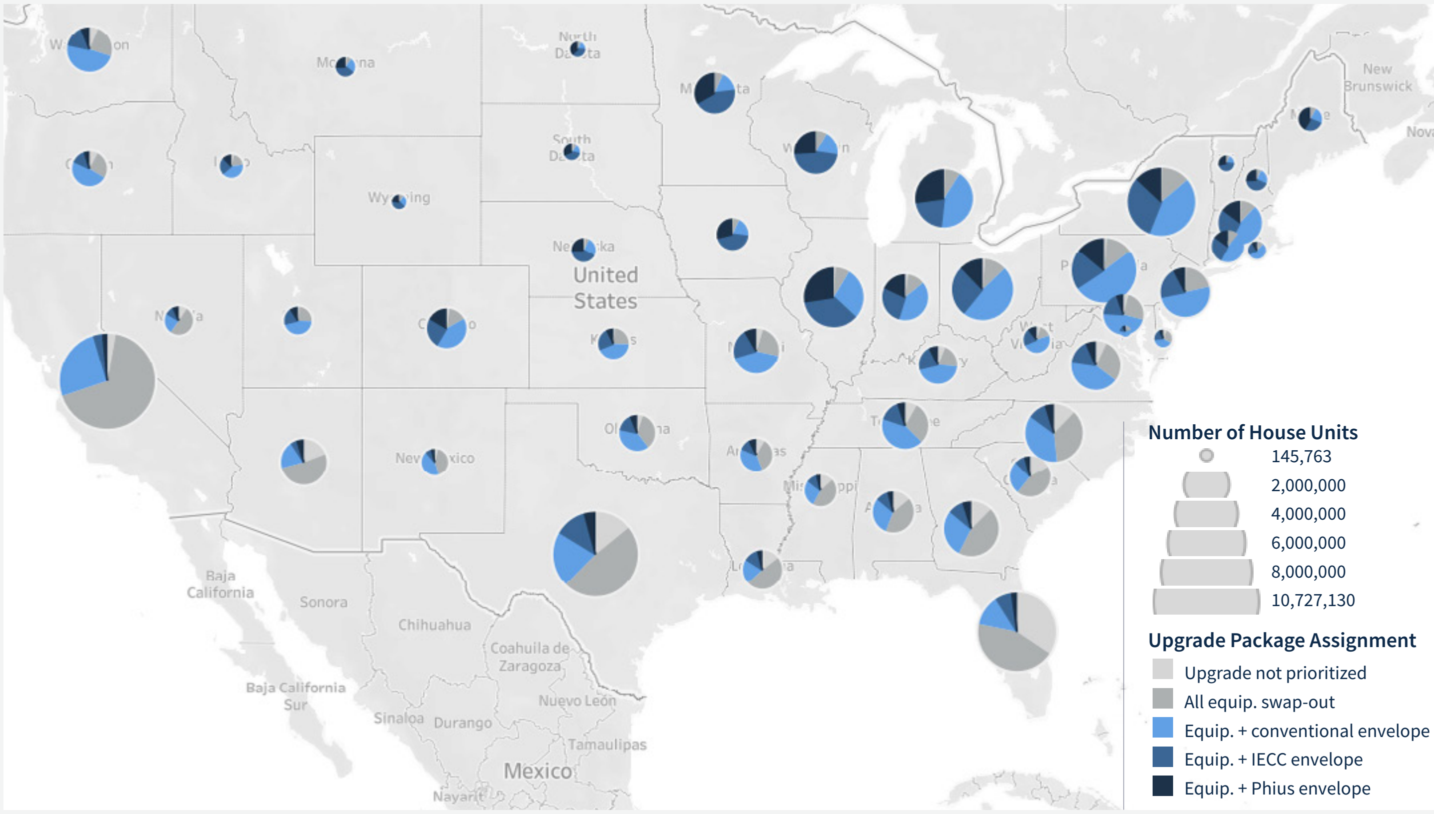


Exhibit 19.
Total Number of Housing Units and Share of Stock Assigned Each Package for Single-Family and Multifamily Building Types

Building Type	Prioritized Upgrade Package	Number of Housing Units (million)	Share of Stock
Single-family/small multifamily • Single-family detached • Single-family attached • Multifamily, 2–4 units	Upgrade not prioritized	7.3	7%
	All equipment swap-out	30.7	30%
	Equipment + conventional envelope	33.4	34%
	Equipment + IECC envelope	18.8	19%
	Equipment + Phius envelope	10.4	10%
Large multifamily housing • Multifamily, 5+ units, 1–3 stories • Multifamily, 5+ units, 4–7 stories • Multifamily, 5+ units, 8+ stories	Upgrade not prioritized	2.7	12%
	All equipment swap-out	9.3	40%
	Equipment + conventional envelope	7.8	34%
	Equipment + IECC envelope	2.6	11%
	Equipment + Phius envelope	0.7	3%

Exhibit 20.

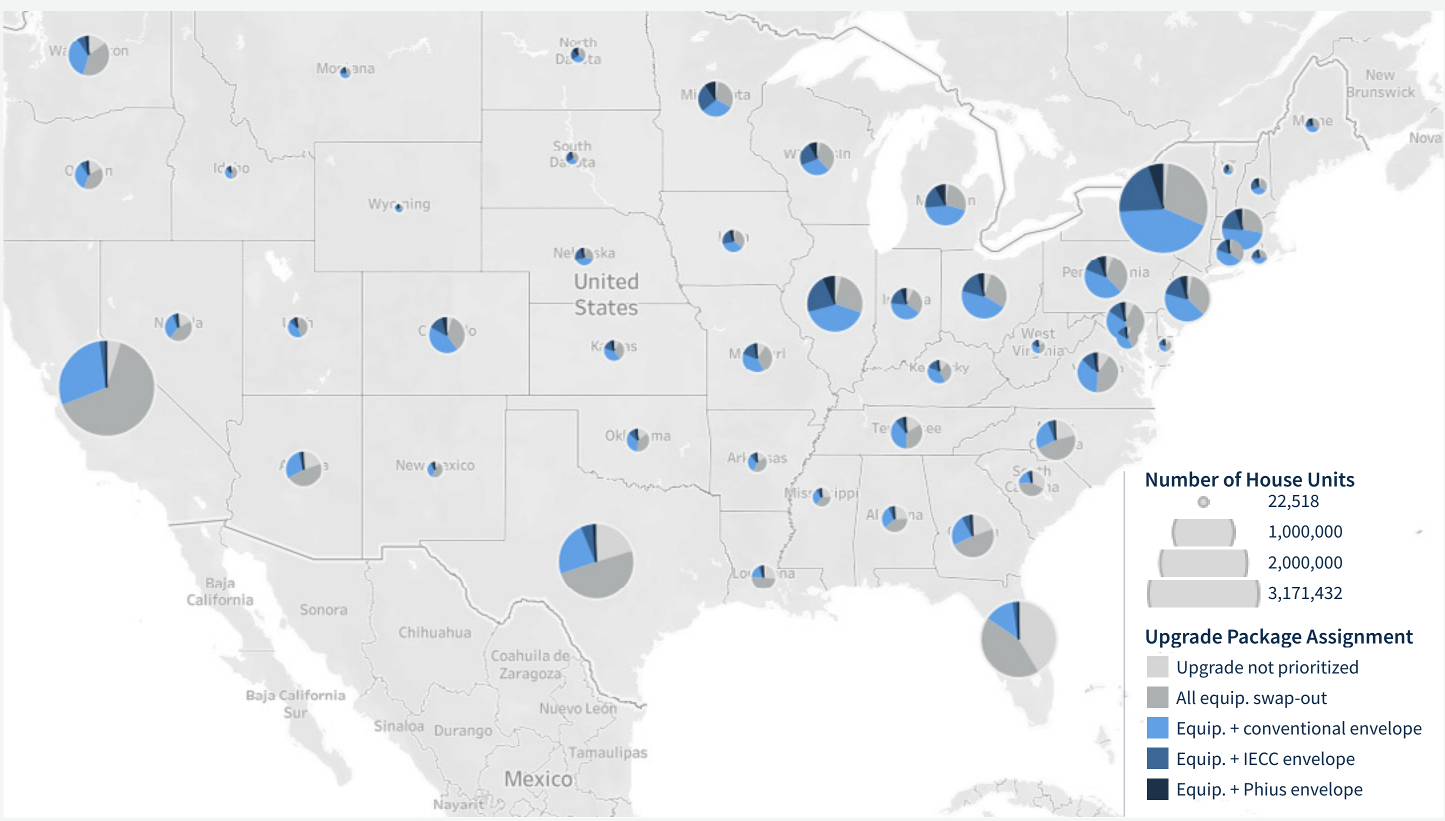
Retrofit Upgrade Package Assignments by State and Number of Housing Units for Single-Family and Small Multifamily Buildings



Source: **ABC Market Guidance for Zero-carbon Aligned Residential Buildings** by NREL Building Stock Analysis.

Exhibit 21.

Retrofit Upgrade Package Assignments by State and Number of Housing Units for Large Multifamily Buildings



Source: **ABC Market Guidance for Zero-carbon Aligned Residential Buildings** by NREL Building Stock Analysis.

In 2021, site energy consumption from residential buildings in the United States was 11.8 quads. If all residential buildings that we assign an upgrade received the package as determined by our decision criteria (see Exhibit 19 with the percentage of stock in each package assignment), residential site energy consumption would be an estimated 4 quads. This amounts to a 66% decrease and 7.8 quads of energy savings.

Summary of Priority Market Segments for ABC Retrofits

This section presents the results of the previously outlined segment prioritization steps. These build upon the package assignments and filter the results based on which segments are assigned upgrades that are the focus of ABC, while also prioritizing high-potential geographic markets. Exhibit 22 presents the top 10 single-family segments ranked by number of housing units in the segment. In some cases, the assigned package differs for aggregations of housing units with matching climate zone, building type, heating fuel, and building vintage characteristics.[i] An important caveat to these results is that ranking segments by number of housing units is a limited approach in that it does not capture other important factors that might influence how industry would prioritize building segments, such as economic or feasibility factors not included here. Our motivation is to provide guidance for the largest segments of the market that should be targeted for ABC adoption based on the assignment criteria developed previously; the following section discusses an approach to estimating cost targets and guidance for the different packages, which could further inform segment prioritization.

Given that stakeholders may have specific lines of inquiry around these results, we have developed an interactive dashboard with figures and data for download.[ii] In addition, in order to expand usage beyond industry professionals and encourage homeowners or building owners to use this guidance, we have developed an interactive tool that provides directional guidance and recommendations based on limited user input of select characteristics of a given building.[iii]

In the top 10 single-family segments, four climate zones are represented, but only one building type is represented, owing to the dominance of the single-family detached building type in terms of total number of housing units in the United States. The dominant heating fuel among these segments is natural gas, and building vintage is primarily mid-century (1940–1979). Most segments are assigned the “equipment + conventional envelope” upgrade, although there are several segments that are assigned the higher-performance “equipment + IECC envelope” and “equipment + Phius envelope” packages. In total, these 10 single-family segments represent around 7% of the single-family housing stock.

Exhibit 22. Top 10 Priority Single-Family Segments, Ranked by Number of Housing Units

Climate Zone	Building Type	Heating Fuel	Building Vintage	Upgrade Package Assignment	Number of Housing Units
Cold & Very Cold	Single-family detached	Natural gas	1940–1979	Equip. + conventional envelope	1,541,890
Cold & Very Cold	Single-family detached	Natural gas	1940–1979	Equip. + IECC envelope	991,768
Cold & Very Cold	Single-family detached	Natural gas	1980–present	Equip. + conventional envelope	807,991
Cold & Very Cold	Single-family detached	Natural gas	1940–1979	Equip. + Phius envelope	770,703
Hot-Dry & Mixed-Dry	Single-family detached	Natural gas	1940–1979	Equip. + conventional envelope	717,434
Cold & Very Cold	Single-family detached	Natural gas	Pre-1940	Equip. + conventional envelope	611,380
Hot-Humid	Single-family detached	Electricity	1940-1979	Equip. + conventional envelope	522,518
Hot-Humid	Single-family detached	Electricity	1980–present	Equip. + conventional envelope	490,315
Marine	Single-family detached	Natural gas	1940–1979	Equip. + conventional envelope	471,186
Cold & Very Cold	Single-family detached	Natural gas	Pre-1940	Equip. + IECC envelope	470,460

i. This nuance results from the fact that the package assignment criteria are based on characteristics beyond those shown in the table (e.g., site energy use and HVAC equipment capacity). So it is possible that housing units that share a climate zone, building type, heating fuel, and vintage are assigned different upgrade levels and thus appear as duplicate segments in the table.

ii. These resources can be accessed online at: **https://public.tableau.com/views/ABCMarketGuidanceforZero-carbonAlignedResidentialBuildings_16759824008870/PackageDefinitions?:language=en-US&:display_count=n&:origin=viz_share_link**.

iii. See: **https://basc.pnnl.gov/retrofit_decision_tool**.

Exhibit 23.

Top Five Single-Family Segments in Each Climate Zone, Ranked by Number of Housing Units (Includes Overall Segment Rank)

Climate Zone	Building Type	Building Vintage	Heating Fuel	Wall Structure Type	Window Insulation Level	Upgrade Package Assignment	Number of Housing Units	Segment Rank (Based on Number of Housing Units)
Cold & Very Cold	Single-family detached	1940–1979	Natural gas	Wood frame	Double-pane	Equip. + IECC envelope	1,911,382	1
Cold & Very Cold	Single-family detached	1940–1979	Natural gas	Wood frame	Double-pane	Equip. + conventional envelope	1,319,614	2
Cold & Very Cold	Single-family detached	1980–present	Natural gas	Wood frame	Double-pane	Equip. + conventional envelope	1,266,103	4
Cold & Very Cold	Single-family detached	1980–present	Natural gas	Wood frame	Double-pane	Equip. + Phius envelope	1,242,616	5
Cold & Very Cold	Single-family detached	1980–present	Natural gas	Wood frame	Double-pane	Equip. + IECC envelope	1,083,052	7
Mixed-Humid	Single-family detached	1940–1979	Natural gas	Wood frame	Double-pane	Equip. + conventional envelope	1,272,156	3
Mixed-Humid	Single-family detached	1980–present	Natural gas	Wood frame	Double-pane	Equip. + conventional envelope	1,086,926	6
Mixed-Humid	Single-family detached	1980–present	Electricity	Wood frame	Double-pane	Equip. + conventional envelope	987,168	9
Mixed-Humid	Single-family detached	1940–1979	Natural gas	Wood frame	Single-pane	Equip. + conventional envelope	909,444	11
Mixed-Humid	Single-family detached	1940–1979	Electricity	Wood frame	Double-pane	Equip. + conventional envelope	728,087	13
Hot-Humid	Single-family detached	1940–1979	Electricity	Wood frame	Single-pane	Equip. + conventional envelope	235,835	55
Hot-Humid	Single-family detached	1940–1979	Natural gas	Wood frame	Single-pane	Equip. + conventional envelope	207,022	65
Hot-Humid	Single-family detached	1980–present	Electricity	Wood frame	Double-pane	Equip. + conventional envelope	175,787	73
Hot-Humid	Single-family detached	1940–1979	Electricity	Wood frame	Single-pane	Equip. + IECC envelope	169,733	77
Hot-Humid	Single-family detached	1940–1979	Electricity	Brick	Single-pane	Equip. + conventional envelope	162,469	82
Hot-Dry & Mixed-Dry	Single-family detached	1940–1979	Natural gas	Wood frame	Single-pane	Equip. + conventional envelope	413,075	25
Hot-Dry & Mixed-Dry	Single-family detached	1940–1979	Natural gas	Wood frame	Double-pane	Equip. + conventional envelope	364,649	29
Hot-Dry & Mixed-Dry	Single-family detached	1980–present	Natural gas	Wood frame	Double-pane	Equip. + conventional envelope	345,763	34
Hot-Dry & Mixed-Dry	Single-family detached	1980–present	Natural gas	Wood frame	Single-pane	Equip. + conventional envelope	153,753	86
Hot-Dry & Mixed-Dry	Single-family detached	1940–1979	Electricity	Wood frame	Single-pane	Equip. + conventional envelope	144,794	89
Marine	Single-family detached	1940–1979	Natural gas	Wood frame	Double-pane	Equip. + conventional envelope	302,179	39
Marine	Single-family detached	1980–present	Natural gas	Wood frame	Double-pane	Equip. + conventional envelope	289,830	44
Marine	Single-family detached	1940–1979	Natural gas	Wood frame	Single-pane	Equip. + conventional envelope	269,249	48
Marine	Single-family detached	1940–1979	Electricity	Wood frame	Double-pane	Equip. + conventional envelope	135,109	99
Marine	Single-family detached	1980–present	Electricity	Wood frame	Double-pane	Equip. + conventional envelope	112,833	122

Note: Segment ranking is based on all single-family segments across all climate zones.

Exhibit 24. Top 10 Priority Multifamily Segments, Ranked by Number of Housing Units

Climate Zone	Building Type	Heating Fuel	Building Vintage	Upgrade Package Assignment	Number of Housing Units
Hot-Humid	Multifamily with 5+ units, 1–3 stories	Electricity	1980–present	Equip. + conventional envelope	289,588
Hot-Humid	Multifamily with 5+ units, 1–3 stories	Electricity	1940–1979	Equip. + conventional envelope	205,569
Cold & Very Cold	Multifamily with 5+ units, 1–3 stories	Natural gas	1940–1979	Equip. + conventional envelope	205,327
Cold & Very Cold	Multifamily with 5+ units, 1–3 stories	Electricity	1940–1979	Equip. + conventional envelope	191,525
Mixed-Humid	Multifamily with 5+ units, 1–3 stories	Natural gas	1940–1979	Equip. + conventional envelope	178,450
Cold & Very Cold	Multifamily with 5+ units, 1–3 stories	Natural gas	1980–present	Equip. + conventional envelope	153,268
Cold & Very Cold	Multifamily with 5+ units, 1–3 stories	Electricity	1980–present	Equip. + conventional envelope	140,678
Hot-Dry & Mixed-Dry	Multifamily with 5+ units, 1–3 stories	Natural gas	1940–1979	Equip. + conventional envelope	134,624
Hot-Dry & Mixed-Dry	Multifamily with 5+ units, 1–3 stories	Electricity	1940–1979	Equip. + conventional envelope	112,590
Hot-Dry & Mixed-Dry	Multifamily with 5+ units, 1–3 stories	Electricity	1980–present	Equip. + conventional envelope	98,305

In Exhibit 23, we show the top five single-family segments in each climate zone (25 segments total), ranked by number of housing units, to provide more insight into the largest regional markets for ABC. The segment's rank in the overall list of single-family segments is also included. Additional columns indicate the building's wall structure/type and window insulation level.

Exhibit 24 presents the top 10 multifamily segments, which feature representation from four climate zones, predominance among mid-century building vintages, and a more mixed spread of heating fuel. All represented building types are low-rise multifamily buildings with five or more units, reflecting the relative size of this segment in the multifamily housing stock. In terms of assigned packages, all of the top segments are assigned the "equipment + conventional envelope" upgrade.

Exhibit 25 shows the top five multifamily segments in each climate zone. As above, these segments are ranked within each climate zone by their number of housing units, but the rightmost column indicates the segment's overall ranking within all multifamily building segments.

The results above make clear that after assigning packages and prioritizing segments with the largest number of housing units, there is little variation across building type and assigned package for the largest segments. All of the largest single-family segments are detached homes, and the vast majority of them are assigned the "equipment + conventional envelope" package. Further, wood frame construction is the most common wall type among these segments. For large multifamily buildings, the largest segments are all one to three stories, and these are all assigned the "equipment + conventional envelope" package as well. Wood frame wall construction dominates in these segments. For both single-family and multifamily buildings, the top segments see more variation in terms of vintage, heating fuel, and window performance level.

These nuances are mostly a result of the predominance of specific building types in the existing housing stock. Similarly, most of the top segments have the "equipment + conventional envelope" package assignment because 1) it is the most commonly assigned package in our analysis, and 2) we explicitly chose to exclude the "all equipment swap-out" package from this prioritization exercise because ABC focuses on upgrades that include some level of envelope performance upgrade.

Exhibit 25.

Top Five Multifamily Segments by Climate Region, Ranked by Number of Housing Units (Includes Overall Segment Rank)

Climate Zone	Building Type	Building Vintage	Heating Fuel	Wall Structure Type	Window Insulation Level	Upgrade Package Assignment	Number of Housing Units	Segment Rank (Based on Number of Housing Units)
Cold & Very Cold	Multifamily with 5+ units, 1–3 stories	1980–present	Electricity	Wood frame	Double-pane	Equip. + conventional envelope	187,409	2
Cold & Very Cold	Multifamily with 5+ units, 1–3 stories	1980–present	Natural gas	Wood frame	Double-pane	Equip. + conventional envelope	182,082	3
Cold & Very Cold	Multifamily with 5+ units, 1–3 stories	1940–1979	Electricity	Wood frame	Single-pane	Equip. + conventional envelope	153,995	5
Cold & Very Cold	Multifamily with 5+ units, 1–3 stories	1940–1979	Natural gas	Wood frame	Single-pane	Equip. + conventional envelope	138,983	6
Cold & Very Cold	Multifamily with 5+ units, 1–3 stories	1940–1979	Electricity	Wood frame	Double-pane	Equip. + conventional envelope	128,571	10
Mixed-Humid	Multifamily with 5+ units, 1–3 stories	1980–present	Electricity	Wood frame	Double-pane	Equip. + conventional envelope	279,177	1
Mixed-Humid	Multifamily with 5+ units, 1–3 stories	1980–present	Electricity	Wood frame	Single-pane	Equip. + conventional envelope	135,351	7
Mixed-Humid	Multifamily with 5+ units, 1–3 stories	1940–1979	Electricity	Wood frame	Single-pane	Equip. + conventional envelope	133,656	8
Mixed-Humid	Multifamily with 5+ units, 1–3 stories	1940–1979	Natural gas	Wood frame	Single-pane	Equip. + conventional envelope	115,496	13
Mixed-Humid	Multifamily with 5+ units, 1–3 stories	1980–present	Natural gas	Wood frame	Double-pane	Equip. + conventional envelope	97,094	19
Hot-Humid	Multifamily with 5+ units, 1–3 stories	1980–present	Electricity	Wood frame	Single-pane	Equip. + conventional envelope	157,143	4
Hot-Humid	Multifamily with 5+ units, 1–3 stories	1940–1979	Natural gas	Wood frame	Single-pane	Equip. + conventional envelope	128,813	9
Hot-Humid	Multifamily with 5+ units, 1–3 stories	1980–present	Electricity	Wood frame	Double-pane	Equip. + conventional envelope	73,849	30
Hot-Humid	Multifamily with 5+ units, 1–3 stories	1980–present	Electricity	Wood frame	Single-pane	Equip. + IECC envelope	53,753	44
Hot-Humid	Multifamily with 5+ units, 1–3 stories	1940–1979	Electricity	Wood frame	Double-pane	Equip. + conventional envelope	48,184	51
Hot-Dry & Mixed-Dry	Multifamily with 5+ units, 1–3 stories	1940–1979	Electricity	Wood frame	Single-pane	Equip. + conventional envelope	99,273	17
Hot-Dry & Mixed-Dry	Multifamily with 5+ units, 1–3 stories	1940–1979	Natural gas	Brick	Single-pane	Equip. + conventional envelope	96,852	20
Hot-Dry & Mixed-Dry	Multifamily with 5+ units, 1–3 stories	1980–present	Natural gas	Wood frame	Single-pane	Equip. + conventional envelope	91,767	23
Hot-Dry & Mixed-Dry	Multifamily with 5+ units, 1–3 stories	1980–present	Electricity	Brick	Double-pane	Equip. + conventional envelope	81,113	28
Hot-Dry & Mixed-Dry	Multifamily with 5+ units, 1–3 stories	1980–present	Electricity	Brick	Double-pane	Equip. + conventional envelope	63,922	35
Marine	Multifamily with 5+ units, 1–3 stories	1980–present	Electricity	Brick	Double-pane	Equip. + conventional envelope	81,840	26
Marine	Multifamily with 5+ units, 1–3 stories	1940–1979	Electricity	Wood frame	Single-pane	Equip. + conventional envelope	63,680	36
Marine	Multifamily with 5+ units, 1–3 stories	1940–1979	Electricity	Brick	Double-pane	Equip. + conventional envelope	41,162	59
Marine	Multifamily with 5+ units, 1–3 stories	1980–present	Natural gas	Wood frame	Single-pane	Equip. + conventional envelope	38,498	68
Marine	Multifamily with 5+ units, 1–3 stories	1940–1979	Electricity	Wood frame	Single-pane	Equip. + conventional envelope	30,750	80

3.4 Package Cost Target Analysis

One of the aims of this guidance is to provide industry with state-level cost targets for the whole-building upgrade packages assigned to various segments of the building stock in the previous sections. Given the minimal levels of adoption of these packages today, we expect initial package costs to be high. While we expect to see these costs come down with innovation and scale, they are unlikely to be supported by utility cost savings alone, at least in the near term.

In most states, utility-administered energy efficiency programs calculate cost-effectiveness using tests that do not account for societal, environmental, or participant health benefits, thus limiting the ability of whole-building deep retrofits to pass these tests.[53] In this environment, cost compression, as well as appropriate calculation and incorporation of energy and non-energy impacts, is essential for scaling these whole-building packages. The cost targets presented in this section are based on conservative estimates of a full value stack that the assigned ABC packages could provide. A high-level overview of our approach to developing and estimating cost targets is included in Exhibit 26.

Exhibit 26. Overview of Cost Target Methodology and Specification Details

	Total Cost Target	
Description	**What this package should cost "all in," considering the value from avoided business-as-usual equipment and roof/siding replacements**	
Cost Target Range	More aggressive (more cost compression required)	Less aggressive (less cost compression required)
Revenue and Other Elements of the "Value Stack" That Are Included	• Utility bill savings • Avoided costs of business-as-usual upgrades (regular replacements that would otherwise be needed)	• Utility bill savings • Avoided costs of business-as-usual upgrades (regular replacements that would otherwise be needed) • Non-energy impacts (including both occupant and building added value, but not broader system benefits)

Cost targets are calculated for each package based on the maximum project cost that would achieve a positive lifetime net present value (NPV), accounting for the revenue, avoided equipment and envelope maintenance costs, and value of NEIs outlined above in Exhibit 27. The cost target considers a reference case in which the building would undergo conventional equipment, appliance, and envelope component replacements and includes these costs in the cost target. The reference case equipment upgrades are like-for-like replacements of existing heating/cooling systems and appliances (meeting federal minimum performance standards).

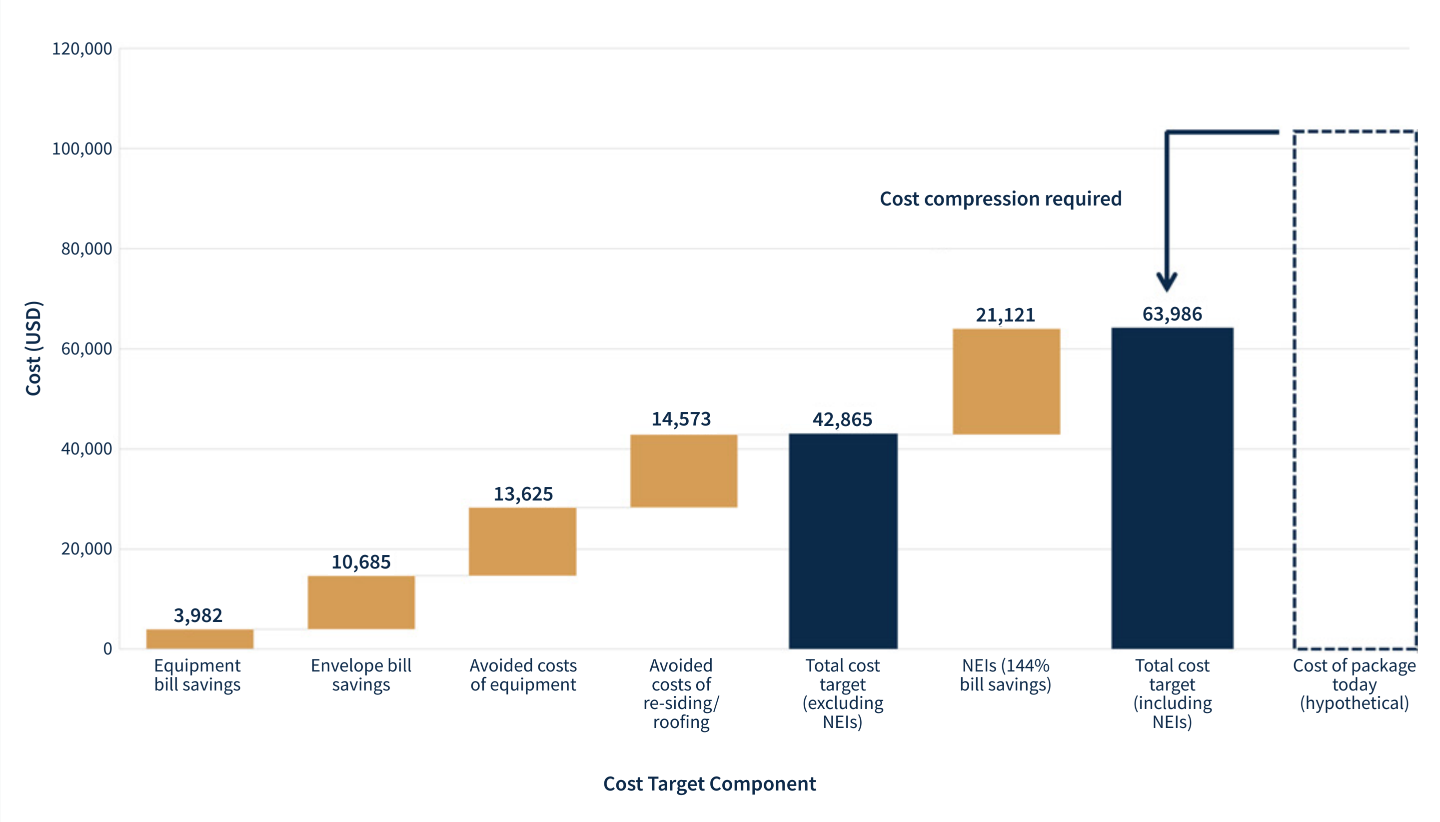
To calculate the avoided costs of reference case envelope upgrades, we assume that single-family and small multifamily housing units would undergo a re-siding and reroofing project in the reference case (it is reasonable to assume most of these buildings would require such replacements before 2050). We integrate these costs into our cost target equation using average home renovation expenditures for re-siding projects, resolved at the level of census divisions,[54] and national average home expenditures for reroofing projects.[55] We do not include these expenditures for large multifamily buildings due to limited available data with which we could estimate the cost of a reference re-siding or reroofing job for these buildings (which makes the cost targets for multifamily buildings slightly more conservative). Furthermore, for neither building type do we include the reference cost of window replacements. While these would yield additional cost savings, it is also the case that window replacements would deliver energy savings, so our energy savings estimates for the upgrade packages (which are modeled in comparison to the reference case) would no longer be accurate. We include re-siding and reroofing costs based on the assumption that these reference case replacements would deliver negligible energy savings.

In addition to the reference case equipment and envelope costs, we include each package's modeled lifetime utility bill savings, based on statewide average utility rates, as well as a multiplier on energy savings to represent the value attributable to the NEIs of the project. To calculate the cost target, we take the combined NPV of these savings to estimate what the installed cost of the package should be if the project is to have a positive lifetime NPV.

While there are numerous approaches to assessing NEIs and quantifying their monetary benefits, we adopt a simple approach based on a meta-analysis of NEI savings as a percentage of utility bill savings.[56] We take a conservative approach and include only the savings that accrue directly to the occupant — rather than those that also accrue to utilities or society — which are estimated to total 144% of the project's utility bill savings.[57] Importantly, these values are derived from studies primarily of weatherization programs, so they likely underrepresent the benefits of the higher-performance upgrade packages considered in this analysis.

Exhibit 27 presents an illustrative diagram for one of the upgrade packages ("equipment + IECC envelope") to show each of the cost target components described above. The sum of these components yields a total cost target, which is likely lower than the hypothetical cost of this example retrofit package today (represented with a dashed outline in the exhibit), thus necessitating a certain amount of cost compression.

Exhibit 27. Illustrative Cost Target Breakdown for the "Equipment + IECC Envelope" Package for Single-Family Homes



Note: This illustrative diagram shows both more aggressive (excluding NEIs) and less aggressive (including NEIs) calculations.

Cost Target Results

Exhibit 28 presents distributions of cost targets for single-family and small multifamily buildings, per dwelling unit, and Exhibit 29 presents the same for large multifamily buildings. Each sample is represented by a dot, while the gray bands represent the interquartile range (25%–75% of the distribution) and the black bar represents the median cost target. The results below include the value from NEIs in the cost targets; we include additional results tables for both building type groupings in Appendix C5.

These cost targets are specified for the subset of housing units in each state that are assigned the relevant upgrade package. For instance, the "equipment + conventional envelope" cost target in California is based on the modeling results from housing units that are assigned this package using our assignment approach described in the previous section. Cost targets are only presented for the upgrades that include envelope measures, but in all cases these upgrades also include the equipment electrification and appliance replacements in the "all equipment swap-out" upgrade.

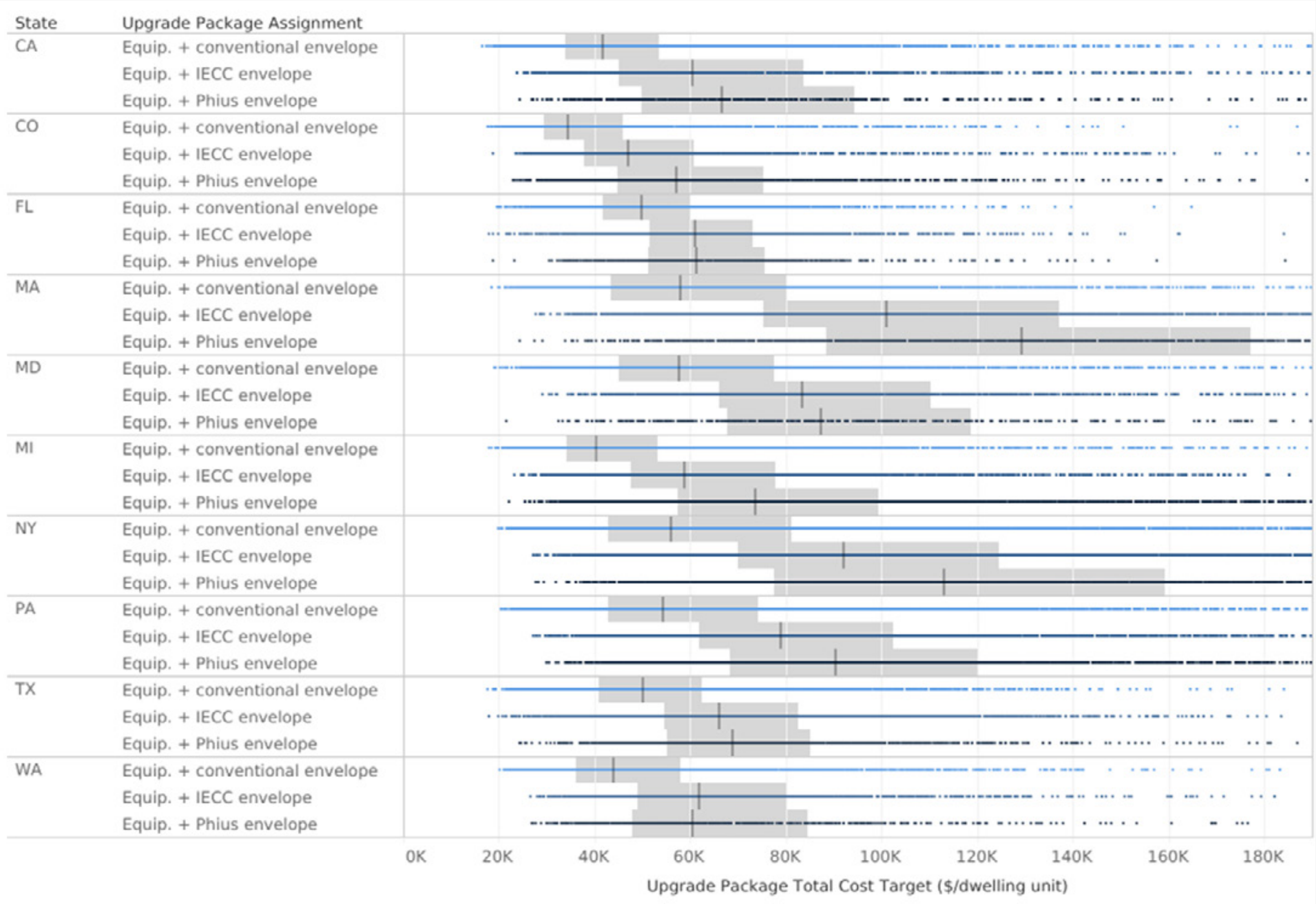
Our analysis finds that cost targets based on the various aspects shown above, which include components that are often excluded from typical cost-benefit analyses, are still quite aggressive. For example, in the single-family and small multifamily group, median cost targets for the "equipment + conventional envelope" package range from $35,500 per housing unit in Colorado to nearly $60,000 per housing unit in Maryland, whereas the range for the "equipment + Phius envelope" package is around $60,000 per unit in the lowest case (Washington) and up to $135,000 per unit in Massachusetts. As discussed previously, these targets are based on a comparatively expansive approach to quantify and monetize the benefits of retrofits by including NEIs. However, we did not include other aspects that could further raise these cost targets (i.e., necessitate less cost reduction for these packages to ensure they are cost-neutral to existing replacements), such as utility system or societal benefits.

In comparison with the single-family and small multifamily cost targets, the large multifamily targets are quite a bit lower per unit for two primary reasons. First, the utility bill savings are generally lower for these projects due to lower baseline energy use in these homes. And second, we do not include the avoided costs of re-siding or reroofing for these building types (for the data availability reasons explained above). However, these dwelling units are also located in larger buildings where economies of scale from a building-wide retrofit project may make the per-dwelling-unit cost targets more achievable. We find that median costs and cost distributions vary widely among states — and among different packages within the same state. Given that these results are based in part on utility bill savings, it is unsurprising that they vary considerably across states, as state-level electricity and non-electric fuel prices vary considerably, as well. For single-family/small multifamily buildings, in most states, the cost targets increase for the successively higher-performance packages. That is, in most cases, the cost target for the "equipment + conventional envelope" package is lower than that for "equipment + IECC envelope," which is lower than the target for "equipment + Phius envelope." This results from the greater utility bill savings for the higher-performance envelope measures.

The trend differs slightly in large multifamily buildings: the cost targets in many states for the "equipment + IECC envelope" package are greater than those for the "equipment + Phius envelope" package. This is due to nuances in our prioritization logic, which incorporates factors beyond energy (and related utility bill) savings, such as the incorporation of criteria around HVAC capacities and solar PV potential. In certain cases, these factors lead to the assignment of a more aggressive package to housing units where the utility savings opportunity is simply quite low.

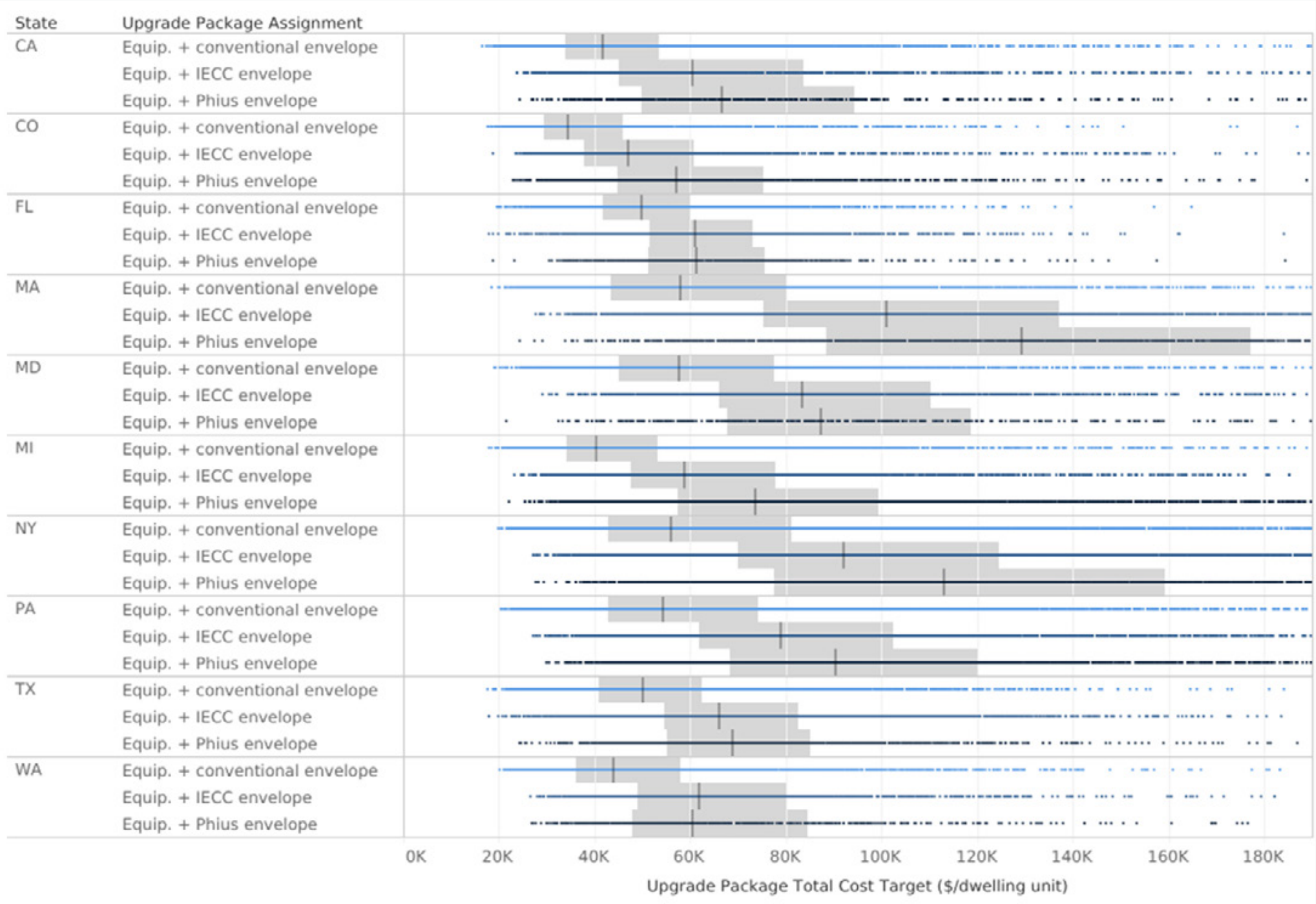
Photo credit: RMI

Exhibit 28. Single-Family and Small Multifamily Cost Targets in Priority States



Note: These per-unit cost targets include costs of reference case replacements as well as non-energy impacts.

Exhibit 29. Large Multifamily Cost Targets in Priority States



Note: These per-unit cost targets include costs of reference case replacements as well as non-energy impacts.

Cost Compression Opportunities

Achieving the indicative cost targets specified above will require a substantial compression of costs across the technologies included in each package and the delivery of those packages. Even if long-term financing options are available to building owners and occupants, the loan amounts that could be supported by the projects' energy cost savings are likely insufficient to cover the full installed costs of the packages without cost compression. And while it is not common practice to include the value of NEIs in consumer cost-effectiveness calculations for building retrofits, accurately measuring and quantifying these benefits can help reduce the cost compression needed. Still, scaling the adoption of these packages will require reducing their costs.

This section briefly outlines some of the most promising opportunities for cost compression of deep retrofit projects such as those outlined and prioritized in this report. Most of this summary draws on a comprehensive survey of the costs and opportunities for cost compression of deep retrofit projects in US homes by Less et al.[58] They identify several distinct categories of cost compression, which we summarize briefly here:

- Technology improvements
- Policy mechanisms
- Business model innovation

These three categories do not constitute an exhaustive list of cost compression opportunities. There are numerous other ways to improve the economics of deep retrofit projects, including several no- or low-cost solutions related to consumer behavioral changes that can ensure projects achieve their expected savings and/or can supplement savings via additional revenue streams. We do not discuss these opportunities at length in this summary (nor do we make any recommendations on potential policies) but note that they could also help compress costs for deeper retrofit projects to facilitate more uptake in the residential market.

Technology Improvements

Opportunities for technological cost compression can include changes that directly reduce the material cost of technologies, improvements in technology performance that increase project return on investment, and cost reductions related to learning and economies of scale. Leveraging technology innovations that are emerging from new industrialized approaches to construction can achieve cost reductions in both materials and installation for projects that include envelope retrofits.[59] For building electrification projects specifically, alternative low-cost technology pathways to avoid costly utility service or circuit breaker upgrades (e.g., smart circuit splitters and low-voltage, power-efficient appliances) can also make projects more cost-competitive for consumers.[60] A forthcoming report on ABC research opportunities will detail technology areas important to ABC where there is a need for technology improvements.

Policy Mechanisms

Rebates and incentives are direct policy mechanisms that can help compress the installed costs of home decarbonization projects and stimulate the market. Policies have directed these mechanisms toward consumers but also toward upstream and midstream actors in the retrofit market, such as equipment manufacturers, distributors, or installers. Examples of each can be found in the IRA. The IRA allows for a range of rebates and tax credits applicable to building retrofit projects.

Business Model Innovation

Business model innovation can provide cost compression for retrofit projects by reducing project soft costs, bundling measures into packages to reduce costs of installation, or achieving savings via volume purchasing discounts from manufacturers. A review of the literature on home decarbonization upgrades found that gross margins (soft costs, overhead, profit) are higher for home performance contractors than other construction industry averages.[61] Business model innovation could particularly help compress project costs by reducing soft costs, as these often account for half of a project's total budget. Some of the key opportunities to reduce soft costs include:

- Outsourcing customer acquisition to programs with marketing and sales expertise
- Using remote approaches for customer acquisition, management, and sales
- Simplifying initial feasibility evaluation and scoping with streamlined digital tools and systematized processes
- Automating HVAC equipment sizing using rapid, block load software programs
- Reducing diagnostic testing and commissioning costs (e.g., those related to combustion safety)

3.5 Additional Retrofit Considerations

Implementation Considerations

The guidance in this report does not present construction methods or specific technologies needed to achieve the performance targets in the retrofit packages described above.[i] Implementation challenges range from electrical upgrade and material abatement requirements to deferred maintenance (and unforeseen conditions) in the existing building stock to the great variety of architectural features on existing building facades. These topics will be covered in detail in the forthcoming report on ABC research opportunities, and readers are encouraged to look there for a discussion of implementation challenges and innovations needed to deliver these retrofit packages at scale.

Utility Rates

The cost targets presented above depend largely on utility bill savings estimates that use statewide average utility rates for both electricity and non-electric fuels. They do not, therefore, account for the impact of future rate design on project-level economics, nor do they capture time-varying electricity pricing, which many utilities in the priority states are beginning to roll out. Both factors will undoubtedly impact the utility bill savings of specific retrofit projects, implying that the cost targets should be viewed as preliminary, static estimates that could be updated over time or for future years based on projected utility rates.

In certain states, the so-called "spark spread"— the difference between electricity and natural gas prices per unit of energy delivered — is greater than the efficiency difference between fossil fuel equipment and heat pump equipment. In these cases, even efficient equipment replacements will increase customer utility bills. (In our analysis, around 16% of all housing units show annual utility bill increases when assigned the "all equipment swap-out" package.) This will be exacerbated in colder climates with high thermal energy demands (75% of the housing units with bill increases are in the "Cold & Very Cold" climate region). Envelope interventions can increase utility bill savings by yielding additional energy savings, but, in general, the higher the spark spread, the worse the ZCA retrofit economics. Exhibit 30 below shows the annual utility bill savings for the "equipment + conventional envelope" package (the package with the highest assignment percentage) versus the ratio of electricity to gas prices by state. The figure shows data only for homes with natural gas as the existing heating fuel. The correlation shows that as the electricity-to-gas ratio goes up, the annual bill savings for this package go down, highlighting the importance of rate design and utility business model alignment with decarbonization goals.

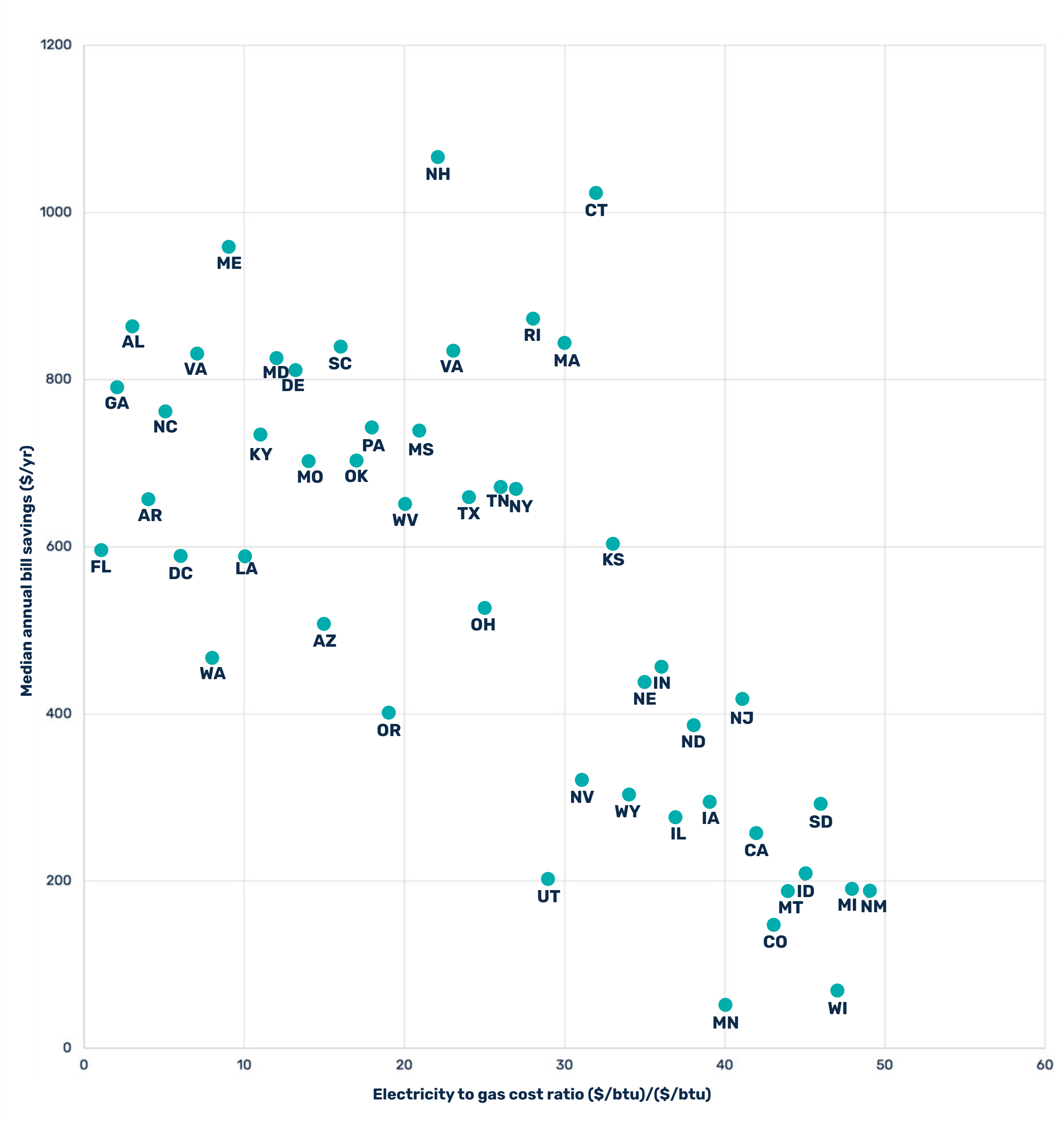
Relatedly, we do not account for the impact of natural gas price volatility, but there is recent evidence, especially from Europe, that natural gas prices are rising as prices for renewable energy technologies continue to decline.[62] Rising natural gas prices will help close the spark spread discussed above and increase the cost-competitiveness of ABC retrofit packages.

Photo credit: Dextall

i. Exhibits XX–XX in *Appendix D: Embodied Carbon* provide a few examples of envelope assemblies that could provide performance in line with each of the three envelope-inclusive retrofit packages modeled. Additionally, PNNL's report *Wall Upgrades for Energy Retrofits: A Techno-Economic Study* evaluates a range of wall retrofit assemblies; this may be of interest to those seeking details on specific materials and methods. See: **https://www.pnnl.gov/publications/wall-upgrades-energy-retrofits-techno-economic-study**.

Exhibit 30.

Median Bill Savings for the "Equipment + Conventional Envelope" Package versus the Ratio of Electricity to Gas Prices by State



Retrofit Market Conclusions

- An immense number of homes need to be retrofitted to achieve a ZCA residential building stock. Retrofits are needed on around 115 million dwelling units — 94.5 million single-family and small multifamily units and 20.4 million large multifamily units. However, a large majority of the existing US housing stock can become ZCA through electrification and modest improvements to the building envelope.
- Around 60% of the housing stock (some 75 million housing units) requires upgrades to building envelope components with varying levels of performance. This represents a massive market opportunity for ABC innovations that can improve the speed and scale of deploying these types of whole-building retrofits.
- Because building type, vintage, and wall construction are among the most important factors in the design of ABC innovations for whole-building retrofits, and given that most of the largest building segments share these characteristics across climate regions, these segments could be aggregated to larger shares of the building stock, thus increasing the potential market for such innovations.
- Some segments that are not prioritized in the tables above because of their small size and limited potential for aggregation may still be particularly advantageous for early ABC adoption (e.g., due to their project economics or their potential to deliver outsize benefits to occupants). In particular, homes that currently heat with fuel oil or propane will likely have large potential utility bill savings and thus could support higher installed project costs. Similarly, these segments may also yield more immediate benefits to occupants in terms of household energy burdens and NEIs such as occupant comfort and health. Furthermore, buildings with existing electric resistance heat in regions where the electricity grid is highly emissions-intensive are likely to have better project economics and to offer societal benefits from retrofits in the form of near-term emissions reductions.
- Incorporating NEIs and avoided business-as-usual building maintenance costs, in addition to utility bill savings, creates aggressive but not unrealistic cost targets for ABC packages. Finding real ways to monetize these value streams will aid in ABC package adoption. Additionally, these NEIs can provide considerable value to building owners and inhabitants, and owners should consider incorporating higher levels of efficiency beyond the minimum ZCA guidance in this report to support greater resilience, comfort, and health benefits for building occupants.
- The cost targets for the priority states vary widely. Contractors, manufacturers, and developers should focus on the building types/characteristics with the highest targets first, as these represent the “low-hanging fruit” for package deployment. Cost compression can be achieved through technology and process improvements, policy mechanisms, increased provider experience, and business model innovation while targeting these “high-value” projects in the near term.

Photo credit: RMI

Photo credit: Timber HP

4. Embodied Carbon

Embodied carbon (EC) refers to the greenhouse gas emissions that are "embedded" in a product (or building) throughout its full life cycle, including its manufacturing, transportation, installation (or construction), maintenance, and disposal. In the US buildings sector (including construction), EC accounts for a growing share of full life-cycle emissions, especially as operational emissions from the sector decrease due to energy efficiency and the energy system's transition away from fossil fuels. As one example of the EC problem in these industries, in 2018, the United States generated more than two times as much construction debris as municipal solid waste, with nearly 455 million tons ending up in landfills.[63] Despite recent attention from both government and nongovernmental actors on these and related issues, a significant opportunity remains to decrease the EC in the US building stock.

As a supplement to this report, we undertook an analysis to assess the EC of several different insulation materials that are commonly used in whole-building home retrofits.[i] Developing and deploying insulation materials with lower life-cycle greenhouse gas (GHG) emissions is an important intervention point for reducing EC in the built environment. Of course, there are many other issues pertinent to EC in both new construction and building retrofits that require attention from industry, but here we focus on insulation given its relevance to the retrofit upgrade packages introduced in the previous section.

In *Appendix D* we present a detailed overview of the topic of EC and related approaches for measurement, such as life-cycle assessment (LCA) and the use of these measurements to develop Environmental Product Declarations (EPDs) for different building materials. We also include additional methodological details on the database that was compiled to compare the EC of different building insulation materials, which expands on recent research from Efficiency Vermont,[64] as well as the approach to estimate GHG impacts in terms of global warming potential (GWP) for both building mechanical equipment and envelope components. This approach was then applied to the retrofit upgrade packages to determine the best options to meet the performance levels specified in each of the packages while choosing low-EC materials.

Exhibits 44–54 in *Appendix D* present detailed wall assembly layer information for each of the upgrade packages, including recommended materials and product specifications. These are intended to provide initial, informational guidance on meeting the performance targets specified in this report while simultaneously reducing full life-cycle GHG emissions by selecting lower-EC insulation products.

i. Additional analysis of embodied carbon in retrofits is available in RMI's 2023 report *Transforming Existing Buildings from Climate Liabilities to Climate Assets* (**https://rmi.org/insight/transforming-existing-buildings-from-climate-liabilities-to-climate-assets/**).

Photo credit: RMI

5. Conclusion

This report offers information on priority markets, performance levels, and target costs for ZCA new construction and retrofits. But there is still a great need for broader availability of specific physical solutions — such as construction products and assemblies — that can achieve necessary performance levels and are feasible to build or install across a large volume of projects. Similarly, there is a need for innovations beyond the immediate scope of this report: business models that can deploy these physical solutions competitively at scale and enabling financial and technical tools. Industry must play an important role in filling these needs.

With the market opportunity increasingly clear, existing and emergent manufacturers, fabricators, and other supply-side actors can apply the guidance in this report to develop, refine, or further invest in much-needed repeatable ZCA physical solutions appropriate for key market segments and major typological tranches.

Providers that deliver these physical solutions — whether vertically integrated or separate contractors — can use insights from this report to prioritize their creation or acquisition of project pipelines. Taking this view, providers have an opportunity to deploy innovative business models that capitalize on the shortcomings of traditional approaches to construction, which deal with individual projects in isolation and take a narrow treatment of benefits and risks. Business models built on expanded concepts of value, repeatability in procuring both projects and the products used in them, and continuous improvement of execution processes are key to scaling ZCA new construction and retrofits.

These physical solutions and business models will benefit from enabling tools such as financial, insurance, and software products that are built for integrative projects at speed and scale and eschew arbitrary barriers born of convention — too often a challenge in these areas.

Any market will develop more robustly with clear demand signals. It is incumbent upon demand-side stakeholders like real estate owners, operators, and developers to recognize and act on the fact that the future of the buildings sector necessarily lies in zero-carbon alignment — and that this shift will yield benefits beyond utility savings and even emissions reductions. (In residential buildings, many of these benefits can especially improve the lives of disadvantaged or vulnerable community members.) This future must be embraced broadly and rapidly, with ABC as part of the way forward. Demand stakeholders have a critical role to play in bringing a holistic lens to their construction pipelines and building portfolios — something this report seeks to support — and cooperatively engaging with forward-looking supply-side providers to apply ZCA solutions.

Beyond industry, public-sector stakeholders can consider using the technical information in this report to inform decision-making around building performance requirements and the allocation of resources relating to the building stock, with an eye toward repeatability and scale.

Given the magnitude of the task ahead, there is an opportunity for virtually all types of buildings sector stakeholders to participate in and prosper as part of a suitably rapid transition toward zero-carbon alignment, but an uncommon degree of foresight, innovation, and collaboration will be essential to success.

Appendix A: Introduction

Appendix A1: Use of Energy as a Primary Metric and Grid Impacts

Use of Energy as a Primary Metric

In much of this report, we use site energy consumption and energy savings as primary metrics for determining the appropriate performance levels for certain buildings and providing performance guidance. We decided to use energy as the primary metric for several reasons, which we discuss here to address methodological questions that might arise in the following sections.

We acknowledge that cost- and carbon-related metrics are integral to accelerated decarbonization of the built environment, but these metrics may be less reliable in terms of current data quality and methodological certainty. Reliable sources of both up-front project costs and savings estimates are needed to employ a cost metric. The presently available data on installed costs for energy efficiency upgrades and high-performance new construction is highly variable and often location- and project-specific.[65] Additionally, the available cost data does not typically represent the types of industrialized construction techniques that ABC focuses on. Looking ahead, work is ongoing to systematically collect and validate project cost data to improve data availability and quality. Additionally, as the ABC market matures, we anticipate increased availability and consistency of cost data from projects that use ABC solutions.

Carrying out a granular calculation of the cost savings of energy efficiency upgrades would involve assumptions around fuel costs, which are highly variable as well as being customer- and rate-dependent. Thus, any estimate of cost-effectiveness, particularly for ABC deployments, would be highly uncertain. In the retrofit guidance presented in this report, instead of using cost-effectiveness to determine the decarbonization pathway, we define ZCA packages based on energy use and savings, then back out the up-front costs of these packages that would be needed for them to scale. We use state-average utility costs for electric and non-electric fuels to estimate savings. While this approach certainly misses some complexities in rate design, as well as future variability in fuel costs (which was especially pronounced in early 2022, when the natural gas spot price nearly doubled from January to May), it provides a simple and location-specific approach to estimate savings from ABC interventions, as well as a foundation to provide cost targets for market guidance.

Similar methodological and data reliability questions arise for calculations of CO2 emissions savings. While CO2-equivalent emissions from non-electric fuels are more straightforward to calculate and estimate for energy-saving projects, electricity emissions are highly location- and time-dependent. Even for a specific location, an analysis of CO2 emissions reductions from electricity savings will depend on assumed use of a specific type of emissions factor (e.g., short-run/long-run marginal emissions factors versus average emissions factors).[66]

Furthermore, projecting future CO2 emissions savings from energy efficiency or electrification projects requires assumptions around grid decarbonization. Selecting a scenario or scenarios for these calculations can greatly affect the estimated emissions savings potential of a given project, and these scenarios have high degrees of uncertainty. Over time, the emissions value of energy efficiency measures will need to be reevaluated under assumed rapid rates of power sector decarbonization, given that electrification measures will yield relatively large CO2 emissions savings when the power sector is fully decarbonized, whereas energy efficiency measures will yield none.[67] However, many of the substantial non-energy and non-carbon benefits of energy efficiency measures will remain, even with a decarbonized power sector. For example, site energy consumption still matters with a decarbonized power sector, because it affects the amount of clean power generation, transmission, and distribution capacity that must be built and maintained, as well as the reliability of the grid.

In this report, we do present cost and carbon savings results for the modeled packages, and we explicitly define our assumptions. (We also use energy cost savings as one element in calculating indicative cost targets.) Because of the questions around assumptions and data reliability mentioned above, however, we do not use these for the primary task of determining an appropriate level of energy performance for the building segments.

Grid Impacts

Transitioning end-use equipment in buildings from fossil fuels to electricity will, in many cases, add load to the electrical grid. In cold and mild climates, sufficient levels of building electrification will likely increase annual grid peaks and flip the timing of these peaks from summer to winter. While some amount of heating electrification can occur within the existing capacity constraints, many areas will need to expand power system capacity at all levels — distribution, transmission, and generation — at the same time that many regions work to incorporate increasing levels of renewable energy.[68]

Given the relatively reduced availability of renewable energy in winter months, particularly solar PV, minimizing winter peaks through energy efficiency and demand flexibility will both decrease power system costs and aid in electricity system decarbonization. In hot climates, even at high penetrations of building and transportation electrification, annual grid peaks are likely to remain in the summer. In these regions, building efficiency and demand flexibility will help to minimize the necessary capacity expansion to meet newly electrified loads and firm up intermittent renewable supply.

Identifying the optimal mix of building-level versus power system investments to reach a decarbonized future is beyond the scope of this report. However, the guidance presented here is well grounded in the reality that building and electricity decarbonization are inextricably tied, and that considering either in a vacuum will ignore important aspects of creating an equitable, low-cost, and rapid transition.

Appendix A2: Additional Benefits and Non-Energy Impacts

While electrification and energy efficiency improvements in both existing buildings and new construction can substantially affect energy usage, they often yield additional benefits known as non-energy benefits (NEBs). Research in this area often uses the more neutral term "non-energy impacts" (NEIs) to acknowledge that interventions, although frequently beneficial, can have both positive and negative impacts.[69] Considering NEIs supports a more complete understanding of the attributes of high-performance buildings and the effects of building upgrades, and it can be especially relevant when assessing the value of whole-building retrofits.[70]

In addition to the grid impacts described above, NEIs can include occupant factors (e.g., health, comfort, and productivity), building or dwelling factors (e.g., resilience, durability, maintenance needs, and building equity value), and broader environmental and societal factors (e.g., public health, environmental pollution, and economic factors related to job growth and development), among others.[71]

These impacts are important to measure, quantify, and, where possible, monetize to scale the adoption of high-performance building upgrades. This is because the up-front or installed costs of building efficiency and electrification technologies may not be offset by near-term utility bill savings alone.[72] In such cases, collective mechanisms can play a role in supporting decarbonization (which has a clear overall societal benefit), even where cost compression and value augmentation (such as through monetization of some NEBs) do not result in a payback acceptable to individual market actors.

In this appendix, we review the evidence for several NEIs that we consider most relevant and promising in the context of this market guidance. The appendix is neither a comprehensive nor systematic review but rather a summary of key NEIs and their supporting evidence. We group these broadly into three categories: NEIs related to occupant health and well-being factors; NEIs related to building factors, such as resilience, durability, reduced maintenance, and home resale value; and NEIs related to community-level benefits, such as local development and job growth. These categories are not mutually exclusive and often include overlapping NEIs.

Occupant Health, Well-Being, and Productivity

Occupant health and well-being impacts are among the most well-researched NEIs. This category of NEIs refers to impacts that limit exposure to environmental factors that affect health, well-being, and productivity. Energy efficiency upgrades such as increased insulation and window performance, draft-proofing, better ventilation, more efficient and all-electric heating and cooling systems, and electric cooking appliances can improve indoor air quality and thermal comfort. A thorough review of these NEIs and the evidence supporting them appears in studies by Hawkins et al. and the IEA.[73]

Energy efficiency–induced reductions in energy consumption can also yield reductions in local air pollution due to avoided emissions of fine particulate matter (PM2.5) and other pollutants that stem from electricity generation.[74] Many studies have demonstrated a relationship between improved indoor air quality and occupant or worker performance and productivity,[75] and while this relationship was previously applicable primarily to office and workplace settings, the shifts to work-from-home that have resulted from the COVID-19 pandemic make this NEI more applicable to the home environment, as well.

Reduced exposures to health-related environmental factors have primarily positive outcomes for occupants. These include reductions in mortality, injuries, diseases, and other afflictions such as depression and stress. According to the IEA review,[76] the evidence is strongest for reduced excess mortality from cardiovascular disease and related illnesses due to better indoor air quality, as well as reductions in respiratory diseases due to reductions in gas and harmful particulates. In addition, a reduction in mortality related to temperature extremes has strong supporting evidence, but this NEI will be discussed in the following section. In a recent paper by Dessouky et al. that synthesizes a large body of research on occupant NEIs,[77] the authors find that of the 17 studies that report on health-related NEIs, only three indicate a negative impact. Most often, these are related to buildings becoming "too tight" without proper ventilation, leading to insufficient outdoor air (historically brought in through infiltration) and increased levels of existing exposures, such as mold.[78]

The positive health and well-being impacts that energy efficiency upgrades can provide to occupants have considerable value. Avoided deaths, hospitalizations, and emergency room and physician office visits contribute to large monetized benefits for participants in energy efficiency programs. An evaluation of NEIs on low-income participants in a Massachusetts weatherization program found that the household benefit from reduced asthma symptoms, cold- and heat-related thermal stress, and reduced carbon monoxide (CO) poisoning totaled over $650 per year, or a present value of over $12,000 on a 20-year basis.[79] The same study reported an estimated $240 per year ($3,500 20-year present value) benefit due to fewer missed days of work and improved home productivity.

Regarding reductions in outdoor air pollution as a result of energy efficiency–induced reductions in electricity generation, the US Environmental Protection Agency (EPA) estimates a benefit as high as 7 cents per kilowatt-hour (kWh) of avoided electricity consumption in some regions of the United States.[80] This represents more than 50% of the 2021 US average residential retail electricity rate of 13.7 cents per kWh.[81]

Building Resilience, Durability, and Resale Value

In addition to their health, well-being, and comfort impacts for occupants, energy efficiency and electrification upgrades can improve the resilience and durability of buildings, reduce necessary maintenance throughout their lifetimes, and increase their value when they are resold. Building resilience impacts overlap with some of the health-related factors mentioned above; an active body of literature explores the mortality and economic burdens associated with nonoptimal ambient temperatures. Zhao et al. estimate that the annual average of excess deaths due to nonoptimal indoor temperatures ranges from 48 to 64 per 100,000 residents,[82] and a comprehensive review of the medical costs associated with heat stress, published by Wondmagegn et al., finds that heat exposure causes a substantial economic burden on healthcare systems.[83]

Energy efficiency and electrification upgrades can reduce exposure to prolonged heat and cold stress via resilient design strategies. The building science term for these strategies is "passive survivability," which refers to the ability to maintain safe indoor thermal conditions in the absence of functioning mechanical heating or cooling.[84] Energy efficiency upgrades have been shown to considerably reduce risks related to heat stress during heat waves.[85] Regarding cold stress, Fyfe et al. find in a study of nearly 1 million residents in New Zealand that a national home insulation intervention was associated with significantly fewer hospital admissions.[86]

Building durability and maintenance requirements for mechanical heating and cooling systems are two additional NEIs that provide value in the context of energy efficiency upgrades. Homes built with more structurally sound materials or those with high-performance heating and cooling equipment are more durable to hazardous events, such as fires and tornadoes, and they also require less maintenance.[87] Barkett et al. find that occupants place a high value on increased home durability and reduced maintenance as a result of efficiency upgrades (around 15% of the value of the energy savings of such upgrades).[88]

Reduced risk from fire is another building durability–related impact of energy efficiency upgrades. Hawkins et al. find that the measures that have the greatest impact on fire risk reduction include central space heating systems, electrical repairs, clothes dryer vent repairs/replacements, and insulation.[89] These measures, too, can provide significant monetary value to the extent that they reduce hospital admissions and other medical-related incidents or fire-related property damage. Hawkins et al. estimate this value to be around $90 per household per year based on the number of fire-related deaths, hospitalizations, and emergency room or physician office visits that are prevented with household weatherization upgrades.[90]

A fourth type of NEI that has been studied in the literature is the increased resale value of buildings that are retrofitted or constructed with energy-efficient technologies. Both high-performance mechanical systems and increased exterior insulation can improve the value of a home. Shen et al. find that US residences with an air-source heat pump (ASHP) have a 4.3%–7.1% price premium on average, and the authors find that estimated price premiums are larger than their estimated social benefits in most cases.[91] Cespedes-Lopez et al. find that housing in North America with energy performance certificates or labeling shows a 5.4% price premium,[92] and a National Association of Realtors study finds that insulation upgrades and HVAC replacement projects have an average 83% cost recovery based on the resulting increased home value from the remodeling.[93]

Community and Societal Impacts

The final category of NEIs included in this brief review are those that do not directly impact occupants but rather have indirect impacts in local communities. The two most well-researched of these "societal" impacts from energy efficiency and electrification programs are local job creation and economic development. Energy programs can affect local or regional economic development in multiple ways. These are classified in Browne et al. as:

- direct effects, which can be directly linked to program participation, such as when a participant spends incentives or personal funds on new home insulation;
- indirect effects, whereby directly affected industries spur economic activity in supporting industries, such as the insulation industry purchasing fiberglass; and
- induced effects, which occur when households that save money on energy bills and employees in the directly and indirectly affected sectors spend personal funds in the regional economy on new goods and services.[94]

Researchers have estimated the value of these direct, indirect, and induced economic impacts in several state and regional studies in the United States. In a study on an energy efficiency program in Wisconsin, Browne et al. attribute nearly 20,000 new full-time jobs through 2038 to the program, averaging 544 new jobs per year; the authors also estimate the program will generate more than $92 million per year in economic benefits through 2038.[95] A study of the US green construction industry conducted by Booz Allen Hamilton found that every $1 million invested in residential energy efficiency retrofits generates around $477,000 in direct gross domestic product (GDP) and an additional $785,000 in indirect and induced GDP; the study also found that the same investment results in 1.8 direct jobs and 9.8 indirect and induced jobs.[96] A study from the Southeast Energy Efficiency Alliance and the Cadmus Group assessed the economic impacts of the DOE's Better Buildings Neighborhood Programs in the southeastern United States, finding that the program created nearly 350 jobs, $22.5 million in labor income, and total economic output of over $78 million.[97]

While these NEIs related to jobs and economic development are not as easily measured or quantified as other participant or building NEIs, they nevertheless represent an important and often highly valuable source of benefits that can help make a holistic case for energy efficiency and electrification projects.

Appendix A3: ABC Market Opportunities and Challenges

The ABC Collaborative report *Market Opportunities and Challenges for Decarbonizing US Buildings* covers five major areas.
First, it provides market context and the case for ABC. ABC innovations and approaches have been successfully deployed at scale internationally and offer a promising value proposition in the United States if scaled effectively to reach cost-competitive rates. ABC can provide superior energy efficiency and low carbon footprints, faster and less disruptive on-site deployment, and added value (such as better indoor air quality, improved comfort, resilience, and reduced maintenance). Motivated by the promise of ABC to address a confluence of buildings sector challenges, the ABC Collaborative has been established to foster the development and scaling of ABC with the key programmatic goal of a net-zero carbon US built environment by 2050. This will rely on a vibrant ecosystem of domestic industry participants to deliver high-performance, resilient, and cost-effective solutions for both new construction and retrofits.

Second, it discusses major ABC innovations and approaches, including an emphasis on industrialized construction, leveraging modern manufacturing methods and tools to achieve superior energy and carbon performance, improved productivity, faster construction timelines, and increased cost-effectiveness. The report examines various industry case studies (including successful international industries and less successful domestic ventures), outlines related workforce considerations, and comments on the complementary relationships among technology trends relevant to ABC and between building efficiency and industrialized construction.

Third, it provides an analysis to assess and compare market opportunities across geographies and segments in the United States to help prioritize initial market investment. (See the *Market Opportunities Identified in Prior ABC Collaborative Work* section of this market guidance report for additional details on this state prioritization analysis.) Additionally, this portion of the market opportunities and challenges report summarizes a meta-analysis of published materials on innovative construction-related technologies to identify areas of high activity and potential gaps. It also provides an overview of major market segments, including single-family residential, multifamily residential, and select commercial buildings, and examines their points of suitability and drawbacks for implementing ABC.

Fourth, it summarizes the insights from 65 interviews across four stakeholder categories: demand; supply; market enabler; and research, development, and scale-up (R&D). Findings from the stakeholder interviews highlight barriers to implementation of ABC and to delivering on stakeholder needs. These needs are outlined in a stakeholder "wish list" organized into five categories: technical, social, workforce, financial, and political.

Finally, the ABC market opportunities and challenges report summarizes its main findings and lays out recommendations, including major barriers to scaling ABC, strategies for mass adoption, international industry lessons, and select market trends. The contents of the report provide a working plan for ABC actors, including the ABC Collaborative, to take market-facing action, informed by primary research with industry stakeholders, secondary research on market data and trends, and novel analysis. This market guidance report builds on the findings and recommendations of the earlier market opportunities and challenges report.

Appendix B: New Construction

Appendix B1: Energy Codes and Standards

Model Codes and Standards
National model energy codes and standards set minimum energy efficiency requirements for the design and construction of residential and commercial buildings. They are developed using a consensus-based public process and are typically updated on a three-year cycle. The DOE's Building Energy Codes Program (BECP) provides technical assistance to support the development and implementation of these codes.

The International Energy Conservation Code (IECC) is the principal model energy code for residential buildings in the United States. Residential buildings, as defined by the code, generally include one- and two-family buildings, as well as multifamily buildings of three stories or less. Energy efficiency standards for larger multifamily buildings are provided by the Commercial Provisions of the IECC and the national model energy standard for commercial buildings (ANSI/ASHRAE/IES Standard 90.1: Energy Standard for Buildings Except Low-Rise Residential Buildings).

The 2021 IECC includes Solar-Ready and Zero Energy provisions in its appendix that may be adopted by states or local jurisdictions. IECC's Zero Energy Residential Building Provisions (Appendix RC) provide requirements for residential buildings intended to result in net-zero energy consumption over the course of a year. Additionally, compliance with the Zero Energy appendix requires an Energy Rating Index (ERI), which must be completed by an approved third-party agency using an accredited rating tool. Such approved parties have knowledge and expertise in building science and high-performance construction standards.

Standards and frameworks relevant to zero-carbon alignment are evolving rapidly, with contributions from a range of professional societies and other groups. Architecture 2030 developed the Zero Code Energy Efficiency Standard and Renewable Energy Procurement Framework, which provide for energy efficiency specifications and elimination of the direct use of fossil fuel systems.[98] For multifamily buildings not covered by the residential code, ASHRAE recently published an *Advanced Energy Design Guide for Multifamily Buildings* that sets performance goals and provides strategies for achieving zero energy.[99]

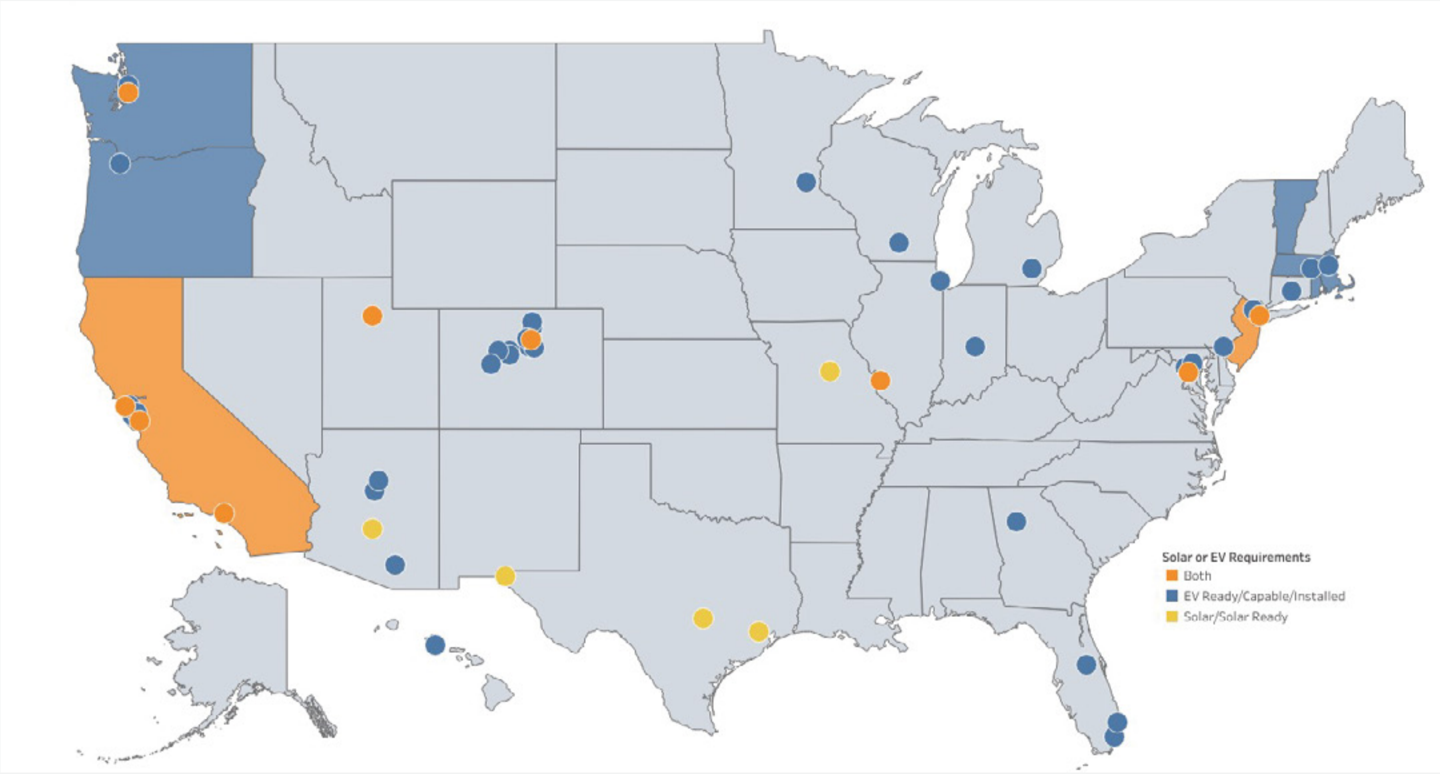
A new ASHRAE standard, the Standard Method of Evaluating Zero Net Energy and Zero Net Carbon Building Performance, is under active development, led by the Standard Project Committee (SCP) 228P. The intent of this standard is to set requirements for evaluating whether a building meets a definition of zero energy. A new ASHRAE Standard for Passive Building Design is also under active development (SPC 227P). And New Buildings Institute has created a Building Decarbonization Code that provides code language to serve as an overlay to IECC and ASHRAE 90.1.[100]

In California, all new residential buildings since 2020 must have solar and be designed to achieve net-zero energy.[101] Additionally, the state plans to ban most gas space and water heaters by 2030. Washington State passed the first state-level mandate requiring all-electric heating, effective in 2023. The mandate also requires 50% of water heating to be supplied with heat pumps. While the mandate applies to large multifamily and commercial buildings, the Washington State Building Code Council has advanced proposals for residential buildings that are currently under review. Exhibit 31 shows state and local jurisdictions with electric vehicle and/or solar requirements as of June 2023.

Code Adoption
Model energy codes may be adopted either wholesale or with modifications by state energy offices, which provide training and support to the construction industry. Amendments to the model energy code may strengthen or weaken it. For each energy code adopted by states, DOE evaluates the code and tracks its relative efficiency against the model energy codes.

Although IECC is updated and released on a three-year cycle, not all states adopt, or stay current with, the model energy code. Additionally, some states do not have a statewide energy code. DOE maintains a public database to track and analyze state code adoption and relative efficiency with respect to the model codes.[102] Exhibit 32 shows the status of state-level code adoption relative to the efficiency levels of model energy codes. Only three states, representing 11% of total residential floor area, have been classified as equivalent to the current model energy code (2021 IECC). The vast majority of states, representing over 50% of total residential floor area, have adopted codes equivalent to or less efficient than the 2009 IECC. DOE estimates that the current model energy code generates more than 25% savings over the 2009 IECC.[103]

Exhibit 31. State and Local Electric Vehicle and Solar Requirements



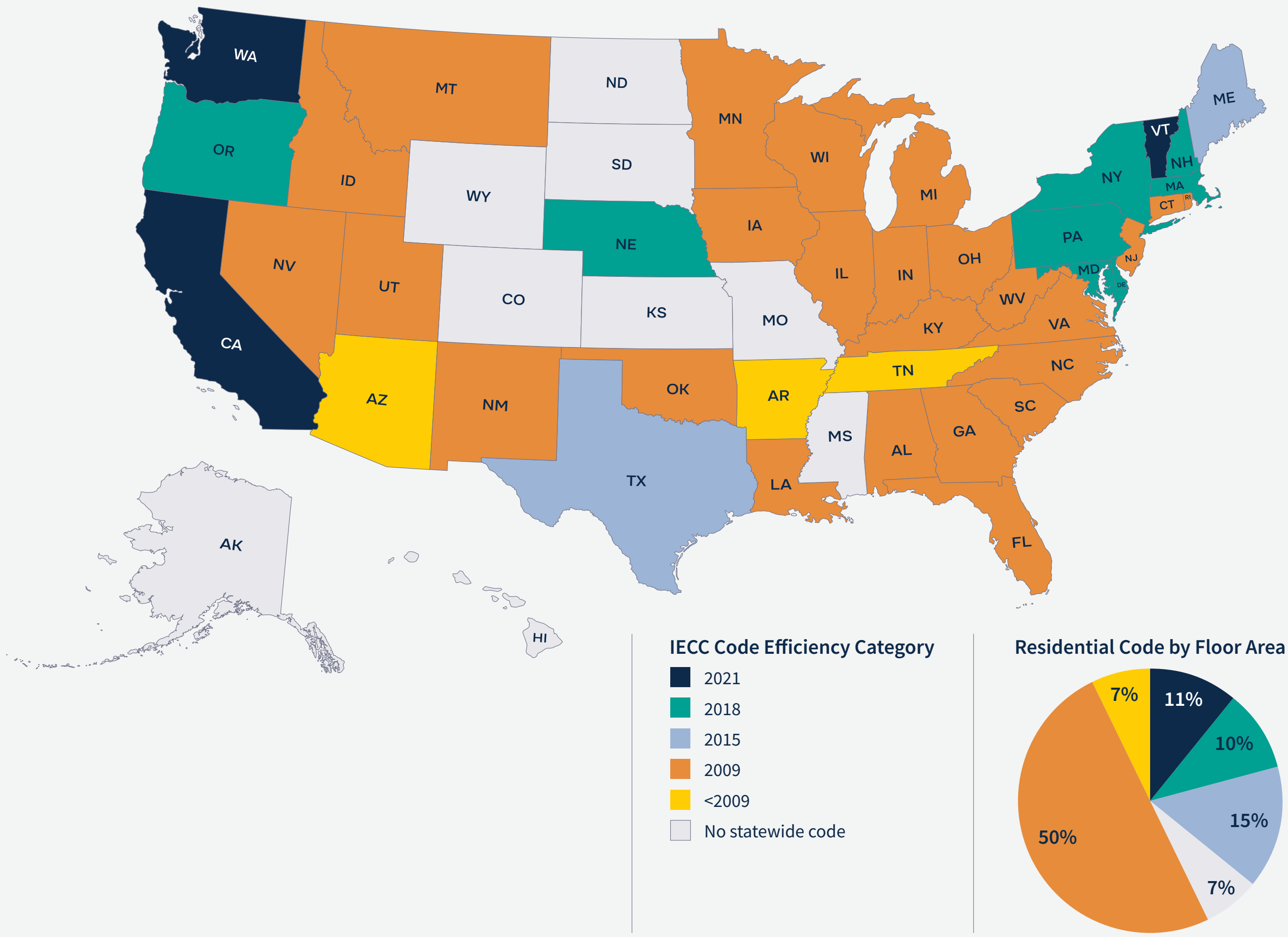
Source: US Department of Energy BECP, "Infographics," **https://www.energycodes.gov/infographics**

Emerging Codes for Industrialized Construction

The International Code Council (ICC) and the Modular Building Institute (MBI) have published two new standards to accelerate the off-site construction industry: the ICC/MBI 1200-2021 Standard for Off-Site Construction: Planning, Design, Fabrication and Assembly; and the ICC/MBI 1205-2021 Standard for Off-Site Construction: Inspection and Regulatory Compliance. These standards are intended to promote consistency of regulatory requirements for off-site construction processes. The ICC has opened a new standards project to develop ICC 1210-202X: Standard for Mechanical, Electrical, Plumbing Systems, Energy Efficiency and Water Conservation in Off-Site Construction.[104]

Beyond what is included in site-built codes, the new standard will also include the componentization and modularization of mechanical, electrical, and plumbing systems and how they incorporate into modular construction. It will also establish planning and preparation requirements for the roles and responsibilities of the construction team, plant and construction site location, engagement, material procurement, and lead times. Additional requirements will address controlled manufacturing environments, supply chain integration, and other steps in the fabrication and assembly process. Notably, the standard would not apply to US Department of Housing and Urban Development (HUD) manufactured housing. The committee responsible for drafting the standards will solicit public comments on the initial draft through the end of 2022 and until a draft is complete.

Exhibit 32. Status of Residential Energy Code Adoption Relative to Model Energy Codes



Source: US Department of Energy BECP, "Status of State Energy Code Adoption: Residential," https://public.tableau.com/app/profile/doebecp/viz/BECPStatusofStateEnergyCodeAdoption/ResidentialDashboard

Appendix B2: Building Performance Program

Building Performance Approaches

Among voluntary building performance programs, there are two main pathways to achieve certification (and, depending on the program, a ZCA building): designed for performance, and measured performance. Designed for performance can be accomplished with either simplified-but-restrictive prescriptive rules, or with a more flexible performance approach that requires energy modeling. Prescriptive guidance specifies minimum levels of efficiency at the assembly and equipment level for envelope, HVAC equipment, lighting, appliances, and sometimes other measures. Under a prescriptive pathway, builders do not have to create an energy model. Performance-based targets give builders greater design flexibility by allowing efficiency trade-offs across building envelope assemblies and mechanical equipment, provided the whole building meets a minimum energy performance target. Compliance with the energy target is calculated using a building energy model, which is referred to as predicted energy use. Measured performance refers to programs that require, for example, one year of measured energy used and renewable energy generated.

Renewable Energy/Carbon Credits

Voluntary building performance programs prescribe ways to achieve zero carbon by installing on-site renewable energy systems, or via directly owned off-site systems, community renewable energy systems, or virtual power purchase agreements. Some programs apply renewable energy factors that discount off-site renewable systems relative to on-site systems to account for transmission losses.
Integrated Design

A key element in achieving ZCA construction is working with the entire project team to set a clear goal and then using an integrated design process from conceptual design through occupancy to realize it. An integrated design team coordinates lighting, mechanical, structural, and massing/envelope decisions to reduce costs and energy use. These strategies, in turn, can result in first cost transfer from mechanical, electrical, and lighting systems to pay for the improvements in the building envelope — a form of integrative design. Voluntary building performance programs embed integrative design practices, which can help design and construction teams achieve zero-carbon alignment with little or no incremental cost compared with baseline construction.

Professional Credentials

Credentials for design and construction professionals were created by voluntary building performance programs to provide training and foundational skills in building science and best practices for high-performance zero-carbon alignment. To become certified, design professionals complete training courses and pass a certification exam. The two paths for professional certification, RESNET and Phius, have similar categories that generally fall into the following three groups:

- **Consultants** are either architects or professionals integrated within the design team who are trained and certified to ensure ZCA principles are embedded in the building design.
- **Builders** are trained and certified to ensure the construction of the ZCA building is executed according to design.
- **Raters/verifiers** are trained and certified to deliver on-site quality assurance.

Quality Assurance

At the design and planning phase, quality assurance is performed by a certified professional who models energy performance based on the design, using accredited energy rating software. The energy model will provide builders with an estimate of the energy performance that can inform whether the selected HVAC equipment, insulation, appliances, and so on meet their energy load and consumption targets. During construction, a certified professional will deliver on-site quality assurance through mid-construction and final inspection and testing.

Creating Consumer Demand

Programs include nationally recognized brands and marketing materials that can be leveraged by design and construction professionals to promote their business. Programs offer national databases, case studies, and awards that promote projects.

Industrialized Construction

Voluntary building performance programs are a natural fit for industrialized construction methods. These programs' building performance targets, integrated design, quality control, and inspections can be easily integrated into factory processes. To comply with third-party inspections and codes governing off-site construction, factories must already create a quality control protocol that includes a quality control manual, a quality control team, and checklists that travel with the prefabricated components through the factory. Energy strategies can be fully integrated into that process, creating standardized housing products that meet voluntary building performance program certifications. An optimized approach to industrialized construction integrates high-performance principles early in the design phase, increasing energy performance and potentially minimizing costs.

Appendix B3: Cost-Effectiveness

Costs

The approach of building energy codes, and above-code energy efficiency programs, is to adopt and implement energy efficiency measures that are cost-effective. The assumption is that widespread adoption of more efficient building construction materials, systems, labor, and so on requires that the benefits outweigh, or are in line with, the cost of implementing them. Benefits may be defined as simply as the utility bill savings resulting from more efficient building operation. However, there are many other benefits that come from more efficient building construction, and some are more difficult to quantify than others. Benefits such as improved building durability, resilience, and occupant health, as well as societal benefits from reducing emissions, improving long-term occupant health, and reducing reliance on energy assistance programs, are all by-products of more efficient construction.

New technologies and/or construction practices may be more expensive initially because there is low demand or a learning curve. As trades become more skilled at the new practices, costs come down. Additionally, when more efficient systems and construction practices are voluntary, the awareness and demand may not be sufficient to bring market costs down. Strong demand, obtained either through enforcement or incentives and a favorable policy environment, can help reduce these incremental costs.

The remainder of this section will provide a brief overview of how cost-effectiveness is applied in energy codes and voluntary building performance programs and review metrics that gauge cost-effectiveness. This section then provides cost targets, estimates of incremental costs, and case study examples where ZERH and Phius levels of construction have been achieved at or near baseline construction costs.

Building Energy Codes

The DOE supports adoption and implementation of the model energy code (IECC) by conducting analysis to demonstrate that measures included in the code are economically justified. These analyses focus on three primary metrics: life-cycle cost (LCC), simple payback, and cash flow. LCC, the primary metric used to gauge cost-effectiveness, assesses the energy cost savings against increased mortgage costs over a 30-year period. The goal is to ensure that all measures required by code are cost-effective and thus readily adopted and implemented. The IECC represents the minimum level of energy efficiency that is economically justified by current market costs.

Voluntary Building Performance Programs

Utility energy efficiency programs also must demonstrate cost-effectiveness at a measure, program, and/or portfolio level. There are many cost-effectiveness tests that states may choose to utilize to ensure that energy efficiency programs are cost-effective. These tests encompass an array of both costs and benefits, as well as various perspectives, such as those of utility ratepayers and people who do not participate in the programs. The incentives to bring down the first cost of more efficient products or practices are evaluated using these tests. Benefits may also encompass health and societal benefits. An increasing number of states have incorporated health and environmental benefits in their cost-effectiveness screening.[i] State and utility energy efficiency program incentives can be a gauge of the incremental cost of implementing a more efficient product or construction practice over the federal minimum standard or adopted energy code.

Cost-Neutral

Building America uses a cost-neutral approach to demonstrate the levels of efficiency over code that can be obtained at no additional lifetime cost. Like the LCC, this calculation includes annual energy savings and mortgage costs over a 30-year period. An array of building envelope assemblies and mechanical system efficiencies are modeled using a building energy modeling (BEM) tool to determine which configurations are cost-neutral with respect to baseline construction (e.g., code).

Justified First Costs

Of all cost-effectiveness approaches and metrics, one variable that is always required is the first cost of a measure. First costs are often difficult to obtain, vary considerably by region, and are impacted by a variety of factors such as volume purchasing. The Pacific Northwest National Laboratory (PNNL) recently published a feasibility study assessing the potential to achieve zero-energy buildings with energy codes.[105] This study utilizes a justified first cost (JFC) approach. A JFC is the first cost of a measure when the cost and benefits are equal over the life of the measure, or the threshold cost when a measure becomes cost-effective. This metric was used by PNNL as an indicator of when a measure is economically justified to be implemented in the energy code. This cost metric can be useful as a guide to identify when high-efficiency measures can be implemented at the same market costs as federal standards or measures currently required by energy codes.

Consistent with the model energy code cost studies, this metric uses the LCC to determine the JFC but inverts the equation. Utilizing the LCC cost-effectiveness calculation such that first costs become an output, rather than an input, enables industry to evaluate efficiency measures relative to current codes and standards — in short, revealing the highest price that is economically justified for a given measure. This is a useful approach when first costs are not known or have significant regional variation, or when purchase volumes vary considerably, as may be the case with industrialized construction. This approach can be more difficult to implement for a portfolio of measures, or for a whole-home approach, when a combination of measures with different measure lives are considered. The JFC method draws on earlier work that is described in a 2016 ACEEE paper.[106] Justified first costs for measures beyond the 2018 IECC are presented below.

i. As of a December 2018 analysis by ACEEE, 19 states account for health and environmental benefits in their cost-effectiveness screenings: https://www.aceee.org/sites/default/files/he-ce-tests-121318.pdf.

Justified First Costs for Measures beyond 2018 IECC

For the PNNL feasibility study, Phius provided prescriptive specifications for the PNNL prototype single-family and multifamily buildings that would meet the 2018 Phius performance requirements. The baseline for this study was the 2018 IECC. Economic parameters used in the LCC calculation are presented in Exhibit 33. measures beyond the 2018 IECC are presented below.

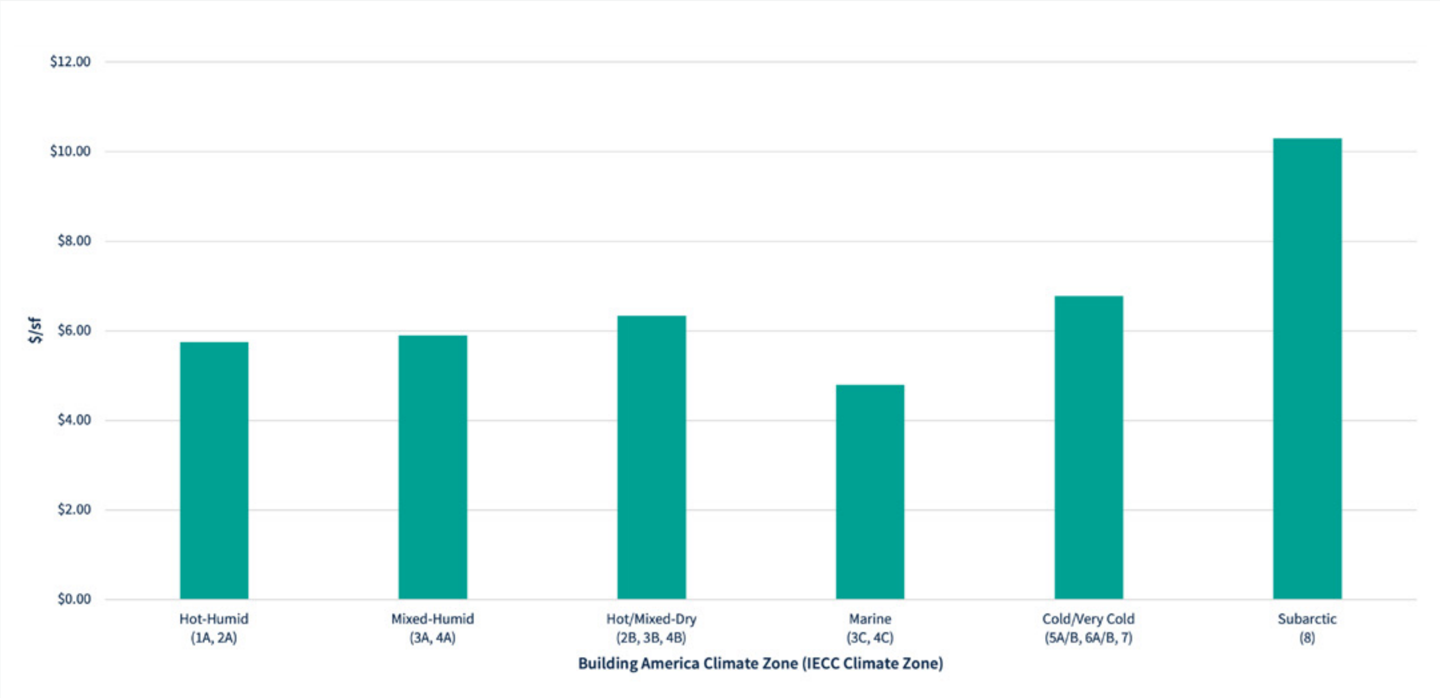
Exhibits 34 and 35 below summarize the JFC results reported by PNNL. The reported costs in the PNNL report were normalized based on residential floor-area values. The data presented below is averaged by Building America climate zone to provide a high-level view by region. Corresponding IECC climate zones are noted because energy code compliance and many voluntary efficiency program specifications are differentiated by these climate zones. With the exception of the subarctic region (IECC climate zone 8), found only in parts of Alaska, the average JFC is just over $6 per square foot to build to 2018 Phius-level requirements.

Exhibit 33. Residential Economic Analysis Parameter Values for PNNL Feasibility Study

Parameter	Value
Mortgage Interest Rate	5%
Loan Term	30 years
Down Payment	10% of home price
Points and Loan Fees	0.7% (nondeductible)
Analysis Period	30 years
Property Tax Rate	1.5% of home price/value
Income Tax Rate	12% federal
Inflation Rate	2.52% annual
Home Price Escalation Rate	Equal to inflation rate

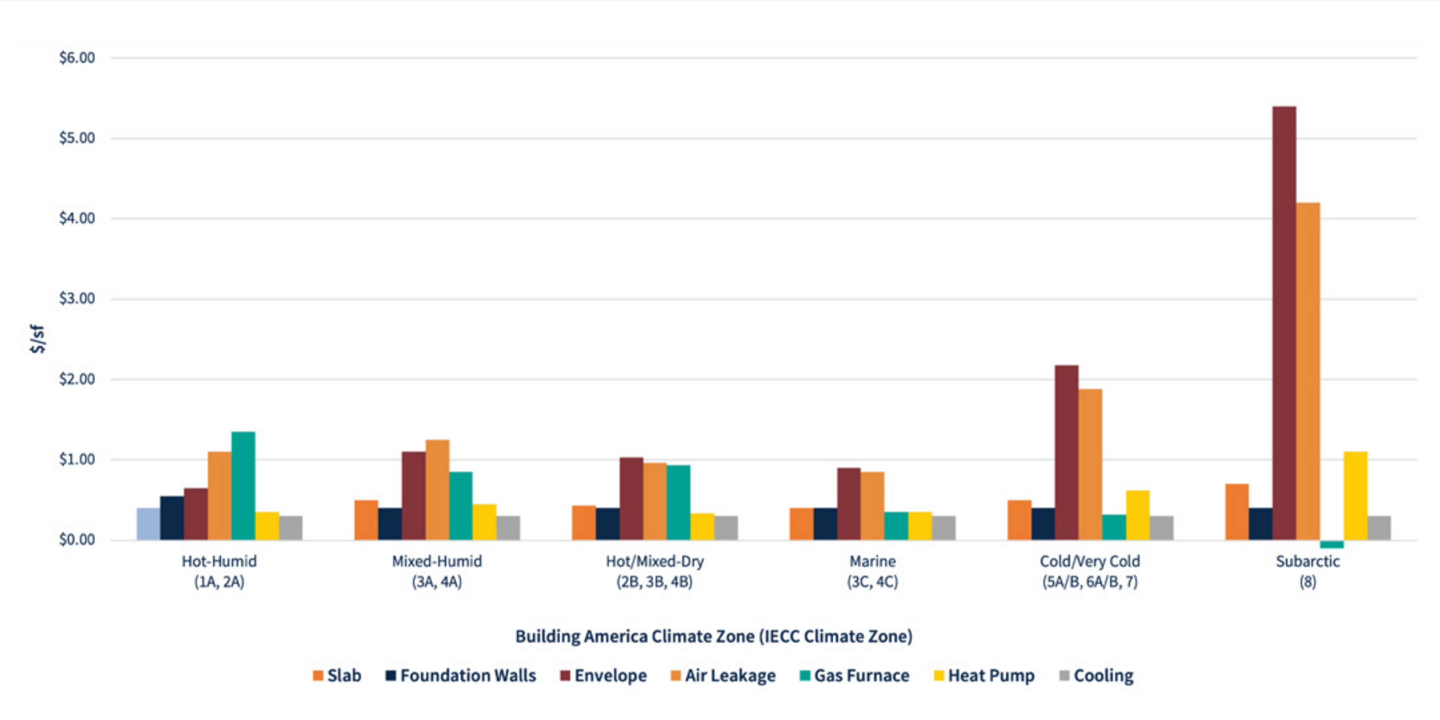
Source: Ellen Franconi et al., *Filling the Efficiency Gap to Achieve Zero-Energy Buildings with Energy Codes*, Pacific Northwest National Laboratory, 2020

Exhibit 34. Incremental Justified First Cost across All Beyond-Code Measures (2018 Phius)



Source: Ellen Franconi et al., *Filling the Efficiency Gap to Achieve Zero-Energy Buildings with Energy Codes*, Pacific Northwest National Laboratory, 2020

Exhibit 35. Incremental Justified First Cost for Individual Beyond-Code Measures (2018 Phius)



Source: Ellen Franconi et al., *Filling the Efficiency Gap to Achieve Zero-Energy Buildings with Energy Codes*, Pacific Northwest National Laboratory, 2020

Appendix B4: Summary of Voluntary Building Performance Programs

ENERGY STAR Homes

ENERGY STAR Homes is EPA's program to promote ABC and is a prerequisite for the DOE and Phius building performance programs listed in this report. ENERGY STAR Homes uses the quality assurance framework provided by the Residential Energy Services Network (RESNET). ENERGY STAR Homes requires a comprehensive thermal enclosure system including air sealing, high-efficiency heating and cooling equipment, low-flow water fixtures, and product specifications that minimize exposure to airborne pollutants. Under the ENERGY STAR NextGen program, designers and builders can follow program guidance to achieve ZCA construction.[107]

Zero Energy Ready Homes

The Zero Energy Ready Homes (ZERH) program is DOE's current voluntary building performance program and requires ENERGY STAR Homes certification as a prerequisite. With all-electric, high-performance equipment and appliances and solar-ready specifications, ZERH can be ZCA.[108]

Phius

Phius's CORE and ZERO programs require ENERGY STAR Homes certification and ZERH as prerequisites, with additional passive and active thermal envelope conservation measures. EPA's Indoor airPLUS is also required. Phius ZERO achieves ZCA construction: it sets the net source energy target at zero, does not allow for fossil fuel combustion on-site, and provides both on-site and off-site renewable energy options to get to zero.[109]

International Living Future Institute

The International Living Future Institute (ILFI) Zero Energy and Zero Carbon paths provide guidance for multifamily buildings using a team of certified professionals who provide consulting, technical assistance, and third-party quality control checks throughout the design and construction process.[110]

LEED

The LEED new construction program uses a combination of mandatory and voluntary credits to promote green and sustainable practices. Two credit categories, Minimum Energy Performance and Annual Energy Use, require reduction in estimated energy use. LEED Zero Carbon requires net-zero carbon emissions from energy consumption through carbon emissions avoided or offset annually. LEED Zero Energy requires a source energy use balance of zero annually. Both certifications require one year of occupancy and energy data post-construction to achieve the certification. Buildings need to recertify every three years.[111]

Appendix B5: New Construction Case Studies

Passive House Market-Rate Single-Family Homes in Greater Austin, Texas




Project	Theresa Passive House	Casa La Vista
Location	Austin, TX	Spicewood, TX
Housing Type	Single Family	Single Family
ASHRAE Climate Zone	2A: Hot-Humid	2A: Hot-Humid
Interior Conditioned Floor Area	2,218 sq. ft.	2,990 sq. ft.
Construction Type	Wood Frame	Wood Frame
Phius Certifications	Phius+ 2018, Phius+ Source Zero	Phius+ 2015
Additional Certifications	DOE ZERH, ENERGY STAR Homes, EPA Indoor airPLUS, Austin Energy Green Building 5-Star	DOE ZERH, ENERGY STAR Homes, EPA Indoor airPLUS, Austin Energy Green Building 5-Star

Theresa Passive House and Casa La Vista are passive house–certified homes in the greater Austin, Texas, area.[112] Key individuals involved in these projects were Trey Farmer of Forge Craft Architecture + Design (owner/architect of Theresa Passive House), Mark Larson of Lake Travis Builders (owner/designer of Casa La Vista), and David Moody of Form to Finish (consultant on both projects). These projects were among the first these professionals designed and built to passive house standards and submitted for certification by Phius.

By deciding to "practice what you preach" and take on these personal projects, Farmer, Larson, and Moody were able to learn from their direct experiences during the design, construction, testing, and occupancy of the homes and apply those learnings to future high-performance projects. Their work continues in designing and building ultraefficient homes, and they anticipate gaining efficiencies through continued, repeated application of passive house design principles. Each shared some of their lessons learned for others in the industry to consider when deciding to target a ZCA standard.

Located in Austin and Spicewood, Texas, respectively, Theresa Passive House and Casa La Vista are both in climate zone 2A and must contend with the unique challenges of a hot, humid climate. Of particular concern was how to deal with high humidity levels both inside and outside the homes while building to passive house superinsulation and airtightness standards. To address this challenge, dedicated dehumidification and energy recovery ventilation systems were designed for the needs of each home. Other key features include:

- Continuous insulation, air- and water-resistive barrier
- Healthy home building materials (e.g., mineral wool, GREENGUARD-certified caulking and adhesives, mineral-based paints)
- Solar photovoltaics and battery backup at Theresa Passive House

The up-front incremental costs of incorporating high-performance standards into these projects were approximately 3% and 8%, respectively, for Theresa Passive House and Casa La Vista. However, by designing homes with low energy loads and incorporating ultraefficient equipment, both projects have produced substantial energy bill savings over comparable homes: an estimated $62 per month for Theresa Passive House and $198 per month for Casa La Vista. These bill savings partially offset the higher up-front costs of building to passive house standards, and the bill savings achieved by these homes will grow as energy prices continue to increase. Moreover, evidence shows that, with more experience, building to passive house standards can cost less than building to code with conventional construction methods, at least in certain segments.

Going beyond energy savings, both homes are noted for their resilience and passive survivability. During the Texas winter storm power outage of 2021, Theresa Passive House and Casa La Vista were able to maintain a safe and comfortable living environment for a much longer period than conventional homes in the area. Both houses are built to withstand more extreme heat, as well, which will continue to increase over time; thus, they will provide a reliable and safe living space well into the future. Farmer notes that industry can move toward passive house or other ZCA standards faster by focusing on and marketing its comfort and safety aspects. Larson agrees, noting that while only half of people care about the carbon impact of their homes, everyone cares about their comfort, health, and quality of life.

The successes of Theresa Passive House and Casa La Vista were not without challenges. Ensuring that each organization involved in the project, from the architectural team to subcontractors, has the necessary skills and is aligned with the vision is critical. Moody notes that finding HVAC design professionals who can properly size HVAC systems for homes of this efficiency level can be a major challenge. Given the importance of properly designed mechanical systems in passive house construction, both for performance of the home and satisfaction and comfort of the owner, working with organizations that adhere to building science design principles is critical to success. Tying all the pieces together and choosing among options to achieve a passive house or other ZCA home can also be challenging. Many organizations in the industry already know how to construct a high-performance envelope or HVAC system, but challenges arise in putting together the various high-performing aspects of the home at low to no added cost. Integrated design is key to success, as is modeling building performance across varying design options and determining the least-cost path for optimizing the home. Both Farmer and Moody note that the building energy modeling for their projects was immensely helpful and that professional support from organizations like Phius was well worth the cost. In particular, Farmer notes the value of the building science expertise of those organizations and that the modeling is helpful not just for optimizing the home but, in the case of affordable housing, for demonstrating the estimated cost savings and payback period to the affordable housing providers.

Theresa Passive House and Casa La Vista are two examples of industry taking on passive house design projects and learning from those experiences to gain insights into how best to design, build, and market services to that efficiency level. Going forward, Farmer notes that his firm is moving toward only designing to passive house standards for single-family homes, and an increasing share of the firm's affordable multifamily pipeline is heading in that direction as well. With experience, the costs of designing and building to high-performance standards will decrease, and the selling points of health, comfort, and quality of life will become even more obvious. Moreover, Farmer notes that industry has a professional responsibility to design and build homes that will meet the climate challenges not only of today, but of the future as well.

Marshall Fire Rebuild, Boulder County, Colorado

In December 2021, the Marshall Fire in Colorado destroyed more than 1,000 homes in Boulder County, Colorado. In the wake of this tragedy, Xcel Energy announced a package of incentives ranging from $7,500 (for building to 2021 IECC standards) to $37,500 (for building to passive house standards) to support the community's clean energy goals and rebuild to a range of leading code and above-code efficiency standards.[113] Through this program, homeowners impacted by the fire could choose to build to code or receive higher incentives for building to some of the building performance standards discussed in this report: ENERGY STAR, Zero Energy Ready Homes (ZERH), and passive house standards.[i] Due to the critical nature of these home rebuilds and the strong desire to maximize the efficiency and resilience of this next generation of homes, Xcel Energy worked with federal partners to establish a certification process for meeting the latest ENERGY STAR and ZERH standards that were not immediately released publicly. In addition, Xcel offered incentives for ENERGY STAR's new certification, NextGen, which prioritizes electrification.

In the wake of natural disasters, there is often pressure to rebuild quickly without regard to meeting higher standards. Adding to this pressure has been the heightened real estate market, which can lead to a leveling off of home performance when anything built will sell. Not wanting the industry to miss this opportunity in Colorado, Xcel designed its incentive program as direct-to-consumer to create demand for high-performance homes. In doing so, the company put a flag out for residents, builders, and other stakeholders to show that it is taking the potential for beneficial electrification very seriously, especially in new construction. So far, it appears to be working, as many homeowners have opted for the higher incentives of voluntary building performance programs.

One company that has been actively engaged in helping homeowners affected by the Marshall Fire rebuild to a higher standard is Diverge Homes. The company notes that the incentives provided by Xcel have given so much hope to residents affected by this tragedy, and in response, Diverge Homes designed a series of 12 model homes specifically for these rebuilding efforts to help the community get back on its feet quickly without sacrificing quality or performance.[114] The company's goal in designing these homes was "to provide affected homeowners cost certainty, combined with the highest methods of structural integrity, finish quality, and speed of construction." Providing these templates to assist homeowners building high-performance homes that meet their needs today and tomorrow has led Diverge Homes to change its business model entirely. Because of the knowledge and experience gained constructing high-performance all-electric homes in these rebuilding efforts, the company has transformed its operation to deploy all-electric homes within all of its developments in Colorado and beyond.

i. The program provides incentives for meeting passive house design standards, including certifications by Phius and Passive House Institute (PHI).

Another company putting its products and services into the Marshall Fire rebuild is B.PUBLIC Prefab, which has been partnering with local Colorado architects designing custom homes and offering standard home plans direct to homeowners working with local builders. B.PUBLIC, which offers products to serve passive house and ZERH projects across the country, has provided both the technical expertise and training necessary to build to these higher standards in areas affected by the Marshall Fire, as well as its "kit of parts" prefabricated panels to achieve the required performance cost-effectively and with speed. Customers have noted that the panelized construction methods provided by B.PUBLIC have added value to their homes by providing passive house energy efficiency and time and cost savings through rapid installation of the building shell and structure.

Given the extraordinary circumstances of the Marshall Fire rebuild, Xcel designed incentives that are more generous than most other programs. However, Xcel has noted that this level of support is not sustainable over the long term, and, under normal circumstances, more moderate incentives are to be expected. Coupled with the labor and skills shortages in many markets, industry will need to build out those skills through training and technical assistance and incorporate products and solutions that bring high-performance homes to market cost-effectively.

B.PUBLIC is helping to fill that gap in Colorado and nearby markets. As a public benefit corporation, it also focuses on education and regional development of green jobs through its installer training for working with high-performance prefabricated panels. This hands-on training series covers building science, structural connections, and work safety. With a regional approach to sustainable home development, B.PUBLIC is helping to establish and grow the building component manufacturing sector to service areas of high need.

Appendix C: Retrofit

This appendix provides further methodological details and results for the market segment prioritization work presented in the *Retrofit* section of the report. The first section provides detailed methodological steps for assigning target upgrade packages to various segments of the residential building stock, and the second section provides supplementary results.

Appendix C1: Package Assignment and Segment Prioritization

As described in the main report, the primary objective of this assignment and prioritization exercise is first to determine appropriate upgrade packages for different segments of the building stock such that they are zero-carbon aligned. The second step is to aggregate building segments by key parameters and prioritize buildings with common characteristics in states with strong market potential for deploying ABC approaches for residential retrofits.

Our approach to assigning upgrade packages and prioritizing segments is described at a high level in the main body of the report. Here, we provide detailed methodology for both parts of the approach. Exhibit 56 presents an expanded overview of the approach with more detailed criteria and steps for both package assignments and segment prioritization.

As described in the main body of the report, our analysis focused on six distinct building types that were identified in advance of the modeling work.[i] These are:

- Single-family detached
- Single-family attached
- Multifamily with 2–4 units
- Multifamily with 5+ units, 1–3 stories
- Multifamily with 5+ units, 4–7 stories
- Multifamily with 5+ units, 8+ stories

As shown in Exhibit 56, the package assignment logic varies slightly between the two higher-level building type categorizations used in our analysis, which are as follows:

- Single-family and small multifamily
  - Single-family detached
  - Single-family attached
  - Multifamily with 2–4 units
- Large multifamily
  - Multifamily with 5+ units, 1–3 stories
  - Multifamily with 5+ units, 4–7 stories
  - Multifamily with 5+ units, 8+ stories

The package assignment approach shown in Exhibit XX and described in detail below relies on a number of key dwelling-level metrics. These include site energy consumption, site energy use targets based on PV generation potential, size or capacity of heating and cooling systems (including both primary and supplementary systems), and other general characteristics of the dwelling, such as heating fuel for space and water heating, presence of insulation (e.g., walls and windows), and others. Before describing the detailed steps in the package assignment approach, we first describe these metrics.

i. A seventh building type not included below is manufactured housing. This building type is included in the *U.S. Building Stock Characterization Study* and the modeled package upgrades analysis, but we do not include manufactured housing in the priority markets for ABC. This is both because no manufactured housing segment is large enough to be included in the top segments and because manufactured homes are not the ABC Collaborative's primary focus.

Exhibit 36. Assignment and Prioritization Steps and Criteria

Performance level assignments

- **Step 01** Determine which building segments should not be prioritized for ABC guidance because they are already "on their way" to being ZCA
- **Step 02** Determine which buildings require envelope retrofits in addition to equipment replacement/ electrification to be ZCA
- **Step 03** Determine which envelope upgrade is needed to achieve zero-carbon alignment while also limiting HVAC capacity (i.e., to facilitate electrification while also mitigating grid impacts)

Typology segment prioritization criteria

- **Step 04** Prioritize building segments in states where ABC solutions can be adopted rapidly due to market and policy conditions
- **Step 05** Prioritize building segments that are assigned upgrade packages that the ABC initiative focuses on (i.e., those that include comprehensive envelope upgrades)
- **Step 06** Aggregate results across key building characteristics (e.g., building type, vintage, existing heating fuel, and wall structure) and rank segments by number of housing units

Metric	Criteria for Prioritization
	All Building Types
State market potential	Prioritize segments by climate region, filtering for those located in high-priority states (CA, CO, FL, MA, MD, MI, NY, PA, TX, WA) as determined by ABC market opportunity analysis
Upgrade performance level assignment	Filter out segments of the building stock assigned either no upgrade or “All equipment swap-out” performance levels (~30% of housing units)
Building characteristics aggregation	Aggregate housing units by characteristics that are relevant for building retrofits, including climate region, building type, heating fuel, building vintage, wall structure/ type, window insulation level, and assigned performance level
Segment size	Rank aggregated segments by total number of housing units to prioritize segments that have potential for demand aggregation

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

Appendix C2: Package Assignment Metrics

Baseline and Upgrade Modeled Site Energy Consumption

The simulated results from the energy efficiency measure package analysis conducted by NREL are used to determine site energy consumption for the baseline and for each upgrade package.[115] These results are used in combination with estimates of each housing unit's target site energy use to determine which package (if any) can reduce site energy use below the respective target (which is estimated using separate approaches for single-family/small multifamily buildings and large multifamily buildings, as described further below).

An additional metric related to site energy consumption that facilitates a more accurate comparison of the impacts of each package is normalized site energy consumption, where site energy consumption for each housing unit is normalized by its weighted R-value for each upgrade package. We calculate this metric by first calculating an aggregate R-value that is the average R-values of the roof, walls, and windows, weighted by the square footage of each envelope component. We do this for each housing unit for each upgrade package (which differ in terms of roof, wall, and window R-values — see *Exhibit 16/XX* for details) to calculate a weighted R-value for each package, which we then use to normalize each package's site energy savings. Using this normalized site energy savings value helps account for the "diminishing returns" of energy savings for increasingly high-performance envelope components and allows for more appropriate comparisons of envelope packages (as simply comparing each upgrade package's site energy savings would almost always show greater savings for the higher-performance packages, but in some cases the incremental savings of these packages may not be justified based on the additional performance gains required). We include this metric in the assignment steps below as a means of determining which envelope upgrade package to assign when several of the other energy- and HVAC-related criteria are not met.

Target Site Energy Use to Achieve Zero-Carbon Alignment

A key tenet of zero-carbon alignment, as introduced in this report, is whether a building or housing unit's annual site energy consumption can be met entirely with electricity generated on-site from a rooftop solar photovoltaic (PV) system. This framing is used in other reports to describe buildings that achieve "net zero" at the individual building or dwelling scale.[116]

In the various retrofit packages that were modeled for this analysis, we did not include the impacts of distributed energy resources such as on-site solar PV, and throughout this guidance, we do not comment at length on supply-side questions related to decarbonization of electricity supply and whether this is best achieved through rooftop PV or other utility-scale clean energy resources. However, existing standards and related analyses support our consideration of a home's solar PV generation potential as a useful threshold for determining the "depth" of energy savings that could enable the home to be designated as net-zero energy (regardless of where its electricity comes from). We use this threshold in our package assignment logic accordingly.

Our determination of a threshold or target for site energy use is different for the two higher-level building types in our analysis. For single-family and small multifamily housing units, we use established methods to estimate their annual rooftop PV production potential. For each housing unit, we use the National Renewable Energy Laboratory (NREL) PVWatts Calculator to simulate annual solar production for a representative 1 kW solar array.[117] Each simulation uses solar insolation values that are specific to the latitude and longitude of each building.

Our methodology assumes systems are roof-mounted and uses default input parameters for system losses, DC/AC ratio, and module type and efficiency from the NREL PVWatts Version 5 Technical Manual.[118] We assume an average tilt angle of 28° based on NREL's rooftop solar potential study,[119] and we calculate solar production for several different panel orientations for each housing unit and then take a weighted average of these based on stock percentages of PV orientation from NREL's ResStock model. Our estimate of usable roof area, which is necessary to determine how much rooftop PV each building could install, varies by zip code and is taken from NREL's rooftop solar potential study (the weighted average from this study is 36% of total roof area). Finally, we include standard assumptions for PV panel size (17.6 ft2) and power output (250W) to calculate each building's annual solar production.

Given the challenges associated with installing rooftop PV on multistory buildings with low roof-to-floor area ratios, we do not use this approach for the large multifamily buildings in our analysis. We instead adopt the site energy use intensity (EUI) targets specified in ASHRAE's *Advanced Energy Design Guide for Multifamily Buildings: Achieving Zero Energy*.[120] These targets are specified by climate zone and are based on an extension of site EUI targets for smaller multifamily buildings, which apply a similar approach insofar as they are designed with the production potential of a hypothetical on-site solar PV system in mind.

We use these methods to determine a target site energy use or energy use intensity for single-family/small multifamily and large multifamily buildings, respectively, which, if met, serve as the criteria by which we assess these buildings as "net zero" or "zero-carbon aligned" from an annual energy use perspective.

Building HVAC Capacities for Heating and Cooling

Another key metric used in our package assignment criteria is the capacity of the upgraded building's HVAC system and any installed supplementary/backup heating capacity.[i] Rightsizing HVAC systems is important for numerous reasons: when equipment is oversized, the initial costs are higher, the equipment efficiency can decrease (and energy costs can increase as a result), and occupant comfort may be compromised.[121] Furthermore, in situations where a home has existing ductwork, the HVAC system size is limited by the capacity of the home's ducts, and limiting the size of the HVAC system can avoid costly, burdensome, and intrusive ductwork upgrades.[122]

i. Detailed methods on the HVAC sizing algorithms in ResStock are included in the 2023 NREL report *Modeled Results of Four Residential Energy Efficiency Measure Packages for Deriving Advanced Building Construction Research Targets*, **http://dx.doi.org/10.2172/1988149**.

Limiting the capacity of supplementary/backup heating systems in cold climates is an important aim for both consumers and the electricity system. For consumers, limiting supplemental electric capacity can avoid costly and burdensome panel or utility service upgrades that might be required when electrifying homes. For the electricity system, limiting capacity can mitigate peak demand and other electricity system impacts that would result from widespread installation of supplemental electric heating.

For these reasons, we include two separate criteria related to HVAC and supplemental heating capacity in our package assignment logic. First, we include a three-ton (36,000 Btu/h) heating and cooling capacity threshold for the primary HVAC system in homes with ducts, as this represents the typical capacity for which home ductwork is designed. Second, we include a 9.5 kW supplemental heating capacity threshold to all homes in counties where the heating season design temperature is less than or equal to 0˚F. The logic here is that supplemental heating capacity greater than 9.5 kW is likely to require an electrical panel or utility service upgrade.[i] In addition, avoiding the need for supplemental systems that use electric resistance heat will also benefit the electricity system by limiting peak demand.

Baseline Building Characteristics

Finally, in addition to developing criteria around rooftop PV production potential, as well as estimated HVAC and supplementary heating and cooling capacities, we include several criteria that are specific to building characteristics. These include the building's location, level of existing wall and window insulation, and fuel type used for space and water heating. These characteristics were determined by the ABC Working Group to be the most important for developing upgrade criteria for different segments of the building stock.

i. This assumes a 40-amp, two-pole, 240-volt circuit breaker and is applied to housing units with a design temperature lower than 0˚F because compressor operation in the ResStock model shuts off at 0°F, meaning that for these homes, electric resistance would be sized to meet the entire design day load.

Appendix C3: Detailed Approach to Package Assignment

The steps described in this section elaborate further on steps 1–3 in Exhibit XX and outline how the metrics introduced above are used to assign packages to all ResStock housing units.

Step 1: Identify building segments that should not be prioritized for upgrades

Decarbonizing the existing residential building stock will most likely require that all buildings undergo some type of retrofit or upgrade, but some existing residential dwellings already meet all of the criteria used in this analysis to represent zero-carbon alignment. As shown in Exhibit XX, these criteria are somewhat different for the two broad categories of building type:

- Single-family and small multifamily
  - The building or housing unit's annual site energy consumption is already less than its estimated rooftop PV generation potential
  - The building or housing unit's space and water heating are already served by electricity
  - The building or housing unit is already insulated (if it is in the Cold & Very Cold climate region)[i]
- Large multifamily
  - The housing unit's annual site energy use intensity (EUI) is already less than the ASHRAE AEDG site EUI target for the unit's climate region
  - The building's space and water heating are already served by electricity
  - The building or housing unit is already insulated (if it is in the Cold & Very Cold climate region)

It is possible that the second condition — that the building/housing unit's space and water heating are already served by electricity — is likely to deprioritize buildings even when they do not yet have an air-source heat pump (ASHP) or heat pump water heater (HPWH) and may, in fact, have inefficient electric heating systems. But, given that the first condition ensures that these buildings already have fairly low energy usage and the second condition ensures they are all-electric, we do not believe these buildings should be prioritized given broader aims related to building sector decarbonization. That does not, however, suggest that none of these buildings should receive an upgrade.

It may also be the case that these buildings offer the best opportunities for electrification from a consumer economics perspective because they will yield higher utility bill savings than, for instance, buildings that switch from natural gas. But given our objective to determine which segments should be prioritized based on our ZCA framework for broader building sector decarbonization, we use this designation to determine which segments of the market will likely not require the kind of whole-building upgrades that the ABC Initiative is targeting.

Step 2: Determine which buildings require exterior envelope retrofits in addition to equipment replacement/electrification to meet ZCA criteria

Next, for all the buildings designated as "upgrade prioritized" in the previous step (around 92% of the residential building stock), we determined where the "all equipment swap-out" package is sufficient. This package includes upgrading to an ASHP and HPWH coupled with duct sealing and insulation and upgrading all appliances. We considered the upgrade sufficient for single-family and small multifamily buildings if it yielded annual site energy usage below the building's estimated rooftop PV generation potential. For large multifamily buildings, we considered it sufficient if it met the climate zone–specific AEDG EUI target, thus achieving the criteria of zero-carbon alignment at the building level.

We use an additional criterion to filter our results at this stage with the aim of ensuring the "all equipment swap-out" upgrade does not result in untenably large heat pump or supplementary heating capacities. We adopt the two thresholds described above — a three-ton (per dwelling unit) limit for primary HVAC heating or cooling capacity in all climates for dwelling units with existing ductwork and a 9.5 kW limit (~2.7 tons) for supplemental heating capacity in all buildings located in counties with a heating season design temperature 0˚F or below. We do not apply the three-ton primary HVAC threshold to buildings that currently have greater than three-ton AC systems (around 13% of existing housing units), and we do not apply the supplementary heating capacity threshold to housing units that currently heat with electricity.

i. "Insulated" here is defined as having insulated walls and double- or triple-pane windows. This criterion is intended to avoid uncomfortable surface temperatures.

Step 3: For buildings that are determined to need an exterior envelope upgrade to meet ZCA criteria, determine necessary envelope package

The third step in our package assignment logic uses the previously introduced metrics to determine which of the three envelope packages (conventional, IECC, Phius) is necessary to meet ZCA criteria. At this step, we assign the lowest-performance envelope upgrade level that can meet the site energy use target (based on either rooftop PV potential or the AEDG EUI target for single-family/small multifamily and large multifamily, respectively).

Next, we apply a similar logic as described in the previous step to limit both primary HVAC capacity (in buildings with ducts and without existing three-ton AC systems) and supplementary heating capacity in buildings that do not currently heat with electricity in cold regions (heating design temperature 0˚F or below). As above, we assign the lowest-performance envelope package that can meet these thresholds.

A sizable share of housing units in both building type categories are unable to achieve either of the metrics and thresholds at this stage of our assignment logic (i.e., they have annual site energy usage or EUI levels above either the rooftop PV generation potential or AEDG EUI targets and/or they have HVAC or supplementary heating capacities above the defined thresholds). Around 9% of all residential buildings do not meet these targets even with the highest-performance upgrade package ("equipment + Phius envelope"). In these instances, we assign the envelope package that maximizes R-value-normalized energy savings (see *Appendix C2* for a description of this metric).

Step 4: Apply geographical filter to prioritize buildings in states with strong market opportunity for ABC adoption

After assigning all residential buildings a given upgrade package, we apply a market opportunity–focused filter to further prioritize the geographies where ABC innovations for high-performance building retrofits have the greatest prospects to be scaled and to deliver co-benefits for local communities.

As described in the *Residential Retrofit Market Opportunities* section of the main report, this analysis developed ranking criteria for states to identify high-potential locations for ABC projects and markets. We incorporate these insights into our prioritization by selecting the top 10 states and filtering our resulting building segments such that we only include buildings located in those high-opportunity states. We ensure that we include states from each climate zone so that guidance can be provided across the United States but also in select states where we believe the prospects for adoption of ABC are most promising.

Step 5: Prioritize buildings for which an envelope upgrade package is assigned

Similar to the geographic filter applied in the previous step, this step applies a filter to the package assignments to include only those buildings that are assigned an upgrade with an exterior envelope component. Given the ABC Collaborative's focus on comprehensive, whole-building approaches to retrofits, this step further targets the guidance in this report to those segments of the stock that are determined to need one of the envelope upgrade packages in our assignment logic.

Step 6: Aggregate prioritized segments across common building characteristics and rank by size of segment

The final step in the market segment prioritization methodology consists of combining the results of the previous five steps with the building stock characterization results to rank both single-family and multifamily building sector segments by their size (number of housing units). In this step, we use the package assignments determined in steps 1–3, filter out buildings that are not located in the priority geographies as determined in step 4, and exclude buildings that are not assigned one of the envelope upgrade packages as determined in step 5.

Finally, we aggregate segments across key building characteristics, including climate region, building type, vintage, heating fuel, wall structure type, and window insulation level, to develop and rank two lists of priority segments: the top 10 segments overall across climate regions and the top five segments in each climate region (see Exhibits XX–XX in the *Summary of Priority Market Segments for ABC Retrofits* section).

Appendix C4: Supplementary Package Assignment Results Inclusive of Building Thermal Resilience

In addition to our package assignment results presented in the report, we present additional assignment results that are based on a sensitivity analysis that assesses how assignments change when criteria related to building thermal resilience are included. This section briefly introduces the concept of building thermal resilience and the metric by which it is assessed in this sensitivity analysis and then presents a second set of assignments (for single-family/small multifamily building types only) that includes criteria related to building thermal resilience.

Building Thermal Resilience

Building thermal resilience is an important metric to consider alongside the primary ZCA criteria introduced in this report. A forthcoming report from DOE, *Enhancing Energy Resilience in Buildings: Development of a Standardized Methodology to Quantify Efficiency Benefits for Energy Resilience*, summarizes a comprehensive research effort from several national laboratories that aims to quantitatively assess the impacts of building energy efficiency measures on thermal resilience. This assessment uses detailed climatological and building modeling to investigate the impacts of grid outages that occur during prolonged extreme heat or cold events and the role of energy efficiency in mitigating occupant exposure. It quantifies thermal resilience across several key metrics, including passive survivability, loss of life, and monetary costs and benefits. While methodological details are available in the report, we provide a brief description of these metrics and how they are adapted to provide resilience-relevant criteria for prioritizing where and in which building segments higher-performance envelope performance upgrades may be warranted from the perspective of occupant exposure and damage in the context of extreme temperature events.

In the report, the authors use two passive survivability metrics to assess livable condition thresholds that align with occupant risks. These are the standard effective temperature (SET) and heat index (HI), as well as a cumulative SET metric, SET degree hours, which is considered over the duration of the extreme event periods modeled. In our prioritization logic, we adapt the SET degree hours metric and thresholds provided in the report. SET considers several factors, including indoor dry-bulb temperature, relative humidity, mean surface radiant temperature, and air velocity in addition to occupant activity and clothing factors. The LEED Pilot Credit IPpc100, “Passive Survivability and Back-up Power during Disruption,”[123] defines livable conditions as SET values of 54˚F–86˚F. This credit is given to residential buildings that do not exceed a cumulative SET degree hours threshold of 216 for a seven-day power outage during an extreme hot or cold event (i.e., the cumulative hours outside of the “livable conditions” do not exceed 216 over seven days).

Application of Thermal Resilience in Package Assignment Logic

After step 3 in our package assignment logic, we apply an additional step based on the resilience criterion and SET degree hours threshold described above. In general, we take a similar approach to the previous steps wherein we assign the lowest-performance package that meets the SET degree hours threshold. This criterion is applied to all buildings/units, regardless of whether they are initially not prioritized for an upgrade or are initially assigned the “all equipment swap-out” upgrade, as buildings that might not be prioritized to receive envelope upgrades based on building energy use or other energy-related criteria (e.g., HVAC capacities) should still be considered for envelope upgrades if those upgrades would improve the building’s thermal resilience.

To apply the SET degree hours threshold, we first determine the climate region of each of the housing units. Next, we apply results from the DOE resilience report, which simulate these metrics for the existing stock and for the “equipment + IECC envelope” and “equipment + Phius envelope” packages in representative cities in each climate region. For either a long-duration (seven-day) hot or cold event, we assign the package that can limit cumulative SET degree hours to below 216. In several climate regions, none of the packages can meet this threshold for either hot or cold events; in these cases, no buildings are reassigned packages.

We apply the resilience criterion as a sensitivity case rather than in our main package assignment logic for two reasons. First, as discussed above, assigning upgrades to limit occupant exposure and risk in the face of extreme events is somewhat different from assigning upgrades based on energy system and decarbonization metrics. Some decision makers may be principally concerned with the former, and others may be more attentive to the latter. But given that the primary focus of the package assignment is to determine which upgrade is necessary to meet ZCA criteria in service of broader building sector decarbonization goals, this additional assignment step is included as a sensitivity analysis because it is not centrally related to decarbonization but might still be of interest to certain stakeholders.

Second, the resilience criterion is based on different data than that used for the assignment logic (for the site energy, HVAC capacity, and building characteristics criteria, all of which come from the modeled package upgrade analysis). The resilience data is limited primarily by its geographic resolution (only representative cities are simulated in the report’s methodology, rather than the much more granular simulations undertaken for the modeled package upgrade analysis), and it is somewhat coarsely applied in this analysis. Further, the resilience assessment includes only single-family homes in the analysis, so we apply this sensitivity criterion and assignment step only to the single-family/small multifamily building type group (given that these buildings are likely similar enough in most instances that the resilience metrics can accurately be applied to these but not to large multifamily buildings).

Results of Package Assignment Sensitivity Analysis

Exhibit XX below presents results of the package assignment sensitivity analysis for single-family and small multifamily buildings. In comparison the results in Exhibit 21 in the main report, many of the housing units' assignments shift to the higher-performance envelope upgrades (IECC/Phius Envelope). This is especially the case for housing units in the Mixed-Humid and Hot-Humid climate zones, which see the greatest shifts in assignments when resilience criteria are included. Table XX shows the percentages of the single-family/small multifamily stock assigned to each upgrade package under both the original results and the sensitivity case results, which demonstrate how applying criteria related to thermal resilience leads to greater prioritization of the upgrades that include exterior envelope components and, especially, the highest-performance packages.

Our inclusion of resilience criteria in this sensitivity case rather than in our main assignment logic should not necessarily suggest that resilience is a secondary concern to building decarbonization. Indeed, we believe resilience is an essential criterion upon which to make assessments of retrofit depth, especially as temperature extremes become increasingly common and damaging. Researchers at Phius are developing a new retrofit standard (REVIVE Pilot) that will use outage resilience as its main determinant of the envelope upgrade package, partly on equity grounds that every building should have this characteristic. They have noted that the "extreme" weather events used in the LEED Pilot Credit for Passive Survivability (and in the DOE study) are extreme weeks from the typical meteorological year, which are not all that extreme compared with recent heat waves and cold snaps (let alone those that are projected to occur in the future under a warming climate). Therefore, the resilience tests applied in the DOE study may not be stringent enough. From a resilience point of view, upgrades inclusive of envelope retrofits may be needed that provide higher performance than those estimated in this sensitivity analysis, and this is an important area for future inquiry.

Exhibit 37. Resilience Sensitivity Case Results for ABC Upgrade Package Assignment by Climate Zone

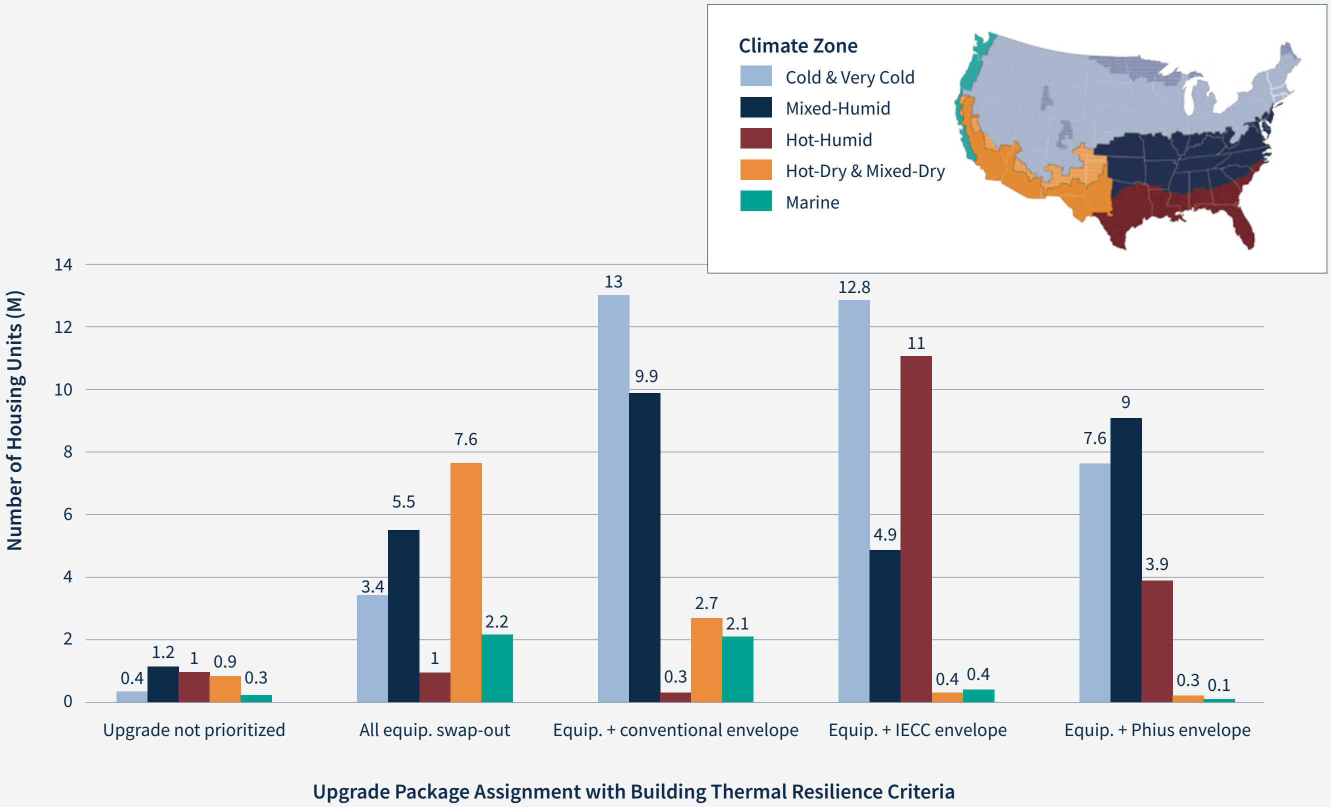


Exhibit 38. Resilience Sensitivity Case Results for ABC Upgrade Package Assignment by Building Type

Building Type	Upgrade Package Assignment	Share of Stock (Initial Results)	Share of Stock (Sensitivity Analysis Results)
Single-family/small multifamily • Single-family detached • Single-family attached • Multifamily, 2–4 units	Upgrade not prioritized	7%	3%
	All equipment swap-out	30%	19%
	Equipment + conventional envelope	34%	19%
	Equipment + IECC envelope	19%	29%
	Equipment + Phius envelope	10%	21%

Appendix C5: Supplementary Methods and Results for Retrofit Cost Target Analysis

In the *Package Cost Target Analysis* section of the report, we present just one type of cost target inclusive of utility bill savings, avoided equipment replacement and envelope costs, and NEIs. In this section we expand on those targets to include an "incremental" cost target that aims to provide guidance for package costs incremental to equipment and envelope costs in the reference case. Additionally, we include a cost target range for both the "total" and "incremental" cost targets. This range is defined by a "more aggressive" case that ignores the hard-to-monetize NEIs and a "less aggressive" case that includes the value from NEIs. Exhibit XX below shows what is incorporated in each type of cost target and the ranges therein.

Exhibit 39. Total versus Incremental Cost Targets

Building Type	Total Cost Target		Incremental Cost Target	
Description	What this package should cost "all in" considering the value from avoided equipment and roof/siding replacements		What this package should cost "incrementally" to the cost of a regular equipment and roof/siding replacement	
Primary Audience	Manufacturers; project developers; builders		Building owners; occupants; policymakers	
Cost Target Range	More aggressive (more cost compression required)	Less aggressive (less cost compression required)	More aggressive (more cost compression required)	Less aggressive (less cost compression required)
Revenue and Avoided Costs Included	• Utility bill savings • Avoided costs of business-as-usual upgrades (regular replacements that would otherwise be needed)	• Utility bill savings • Avoided costs of business-as-usual upgrades (regular replacements that would otherwise be needed) •Non-energy impacts (including both occupant and building added value)	• Utility bill savings	• Utility bill savings • Non-energy impacts (including both occupant and building added value)

Note: NPV of package savings are calculated separately for equipment (assumed 15-year lifetime) and for envelope measures (assumed 30-year lifetime).

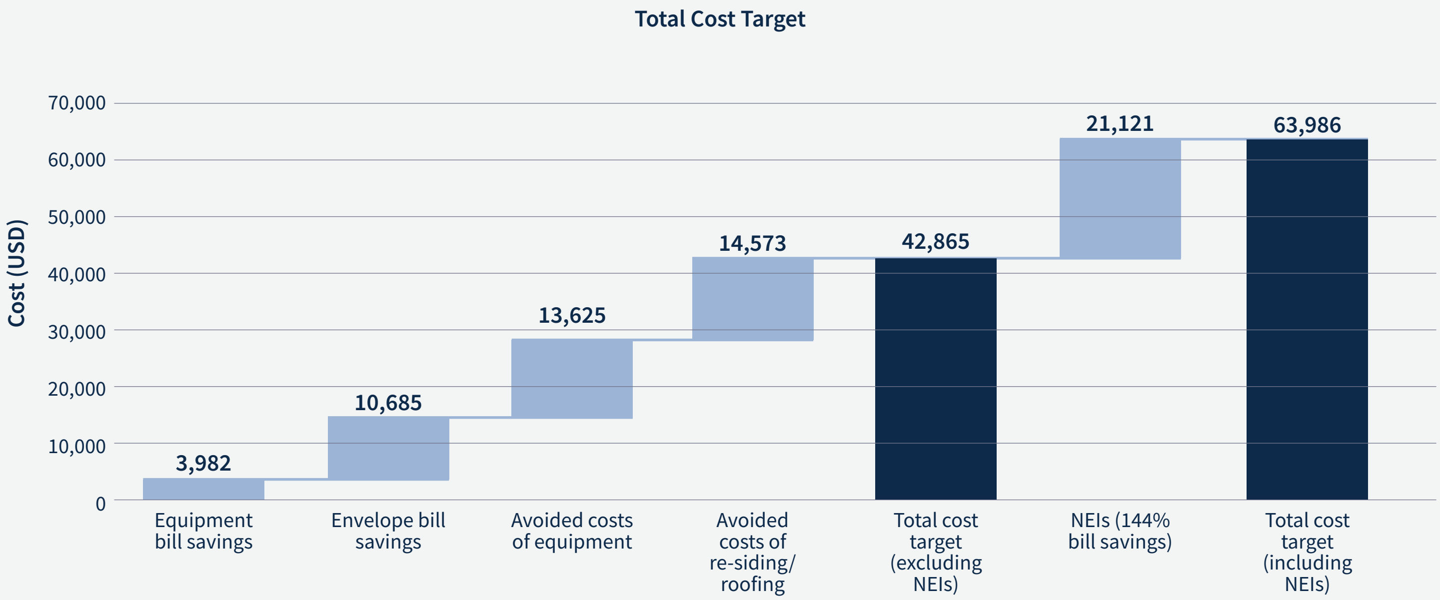
As described in the main body of the report, the "total" cost target considers a reference case in which the building would undergo conventional equipment/appliance/envelope component replacements and includes the value of these interventions in the cost target. The "total" cost target may be more appropriate for manufacturers and project developers who need to know the full installed cost of a given retrofit package, whereas the "incremental" cost target (i.e., the package "premium" incremental to regular equipment and envelope replacements) may be more appropriate for building owners and occupants.

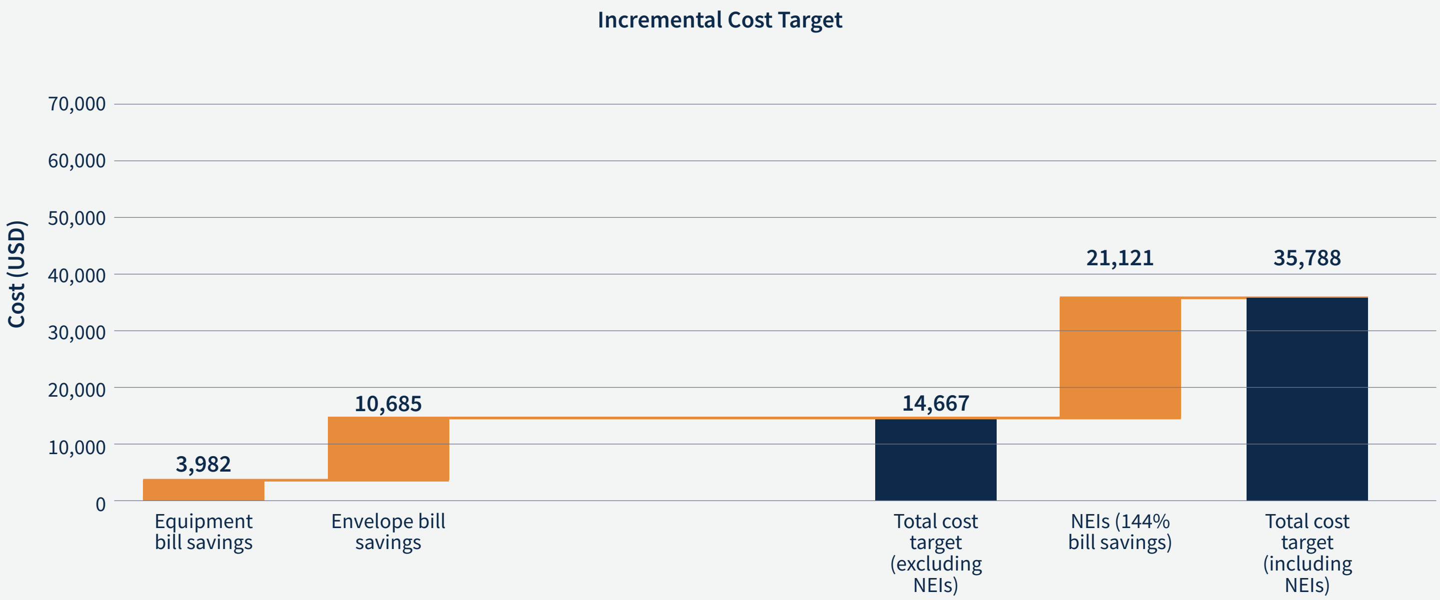
For each of the two types of cost target ("total" and "incremental"), we calculate the targets as a range based on which components are included. We calculate the modeled energy and utility bill savings first from equipment/appliance replacements, which we generally assume to have a 15-year lifetime, and second from envelope upgrades, which we conservatively assume to have a 30-year lifetime. Using flat state average electricity and non-electric fuel prices from 2019,[124] we calculate utility bill savings from a reference case in which the unit receives in-kind equipment replacements (meeting federal minimum efficiency requirements). For the "incremental" cost targets, we take the combined net present value (NPV) of the equipment and envelope savings to estimate what the installed cost of the package should be if the project is to have a positive lifetime NPV. For the "total" cost targets, we add this combined NPV to the value of avoided equipment and envelope replacement costs.

In the less aggressive cost target cases, we incorporate both the package's modeled lifetime utility bill savings (as above), as well as a multiplier on energy savings, to represent the savings attributable to NEIs of the project, as described in the main body of the report. Exhibit XX presents an illustrative diagram for one of the upgrade packages ("equipment + IECC envelope") to show each of the cost target components described above. The diagram shows the "total" cost target (as it includes components for the avoided cost of reference case replacements/renovations) and the "less aggressive" cost target (as it includes the monetized NEIs of the project). As shown in the diagram, these components are summed to get a total cost target, which is likely lower than the cost of the package today, thus necessitating a certain amount of cost compression.

Exhibit 40.

Illustrative Diagram of the "Total" and "Incremental" Cost Target Ranges for the "Equipment + IECC Envelope" Package for Single-Family Homes





Cost Target Results

Exhibit XX presents the median cost target ranges for all four methods ("total" versus "incremental" and "less aggressive" versus "more aggressive") described above for single-family and small multifamily homes. Exhibit XX presents the same for units in large multifamily buildings. These cost targets are specified for the subset of housing units in each state that are assigned the relevant package (i.e., the "equipment + conventional envelope" cost target in California is based on the results from housing units in that state that are assigned the "equipment + conventional envelope" package based on our prioritization approach). Cost targets are only presented for the packages that include envelope upgrades, but in all cases these envelope packages also include the equipment electrification and appliance replacement upgrades in the "all equipment swap-out" package.

Exhibit 41.

Median Cost Targets for Assigned Packages in Priority States for Single-Family and Small Multifamily ($/Housing Unit)

State	Upgrade Package Assignment	Median Incremental Cost Target, Low	Median Incremental Cost Target, High	Median Total Cost Target, Low	Median Total Cost Target, High
CA	Equip. + conventional envelope	5,352	13,060	34,397	41,694
	Equip. + IECC envelope	12,525	30,561	42,299	60,351
	Equip. + Phius envelope	14,571	35,553	45,670	66,674
CO	Equip. + conventional envelope	3,709	9,050	29,483	34,364
	Equip. + IECC envelope	9,063	22,114	34,284	47,031
	Equip. + Phius envelope	12,589	30,717	38,770	57,005
FL	Equip. + conventional envelope	9,101	22,205	36,565	49,678
	Equip. + IECC envelope	12,931	31,551	42,297	61,093
	Equip. + Phius envelope	13,429	32,767	42,412	61,168
MA	Equip. + conventional envelope	12,380	30,207	40,335	57,879
	Equip. + IECC envelope	29,797	72,704	58,483	101,136
	Equip. + Phius envelope	40,611	99,091	70,044	129,223
MD	Equip. + conventional envelope	11,613	28,335	40,806	57,583
	Equip. + IECC envelope	22,044	53,788	52,500	83,425
	Equip. + Phius envelope	23,365	57,011	54,900	87,180
MI	Equip. + conventional envelope	5,166	12,606	33,280	40,315
	Equip. + IECC envelope	12,658	30,885	40,869	58,684
	Equip. + Phius envelope	18,544	45,246	47,006	73,720
NY	Equip. + conventional envelope	11,108	27,104	40,267	55,862
	Equip. + IECC envelope	25,417	62,016	55,410	92,002
	Equip. + Phius envelope	33,483	81,698	64,564	112,974
PA	Equip. + conventional envelope	10,302	25,137	39,841	54,297
	Equip. + IECC envelope	19,905	48,568	50,405	78,900
	Equip. + Phius envelope	24,367	59,455	55,436	90,253
TX	Equip. + conventional envelope	9,101	22,207	36,992	50,017
	Equip. + IECC envelope	15,243	37,193	44,214	66,037
	Equip. + Phius envelope	16,072	39,216	45,390	68,863
WA	Equip. + conventional envelope	7,147	17,438	33,993	43,996
	Equip. + IECC envelope	14,366	35,052	41,276	61,953
	Equip. + Phius envelope	13,495	32,929	41,333	60,546

The inclusion of these additional types and ranges in the cost targets is intended to provide a more nuanced picture of what retrofit package installed costs would need to be in order to scale the market for ABC retrofits. In the main body of the report, the results presented are the higher end of the targets shown above, and they are likely still much lower than a retrofit package that meets the assigned performance levels could achieve today, especially for the more aggressive envelope packages like IECC and Phius. In the above tables, we show that if we only include the cost target components that we know can be monetized (utility bill savings and, if timed correctly, avoided equipment and/or envelope replacement costs), there would be substantially more cost compression required to achieve scale. This highlights three important points:

1. As mentioned in the *Retrofit Market Conclusions* section, finding ways to monetize NEIs associated with high-performance retrofits is critical to scaling the market.
2. Similar to conventional retrofits, timing the intervention for ABC retrofits to align with equipment or envelope asset end-of-life will increase the viability of the project, especially in the near term as the market scales and costs come down.
3. Innovative financing solutions that help alleviate the up-front incremental cost premium for ABC packages will also improve uptake in the market.

The inclusion of NEIs has a much greater effect on the “incremental” cost targets than on the “total” cost targets. For example, in New York and Massachusetts, the median “incremental, high” targets are 2.4 times greater than the median “incremental, low” targets. This is because the NEIs are calculated as a multiplier on utility bill savings and because, for the “incremental” cost targets, utility bill savings make up a greater portion of the overall cost target than they do for the “total” cost targets. As the “incremental” cost target is aimed more at building owners who constitute the hypothetical demand for ABC retrofits, this further highlights the importance of finding ways to monetize these benefits to increase the cost-effectiveness of ABC packages.

Exhibit 42. Median Cost Targets for Assigned Packages in Priority States for Large Multifamily ($/Housing

State	Upgrade Package Assignment	Median Incremental Cost Target, Low	Median Incremental Cost Target, High	Median Total Cost Target, Low	Median Total Cost Target, High
CA	Equip. + conventional envelope	2,275	5,551	10,861	14,324
	Equip. + IECC envelope	4,604	11,234	12,560	19,372
	Equip. + Phius envelope	2,614	6,379	11,226	15,818
CO	Equip. + conventional envelope	2,498	6,095	13,034	16,840
	Equip. + IECC envelope	5,929	14,466	16,610	25,421
	Equip. + Phius envelope	4,737	11,559	15,313	21,527
FL	Equip. + conventional envelope	4,508	11,000	14,904	21,117
	Equip. + IECC envelope	5,964	14,551	15,721	24,283
	Equip. + Phius envelope	5,453	13,306	15,338	22,768
MA	Equip. + conventional envelope	6,842	16,693	15,599	24,759
	Equip. + IECC envelope	17,878	43,622	25,828	51,510
	Equip. + Phius envelope	17,172	41,901	24,874	47,785
MD	Equip. + conventional envelope	5,951	14,521	17,073	25,810
	Equip. + IECC envelope	10,140	24,741	22,570	36,178
	Equip. + Phius envelope	8,868	21,638	20,249	32,636
MI	Equip. + conventional envelope	3,139	7,660	13,481	17,151
	Equip. + IECC envelope	7,817	19,074	17,631	28,282
	Equip. + Phius envelope	8,749	21,347	17,667	29,607
NY	Equip. + conventional envelope	5,867	14,314	13,866	21,861
	Equip. + IECC envelope	15,078	36,789	22,826	44,075
	Equip. + Phius envelope	13,094	31,949	20,390	39,068
PA	Equip. + conventional envelope	5,129	12,514	13,934	21,055
	Equip. + IECC envelope	11,393	27,800	19,612	36,176
	Equip. + Phius envelope	9,306	22,706	18,483	30,130
TX	Equip. + conventional envelope	5,120	12,494	15,751	22,867
	Equip. + IECC envelope	6,675	16,287	17,509	26,943
	Equip. + Phius envelope	6,950	16,957	17,240	27,175
WA	Equip. + conventional envelope	3,381	8,251	9,777	15,013
	Equip. + IECC envelope	6,682	16,304	13,455	23,026
	Equip. + Phius envelope	6,509	15,882	13,194	21,296

Whereas the main body of the report shows the full distributions of the values in the "Total Cost Target, High" column, the above tables present median cost targets for each of the assigned packages, meaning that 50% of the housing units with the assigned package could support higher installed costs while 50% could support lower installed costs. However, in the near term, as the nascent market for ABC retrofits scales up, solution providers (manufacturers, contractors, developers) may be more interested in targeting the projects that can support the higher end of the cost target ranges. Exhibits 58 and 59 show the key characteristics of the modeled buildings that make up the top 10% of the cost target range for each ABC package in each of the priority states.

These tables are intended to provide industry with an idea of the building characteristics that can support higher project costs and therefore may be good targets for ABC retrofits in the near term. For example, for the "equipment + conventional envelope" package in California, existing single-family detached homes that heat with electricity, are wood-framed, and were built between 1940 and 1979 may be a good initial typology to target. Similarly, for the "equipment + conventional envelope" package in Pennsylvania, single-family detached homes that heat with fuel oil, are either wood-framed or brick, and were built between 1940 and 1979 may be a good initial typology to target.

More generally, for single-family and small multifamily housing units, the building type, wall type, and vintage have far less variation than the heating fuel in the top 10% of cost targets, which may suggest heating fuel as a key characteristic to focus on. Not surprisingly, buildings that heat with electricity, fuel oil, or propane are likely to be better typology targets than those that heat with natural gas, due to the relatively higher utility costs associated with electric resistance heat (the predominant electric heating type in existing residential buildings), fuel oil, and propane compared with natural gas.

For larger multifamily buildings, there is a higher prevalence of existing electric heat in almost all states, suggesting that to be the heating fuel that may be worth targeting. There is also more variation in wall type across states, highlighting a need for envelope solutions that can be applied to wood-framed or brick (and to a lesser extent steel) construction. New York has by far the largest number of high-rise (eight or more stories) multifamily projects, which are the leading building type for the "equipment + IECC envelope" package.

An interactive dashboard with building characteristic data for all US states can be found here: **https://public.tableau.com/views/ABCMarketGuidanceforZero-carbonAlignedResidentialBuildings_16759824008870/PackageDefinitions**.

Exhibit 43.

Heat Maps of Key Building Characteristics across Priority States for Housing Units That Have Package Cost Targets in the Top 10% across All Single-Family and Small Multifamily BuildingsUnit)

Conventional envelope

	Space Heating Fuel				Wall Type				Building Vintage			Building Type		
State	Electricity	Natural Gas	Fuel Oil	Propane	Wood Frame	Brick	Concrete	Steel Frame	<1940s	1940-1979	>1980s	Single-Family Attached	Single-Family Detached	Multifamily with 2-4 Units
CA	140844	67518	3630	43560	257004	1694	0	0	38236	164560	55902	8954	248050	1694
CO	51304	3872	0	17666	66792	6050	0	0	7986	35090	29766	1452	68970	2420
FL	72358	2904	0	2420	32912	26378	18634	242	9922	49610	18634	1936	76230	0
MA	29766	13794	53240	5566	84216	6050	11616	484	43560	52030	6776	2904	87362	12100
MD	38720	9196	29766	10406	85184	2904	0	0	21538	51304	15246	6534	81070	484
MI	74778	24684	8954	54450	38236	121968	2662	0	41140	90266	31460	1452	155364	6050
NY	55176	25410	125114	18876	217800	6776	0	0	78166	127534	18876	4356	206910	13310
PA	85184	19602	95832	41624	143506	98252	484	0	87604	113498	41140	16698	222398	3146
TX	123662	20812	0	13794	94380	59290	242	4356	18634	98978	40656	2420	155848	0
WA	70906	4356	15246	15488	102366	2420	726	484	32912	57112	15972	726	104786	484

IECC envelope

	Space Heating Fuel				Wall Type				Building Vintage			Building Type		
State	Electricity	Natural Gas	Fuel Oil	Propane	Wood Frame	Brick	Concrete	Steel Frame	<1940s	1940-1979	>1980s	Single-Family Attached	Single-Family Detached	Multifamily with 2-4 Units
CA	14762	2904	1452	12342	31460	0	0	0	4840	19360	7260	968	30008	484
CO	21296	8470	242	11858	40414	1452	0	0	9922	19118	12826	2420	39446	0
FL	41624	2662	0	2420	25168	15488	6292	0	8712	26620	11616	1210	45738	0
MA	10406	8470	37026	4356	56144	1210	2178	726	21296	32912	6050	2662	53966	3630
MD	14036	3872	11132	5566	34122	484	0	0	5808	20570	8228	4114	30492	0
MI	17908	17908	5082	32912	31944	39930	1694	242	22264	35332	16214	1210	71632	968
NY	18392	25410	88330	27346	157058	2420	0	0	63646	86152	9680	2904	151734	4840
PA	28072	11616	40414	13794	69212	24684	0	0	32428	46706	14762	12100	81070	726
TX	70906	16698	0	8954	66308	25410	0	4840	16698	48400	31460	1936	94622	0
WA	20328	2904	4840	5324	33154	242	0	0	7018	19844	6534	484	32912	0

Phius Envelope

	Space Heating Fuel				Wall Type				Building Vintage			Building Type		
State	Electricity	Natural Gas	Fuel Oil	Propane	Wood Frame	Brick	Concrete	Steel Frame	<1940s	1940-1979	>1980s	Single-Family Detached	Single-Family Attached	Multifamily with 2-4 Units
CA	4598	1694	1210	7018	14520	242	0	0	2178	5566	7018	14520	242	0
CO	6776	12584	0	9196	24442	3872	242	0	7744	10890	9922	28314	242	0
FL	12100	484	0	968	6534	2904	4114	0	1452	9196	2904	13552	0	0
MA	1936	5324	22748	2904	24200	2904	5808	0	15730	13068	4114	31460	726	726
MD	3872	1694	2662	1694	9196	726	0	0	968	5566	3388	9438	484	0
MI	19844	30008	7018	44528	16214	82280	2904	0	31944	45738	23716	99946	726	726
NY	4356	12100	32670	16698	63888	1936	0	0	33396	24442	7986	65340	242	242
PA	17182	11616	26136	10406	29524	35574	242	0	28314	25410	11616	60984	4356	0
TX	21538	6776	242	3388	14036	16214	0	1694	4114	18634	9196	31460	484	0
WA	4840	2662	1452	3388	11374	484	484	0	3872	5324	3146	12342	0	0

Exhibit 44.

Heat Maps of Key Building Characteristics across Priority States for Housing Units That Have Package Cost Targets in the Top 10% across All Large Multifamily Buildings

Conventional envelope

State	Electricity	Natural Gas	Fuel Oil	Propane	Wood Frame	Brick	Concrete	Steel Frame	<1940s	1940-1979	>1980s	Multifamily with 5+ units, 1-3 stories	Multifamily with 5+ units, 4-7 stories	Multifamily with 5+ units, 8+ stories
CA	66308	20570	0	1694	82038	1452	484	7018	7260	50820	32912	65824	18150	7018
CO	18634	0	0	242	15972	1452	242	1210	1694	10406	6776	14036	3630	1210
FL	25168	484	0	0	5566	15730	726	3872	726	13794	11374	18876	3388	3630
MA	25410	726	1694	242	18876	4114	2178	2904	13794	11616	2662	19118	6534	2420
MD	16940	1694	242	0	11858	5808	0	1210	726	11132	7018	16456	1452	968
MI	25168	0	0	484	3630	19602	0	2420	1694	17908	6050	21054	2178	2420
NY	59774	4114	45738	6776	37752	51304	968	26378	57112	51304	7986	52998	37026	26378
PA	26378	0	484	968	2904	21296	0	3630	7502	15730	4598	19360	4840	3630
TX	45738	484	0	0	7502	32670	242	5808	1936	26862	17424	35090	5808	5324
WA	20086	242	242	242	14036	1694	1452	3630	4356	12100	4356	14520	3146	3146

IECC envelope

	Space Heating Fuel				Wall Type				Building Vintage			Building Type		
State	Electricity	Natural Gas	Fuel Oil	Propane	Wood Frame	Brick	Concrete	Steel Frame	<1940s	1940-1979	>1980s	Multifamily with 5+ units, 1-3 stories	Multifamily with 5+ units, 4-7 stories	Multifamily with 5+ units, 8+ stories
CA	5324	484	0	0	5082	0	0	726	242	4598	968	4114	968	726
CO	4840	484	0	484	4356	484	0	968	242	3146	2420	4356	484	968
FL	3146	484	0	0	484	2662	242	242	0	2662	968	2662	726	242
MA	9922	0	726	0	7260	484	484	2420	5082	4598	968	7018	1452	2178
MD	4114	1210	242	0	2904	1452	242	968	242	3388	1936	3872	726	968
MI	9438	726	0	242	2904	6776	0	726	1452	4598	4356	8470	1210	726
NY	15246	10164	28314	2178	16214	20328	0	19360	23958	29524	2420	19602	16940	19360
PA	5808	1452	726	242	968	4840	0	2420	2178	4598	1452	3872	1936	2420
TX	9438	484	0	0	2662	6776	0	484	0	6292	3630	8228	1210	484
WA	3872	0	0	0	2904	0	0	968	242	2904	726	2178	726	968

Phius Envelope

	Space Heating Fuel				Wall Type				Building Vintage			Building Type		
State	Electricity	Natural Gas	Fuel Oil	Propane	Wood Frame	Brick	Concrete	Steel Frame	<1940s	1940-1979	>1980s	Multifamily with 5+ units, 1-3 stories	Multifamily with 5+ units, 4-7 stories	Multifamily with 5+ units, 8+ stories
CA	484	242	0	0	726	0	0	0	0	484	242	484	242	0
CO	484	968	0	0	1452	0	0	0	0	484	968	1210	242	0
FL	242	0	0	0	0	0	0	242	0	242	0	0	0	242
MA	1936	968	0	0	1452	968	242	242	1694	242	968	2420	484	0
MD	1694	242	0	0	726	968	0	242	242	1452	242	1452	242	242
MI	4356	242	0	0	726	3146	242	484	1452	2662	484	2662	1452	484
NY	5324	1936	6050	968	2420	8470	0	3388	7018	6776	484	6776	4114	3388
PA	2904	242	484	0	242	2904	0	484	1936	1694	0	1452	1694	484
TX	2178	0	0	0	484	1452	0	242	0	1452	726	1936	0	242
WA	1210	0	0	0	968	0	0	242	0	968	242	968	0	242

Appendix D: Embodied Carbon

Introduction

Building construction accounts for 17% of global energy use and 28% of global greenhouse emissions.[125] The United States generated more than two times as much construction debris as municipal solid waste in 2018, with nearly 455 million tons ending up in landfills.[126] While the DOE has successfully implemented strategies and programs to increase the efficiency of building technologies, a significant opportunity remains to decrease the embodied carbon (EC) in our building stock.

EC refers to the greenhouse gas (GHG) emissions arising from the manufacturing, transportation, installation, maintenance, and disposal of building materials, and it accounts for a significant percentage of global emissions. In contrast, operational carbon refers to GHG emissions due to building energy consumption. To quantify total emissions and their potential effects on climate change, scientists use a method called life-cycle assessment to track the emissions produced over the full life cycle of a product or process. These emissions are converted into metrics that reflect their potential effects on the environment, including the global warming potential (GWP), which is quantified in kilograms of CO2 equivalent (kg CO2e). This quantity is also commonly referred to as a carbon footprint.

Despite calls for increased transparency, product supply chains remain opaque to key players within industries, let alone consumers. Manufacturers, designers, retailers, and consumers each have a limited vision of the entire life cycle of products. When it comes to making choices about the product's sustainability or environmental impact, each stakeholder makes decisions influenced by factors including their intrinsic motivations, the options available to them, their education about environmental topics, and economic incentives. For this reason, if the building technology sector wants to improve sustainability, it must increase capacity and tooling to support stakeholders' decisions as a starting point for product, service, and policy innovation.

Despite broad agreement on the importance of sourcing and using materials low in embodied carbon and measuring their effects, the industry still lacks a widely accepted mechanism for measuring the EC of building materials. Several open-source or subscription-based tools are available, but design professionals or contractors may not be incentivized to use them due to issues with usability or accessibility.

Life-Cycle Assessments

A life-cycle assessment (LCA) is a common methodology to assess EC in building materials. A building's life cycle is split into various stages (A to D), which are made up of "modules" as described below in Exhibit XX.

Exhibit 45. Life-Cycle Stages as Defined in the European Standard EN 15978

Module	A1-A3			A4-A5		B1-B7							C1-C4				D
Life cycle stages	Product stage			Construction process stage		Use stage							End-of-life stages				Benefits and loads beyond the system boundary stage
Process	Raw materials supply	Transport	Manufacturing	Transport	Construction-Installation Process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/ Demolition	Transport	Waste processing	Disposal	Reuse, recovery, and recycling potential
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Source: Danish Transport and Construction Agency, "Introduction to LCA of Buildings," 2016

Stage A: Product and Construction

This stage begins with the supply of raw materials and ends with the practical completion of the building. This stage relates only to embodied carbon, since the building is not yet in operation. Data for insulation materials is most consistently available for the product stage and manufacturing (A1–A3).

- **A1–A3:** Product stage and manufacturing: accounting for the carbon emissions associated with the "cradle-to-gate" processes: raw material supply, transportation, and manufacturing.
- **A4–A5:** Construction process stage: accounting for the carbon emissions associated with the transportation of the materials to the site and the construction itself (material wastes, construction plant, and machinery).

Stage B: In Use

Throughout this stage, the building is in use. Stage B is divided into five modules relating to EC and two relating to operational carbon.

- **B1–B5:** In-use embodied: accounting for the carbon emissions associated with the maintenance, repair, replacement, and refurbishment of the built asset over its lifetime. For buildings, embodied emissions generally only concern B4 (replacement), owing to the availability of data at the time of reporting.
- **B6–B7:** In-use operational: accounting for the carbon emitted throughout the use of the building (energy and water). Operational energy may be calculated using the current grid energy carbon factor, and it accounts for decarbonization scenarios in line with national assumptions.

Stage C: End of Life

This stage is associated with the demolition and waste processing of construction materials. It generally has a low impact. However, when a building uses biogenic materials, the disposal will release some or all of the sequestered carbon to the atmosphere, depending on the end-of-life scenario considered.

Stage D: Beyond-Life Benefits

This module accounts for benefits or burdens associated with repurposing building elements, e.g., discarded materials from the built asset or energy recovered from beyond the project's life cycle. This accounting seeks to present a wider picture of the environmental impacts of the project and accounts for the future potential of the products and the circular economy. The carbon emissions associated with Stage D are generally not included within the whole-life carbon emissions, as they are outside the building system. The values are, however, interesting in the context of a circular economy.

Environmental Product Declarations (EPDs)

Environmental Product Declarations (EPDs) detail the LCA and information relevant to a product's GWP, ozone depletion potential, water use, and other environmental impact categories. EPDs are valid for five years. They quantify environmental impact information in a way that is designed to allow relatively straightforward comparisons among products.

ISO 21930 is the North American standard for building construction–related EPDs, and EN 15804 is the European standard. Both generally adhere to ISO 14025, which establishes the procedures and format for developing an EPD.[127] EPDs are still relatively new, however, and can vary in presentation and content. Unfortunately, different reporting formats and functional units (i.e., the quantity of product evaluated) can make true product comparisons challenging.

Compilation of Insulation Material EPDs

The data for insulation materials discussed in this report was compiled by Efficiency Vermont,[128] which investigated the following insulation classes:

- Cellular glass: aggregate
- Cellulose: blown/loose-fill and dense-pack
- Expanded polystyrene (EPS): Types I, II, VII, and IX
- Fiberglass: batt, blown/loose-fill, blown/spray, and board
- HempCrete: block
- Mineral wool: batt, blown, and board
- Phenolic foam: board
- Polyisocyanurate: board
- Spray polyurethane foam (SPF): 2K-LP, closed cell, open cell, and roofing; with blowing agents hydrofluorocarbon (HFC), hydrofluoroolefin (HFO), and water
- Straw: panel
- Wood: fiber, batt, and board
- Extruded polystyrene (XPS): 15, 25, 40, 60, and 100 psi

Due to changes in state-specific regulations, new XPS products became available in 2021. California, Colorado, New Jersey, New York, Vermont, and Washington adopted state-level bans on HFC-134a as an XPS-blowing agent on January 1, 2021. Maryland, Massachusetts, and Delaware joined later in the year, and Hawaii, Maine, Virginia, and Rhode Island enacted their versions on January 1, 2022.[129] The new products use HFO-HFC blends as blowing agents in place of HFCs. Therefore HFO-HFC was included as a second class of XPS.

Researchers at Efficiency Vermont developed a database compiling various EPDs of insulation materials and presented the research in a recent report.[130] The researchers grouped the materials by product class and compiled at least three EPDs for each by averaging the GHG impacts. They found that, compared with trends before 2020, industries are increasingly using generic EPDs that show data averaged across several manufacturing facilities, while individual manufacturers are not investing in their own EPDs. This makes it more challenging to disaggregate any differences between products within a certain class. The database prioritized the consideration of EPDs for products manufactured in North America. European EPDs were used only for classes where no North American products existed and the product was sourced exclusively from Europe. Efficiency Vermont used the Embodied Carbon in Construction Calculator (EC3) and Sustainable Minds as the primary sources of the EPDs, with certain European EPDs acquired through the Norwegian EPD Foundation.

Analysis of Embodied Carbon of Insulation Materials

The LCA data considered in the database included modules A1–A3, which are the production stages, as indicated in Exhibit XX. While transportation during the construction process stage (module A4) can be a significant EC contributor or benefit (depending on where the material is sourced from), it was not considered in the database for two reasons. First, it is not commonly found in most LCAs, and second, it is challenging to acquire information on exactly which factory produced a given material. Including this module would also require individually calculating factory-to-construction-site data. Most of the use stage (modules B1–B7) is also not useful for embodied carbon cases, specifically because it does not help significantly differentiate between materials.

Having considered all these factors, Efficiency Vermont considered two other modules as valuable from an EC perspective: A5 (construction-installation process) and B1 (use). A5 is important for materials that are manufactured on-site, such as SPF, and considering this module would allow a fair comparison with products made in a manufacturing facility. B1 can be significant for certain materials, specifically those that off-gas refrigerants over time, such as some foam products. Finally, carbon storage was also considered and was determined based on the mass of elemental carbon in the product. Exhibit XX summarizes GWP and

Exhibit 46. Global Warming Potential and R-Values for Frequently Used Insulation Materials

Material	Form or variant	R-/”	GWP average, kg CO2e [A1+A2+A3] per m2 RSI-1	GWP* average, kg CO2e [A1+A2+A3+A5+B1] per m2 RSI-1	GWP* includes
Cellular glass	Aggregate	1.49	3.93	3.93	A5
Cellulose	Blown/loose-fill, 1.29 pcf	3.38	0.49	-0.83	A5, carbon
Cellulose	Dense-pack, 3.55 pcf	3.56	1.27	-2.16	A5, carbon
EPS (expanded polystyrene)	Board, unfaced Type IX-25psi, graph	4.70	3.47	3.49	A5
Fiberglass	Batt, unfaced, recycled content	3.64	0.67	0.68	A5
Fiberglass	Blown/loose-fill	2.68	1.29	1.30	A5
Fiberglass	Blown/spray	4.00	1.61	1.64	A5
HempCrete	Block	2.14	-7.05	-5.67	A5, B1, carbon
Mineral wool	Batt, unfaced	4.24	3.11	3.25	A5 (1 EPD)
Mineral wool	Board, unfaced, “heavy” density	4.00	4.06	4.06	A5, B1
Phenolic foam	Board, glass tissue faced	7.21	1.54	1.54	Not given
Polyisocyanurate	Board, foil faced	6.53	2.32	2.32	Not given
Spray polyurethane foam	Spray, closed-cell HFC	6.60	3.31	14.86	A5, B1
Spray polyurethane foam	Spray, closed-cell HFO	6.60	3.47	4.00	A5, B1
Spray polyurethane foam	Spray, open cell	4.05	1.42	1.59	A5, B1
Straw	Panel	2.92	-10.95	-10.88	A5, B1, carbon
Wood fiber	Board, unfaced	3.47	-7.13	-7.13	carbon
XPS (extruded polystyrene), HFC	Board, 25 psi	5.00	20.17	46.51	A5, B1
XPS (extruded polystyrene), HFO blend	Board, 25 psi	5.00	6.37	8.73	A5, B1

Note: Although not reflected in this table, closed-cell, HFO-blown, pour-in-place polyurethane fill insulation with a blowing-agent GWP of around 1 has become available on the market (e.g., for discontinuous panel applications).

Source: Adapted from Brian Just, “Choosing Low-Carbon Insulation,” Green Building Advisor, 2021, **https://www.greenbuildingadvisor.com/article/choosing-low-carbon-insulation**

Example Excel Calculation

Efficiency Vermont has developed a building impacts calculator in Excel, but it is currently not available to the public. The inputs to the calculator include building assembly, installed/added R-value, total area (with framing), framing factor (zero for continuous insulation), baseline material, and alternative material.

The calculator uses the average GWP* for a given material to calculate the GWP savings. The results of an example performed on the calculator are presented in Exhibit XX below.[i]

Exhibit 47. Example Calculation

Base Case			Alternative						GHG Impacts		
Insulation: Base Class	Insulation: Base Product	Installed (Added) R-Value	Insulation: Alt. Class	Insulation: Alt. Product	Installed (Added) R-Value	Total Area Incl. Framing (sq ft)	Continuous or Cavity Application	Framing Factor [Cont = 0.00] [2x16oc = 0.23] [2x24oc = 0.20]	GWP: Base [kg CO2e]	GWP: Alternative [kg CO2e]	GWP Savings of Alternative [kg CO2e]
XPS	XPS-Board, 25 psi HFC	15	Cellular Glass	Cellular Glass: Aggregate	15	1,440	Continuous	0	16,437	1,389	15,049
XPS	XPS-Board, 25 psi HFC	20	Polyiso	Polyiso: Board, Foil Faced	20	1,216	Continuous	0	18,507	923	17,584
XPS	XPS-Board, 25 psi HFO/ HFC	15	Cellular Glass	Cellular Glass: Aggregate	15	1,440	Continuous	0	3,085	1,389	1,696
XPS	XPS-Board, 25 psi HFO/ HFC	20	Polyiso	Polyiso: Board, Foil Faced	20	1,216	Continuous	0	3,474	923	2,551

Discussion of GWP Impacts

By far the highest GWP/EC materials are traditional insulation materials containing HFC blowing agents. These should receive immediate attention when it comes to replacement with lower-EC options. For example, in Exhibit XX, the GWP* of closed-cell spray polyurethane foam (HFC) has a high EC of 14.86 kg CO2e per m2 of RSI-1 insulation. Probably the worst choice would be extruded polystyrene products, which have the highest value of 46.51 kg CO2e. On the other hand, better choices include closed-cell polyurethane foam using an HFO blowing agent, which has a much lower EC of 4.00 kg CO2e, and mineral wool batt, with 3.25 kg CO2e. Products that use pentane as the blowing agent have even lower EC, including polyisocyanurate and phenolic foam. Fiberglass materials fare even better, with some having EC of less than 1 kg CO2e. Finally, carbon-containing materials, such as cellulose and wood fiber, can have a negative EC due to their carbon-sequestering capacity.

i The example calculation is also available in an online spreadsheet: https://docs.google.com/spreadsheets/u/1/d/1vUZixyIC5MWN5yjZeBT_IC--tbT9dpxFSwqU7lNvQ1E/edit.

Substitution of Materials

In terms of material substitution, there are factors to consider other than EC, including recycled content, toxic emissions, and performance, most of which are not captured in an LCA. While cellulose is an excellent choice from an EC perspective, it also offers high post-consumer recycled content and favorable transportation costs due to the presence of North American manufacturing. It does, however, have possible health concerns in the form of borate, a flame retardant, and respiratory irritants. The closed-cell spray foam materials rate poorly in recycled content and toxic chemicals, such as methylene diphenyl diisocyanate, which might be released during the installation of polyurethane foam. Those without protective equipment would need to stay away from the building for 24–72 hours after installation.

Building Materials

Buildings consist of primary materials and mechanical systems combined to create a building enclosure (exterior wall systems, load-bearing materials, fenestration, roof systems, and foundations), along with interior finishing materials (gypsum, flooring, paint, etc.), mechanical HVAC systems, lighting, appliances, and additional components.

Exhibit 48. Qualitative summary of select impacts and attributes of common insulation types

Material	GHG impact[(a)]	Recycled content[(b)]	Toxic emissions[(c)]	Notes[(d)]
Wood fiber	Lowest / best			
Cellulose	Lowest / best			
Fiberglass	Low			Avoid formaldehyde binders
Polyisocyanurate	Low			Chlorinated flame retardant (otherwise fairly inert) Toxic manufacturing process
EPS expanded polystyrene	Low			Brominated flame retardant
Open-cell spray foam	Low			Off-gassing under investigation by EPA Chlorinated flame retardant Highly toxic when applied
Phenolic foam	Low		See note	Phenol formaldehyde content but low emissions
Closed-cell poured foam, HFO	Low			
Mineral wool	Medium		See note	Choose low-emitting products
Closed-cell spray foam, HFO	Medium			Off-gassing under investigation by EPA Chlorinated flame retardant Highly toxic when applied
Closed-cell spray foam, HFC	Highest / worst			Off-gassing under investigation by EPA Chlorinated flame retardant Highly toxic when applied
XPS (extruded polystyrene)	Highest / worst			Brominated flame retardant (otherwise fairly inert) Toxic manufacturing process

a) Lowest: < 0 kgCOze including carbon content, per 1 m2 RSI-1. Low: < 5. Medium: 5–10. High > 10. Calculations are based on analysis within this report or manufacturer data.

b) From "BuildingGreen Guide to Insulation." Green indicates significant recycled content or renewable material. Red indicates little or no recycled content and fossil fuel-based materials in typical products.

c) From BuildingGreen Guide to Insulation." Green indicates relatively low toxic emissions during use from typical products. Red indicates potential high toxic emissions from typical products or during manufacturing or application.

d) From BuildingGreen, "Environmental Notes" in "Key Environmental and Performance Factors for Insulation Materials" table.

Exhibit 49. Example manufacturers and products of various insulation types

Material	Example manufacturer / products	GHG Impact[2]	Notes
Wood fiber	TimberHP, Steico, Gutex	Lowest / Best	Boardstock, batts
Cellulose	CleanFiber, GreenFiber	Lowest / Best	Densepack, loosefill
Fiberglass	Owens Corning Fiberglas, CertainTeed Sustainable	Low	Batts, boardstock, loosefill/densepack
Polyisocyanurate	DuPont Thermax	Low	Boardstock; Blowing agent: pentane
EPS (expanded polystyrene)	Atlas, BASF Neopor	Low	Boardstock; Blowing agent: pentane
Open cell spray foam	Demilec APX, Lapolla Foam-Lok 450	Low	Site- blown; Blowing agent: water
Phenolic foam	Kingspan Kooltherm	Low	Boardstock; Blowing agent: pentane
Cellular glass	Glavel, Foamglas	Low	Aggregate, boardstock
Mineral wool	Owens Corning, Rockwool, ThermaFiber	Medium	Batts, boardstock
Closed cell spray foam, HFO	Demilec Heatlok HFO Pro, Lapolla ProSeal HFO	Medium	Site-blown; Blowing agent: HOs
Next gen. XPS*, HFO/HFC	Owens Corning NGX series, DuPont XPS-ST-100 series	Medium / High	Boardstock; Blowing agent: HO/HFC blend
Closed cell spray foam, HFC	Demilec Heatlok XT, Dow Froth-Pak	Highest / Worst	Site- blown; Blowing agent: HFCs
XPS*	Dow Styrofoam (blueboard), Owens Corning (pinkboard)	Highest / Worst	Boardstock; Blowing agent: HFCs

*Extruded polystyrene (XPS)

Source: Efficiency Vermont Home Insulation GHG One Pager

Active Systems

Active systems consist mostly of mechanical HVAC systems, lighting, and appliances. Residential HVAC equipment has stabilized after many years of rapid advances in efficiency from condensing furnaces and higher Seasonal Energy Efficiency Ratio (SEER) systems. Many modern systems are approaching the thermodynamic limitations for efficiency in air conditioning, with the next frontier for residential equipment energy efficiency envisioned to be a focus on proper maintenance, repair, and operation of the equipment in the field.

Repairs to most systems are not currently considered cost-effective, but this could shift with design changes to equipment based on the principles of the circular economy. Incorporating modular design and repair structures could reduce the need to fully replace a heat pump or air conditioner, saving consumers thousands of dollars over the life of the home. Once the repair of equipment becomes cost-effective, manufacturers will be well-positioned to partner for service-based business models.

In a 2019 publication, Barbara Rodriguez Droguett developed a simplified method to assess EC across the life cycle of HVAC and refrigerant systems (HVAC+R).[131] The method uses an independent calculation for each of the three HVAC+R system components: mechanical equipment, distribution systems, and refrigerants, as shown in equation 1:

- **Equation 1:** Total GWP HVAC+R [kg CO2e/m2] = GWP equipment + GWP distribution + GWP refrigerant
- **Equation 2:** GWP equipment [kg CO2e/m2] = MEQ [kgm/m2] * ECCe [kg CO2e/kgm]
- **Equation 3:** GWP distribution [kg CO2e/m2] = DMQ [kgm/m2] * ECCd [kg CO2e/kgm]
- **Equation 4:** GWP refrigerant [kg CO2e/m2] = Rc [kgr/TON] * Cooling capacity [TON] * ECCr [kg CO2e/kgr]

Equation 2 shows the model for GWP of equipment, where mechanical equipment quantities (MEQs) represent the total weight of unitary equipment such as boilers or chillers, which are typically a composite of different materials. In equation 3, distribution material quantities (DMQs) represent a single material that can be quantified individually (copper piping, galvanized sheet metal). HFC gases and refrigerants are quantified separately.

Exhibit 50. Embodied Carbon Estimates for Equipment and Distribution Systems According to Each HVAC+R System Type

Building Type	System Type	Equipment	Distribution	Total (kg CO_2e/m2)
Standard	Packaged rooftop AC + furnace	9.8	25.6	35.4
	Packaged rooftop heat pump	18.0	39.2	57.3
	Variable air volume air-handling units w/ parallel fan-powered terminals	66.8	61.0	127.8
	Water-source heat pump	40.1	44.8	85.0
High-Performance	Dedicated outdoor air system + chilled beam	38.7	21.3	60.0
	Dedicated outdoor air system + variable refrigerant flow	22.2	17.6	39.8
	Dedicated outdoor air system + water-source heat pump	64.7	51.2	115.9
	Dedicated outdoor air system energy recovery ventilator + packaged rooftop heat pump	30.2	52.0	82.3
	Dedicated outdoor air system energy recovery ventilator + variable refrigerant flow	48.2	39.3	87.5

Source: B. X. Rodriguez Droguett, “Embodied Carbon of Heating, Ventilation, Air Conditioning and Refrigerants (HVAC+R) Systems,” University of Washington, 2019

Finish Materials

Although it is commonly understood that the structure of a typical building accounts for the majority of the building’s up-front EC footprint, examining the recurring cycle of renovation over a building’s life reveals the importance of interior finish materials.

In some cases, the cumulative impacts of multiple renovation cycles can surpass the up-front EC accumulated during a building’s construction.[132] A recent report from architecture and design firm Hawley Peterson Snyder conservatively estimated that building interiors are renovated or replaced on a 15-year cycle, adding to the building’s total EC each time.[133] In cities with a high frequency of tenant improvements, this cycle could be much shorter. Building typology is also a key factor in the relative impact of interior fit-outs. For instance, commercial and residential buildings are renovated at higher frequencies than other buildings, leading to higher cumulative impacts of EC.

In a 2019 study, the Carbon Leadership Forum measured the impacts of initial construction combined with mechanical, electrical, and plumbing (MEP) and tenant improvements (TI) recurring at intervals of 15 years. The results indicated that when replacements of MEP and TI accumulate over a 60-year building life span, the combined impacts exceed the initial construction impacts in certain cases.[134] Materials used for interior fit-outs are often made by companies with highly variable product lines, so providing EPDs for each product can be time- and cost-prohibitive.[135]

In another study conducted by the Carbon Leadership Forum, the material categories that were found to carry the highest global warming potential (GWP) in interior fit-outs, such as aluminum-framed storefronts, HVAC components, interior partitions, and wood flooring and underlayment, lacked essential LCA data.[136] These current data limitations are expected to improve as demand grows for low-EC fit-out materials. Design practitioners should reduce the quantity of high-EC materials if a low-impact alternative is not available in their region.

Passive Systems

Envelope systems such as wall and roof systems consist of individual materials that are assembled to deliver thermal and moisture performance. The physical properties of system materials, combined with the physics of air, water, and vapor movement, are complex and require special attention to avoid failure of the assembly. The cold or warm conditions at both the interior and exterior surfaces of the wall structure can allow moisture to condense, which can result in moisture problems if the structure is assembled incorrectly. Thus, thermal and moisture performance are closely intermingled.

Control layers for heat, air, and moisture are incorporated into assemblies using different approaches, depending on climate, to ensure the system is hygrothermally sound.[137] Individual materials combine to create control layers. In buildings, this includes structural materials, insulation materials, air barriers, flashing, and interior finishes. To compare the EC of different wall/roof assemblies, we: 1) assessed new construction wall assemblies versus retrofit assemblies and 2) focused on market-available insulation materials for retrofit systems, capturing EC variations in other elements of the wall assembly by holding three retrofit package types constant.

Retrofit Wall Assembly Package Recommendations

Homes built before 1992, when the DOE's Building Energy Codes Program was established, represent approximately 68% of the residential building stock in the country. Up to 43% of these homes have little to no insulation in the walls and have very high air leakage rates of 10 or more air changes per hour at 50 pascals of pressure (ACH50). There is a significant need for cost-effective, reliable retrofit methods for these homes that include air, moisture, and vapor controls, which are considered best practices for high-performance new home construction. Well-tested and documented wall retrofit systems can help to achieve substantial energy savings and also improve durability, comfort, health, and resilience.

An important element of this report is the analysis of retrofit packages that can be applied to reduce thermal energy use in buildings. This, in turn, can support the development of decarbonization strategies for the US building stock. The four retrofit packages analyzed are outlined in the *Modeled Upgrade Packages for Existing Buildings* section and presented in NREL report *Modeled Results of Four Residential Energy Efficiency Measure Packages for Deriving ABC Research Targets*.[138] The four retrofit packages are as follows:

1. All equipment swap-out
2. Equipment + conventional envelope
3. Equipment + IECC envelope
4. Equipment + Phius envelope

With the retrofit packages established, it is important to make baseline assumptions regarding the sample retrofit building in question. For this embodied carbon analysis, we assumed that the baseline building is a 1950s single-family home in Climate Zone 6b with no cavity insulation, inferior drywall and paint, plank sheathing, and vinyl siding.

Package 2: Equipment + Conventional Envelope

The conventional envelope package includes an envelope consisting of:

- Comprehensive attic upgrade
- Low-e storm windows
- About one inch of exterior insulation installed with re-siding
- Proper ventilation

This package requires one inch of R-6.5/inch continuous insulation (CI) to avoid potential warranty concerns with conventional cladding products. However, polyisocyanurate and phenolic foam boards are currently the only two available continuous insulation materials that can achieve this performance. Due to moisture- and corrosion-related concerns and low market availability, phenolic foam was excluded from this analysis. Therefore, it is recommended to use one inch of polyisocyanurate board, if thickness is a concern, or two inches of EPS, mineral wool board, or rigid fiberglass board if thickness is not a concern. Regardless of the material selected, it is important to avoid XPS continuous insulation, as its embodied GWP is between two and seven times that of EPS, mineral wool, fiberglass, and polyiso, with the range of values resulting from the mix of blowing agents used in XPS production.

Exhibit 51. Detailed Example Wall Layer Information for Package 2: Conventional Envelope

Layer	Assembly Layer	Material Type	Market-Available Specification
1	Cladding	Vinyl lap siding	Lap siding
2	Rainscreen	Wood furring strip	1” × 4” (¾” × 3½”) SPF boards at studs
3	Continuous insulation	Polyiso, EPS, mineral wool, or rigid fiberglass board	1” polyiso or 2” EPS, mineral wool, or rigid fiberglass board
4	Weather resistive barrier	Spun-bonded polyolefin	House wrap
5	Sheathing	Spruce/pine wood sheathing	1” × 6” (¾” × 5½”) spruce/pine boards
6	Cavity insulation	None	None
7	Drywall	Gypsum board	5/8” gypsum board

Source: J. Lstiburek, “The Perfect Wall,” ASHRAE Journal 49, no. 5 (2007), https://search.proquest.com/docview/220446314?accountid=28112; and Chrissi A. Antonopoulos et al., *Wall Upgrades for Energy Retrofits: A Techno-Economic Study*, Pacific Northwest National Laboratory, 2022, https://doi.org/10.2172/1890229

Package 3: Equipment + IECC Envelope

Package 3 includes a 2021 International Energy Conservation Code (IECC) envelope consisting of:

- Envelope aligned with the 2021 IECC
- Infiltration reduced to 3 ACH50
- Energy recovery ventilation (ERV)/heat recovery ventilation (HRV) added

For Climate Zone 6b, the most reasonable assumptions for IECC 2021 are twofold. One would be an R-13(cavity)+10(CI) assembly, which would comprise three inches of EPS, rigid mineral wool, or rigid fiberglass installed as continuous insulation and drill-and-fill cellulose installed within the stud cavity. The exhibit below details a wall assembly that fits the criteria for package 3.

It is also possible to achieve IECC 2021 requirements for Climate Zone 6 via an R-0+20 wall assembly. This retrofit assembly could be achieved via either a panelized retrofit or a site-built continuous insulation layer. To achieve an R-20 continuous insulation layer, this assembly would require five inches of EPS, mineral wool, or rigid fiberglass, or four inches of polyisocyanurate board.

Exhibit 52. Detailed Example Wall Layer Information for Package 3: IECC Envelope (Option 1)

Layer	Assembly Layer	Material Type	Market-Available Specification
1	Cladding	Vinyl lap siding	Lap siding
2	Rainscreen	Wood furring strip	1” × 4” (¾” × 3½”) SPF boards at studs
3	Continuous insulation	Polyiso, EPS, mineral wool, or rigid fiberglass board	2” of polyiso or 3” EPS, rigid mineral wool, or rigid fiberglass board
4	Weather resistive barrier	Spun-bonded polyolefin	House wrap
5	Sheathing	Spruce/pine wood sheathing	1” × 6” (¾” × 5½”) spruce/pine boards
6	Cavity insulation	Blown-in dense-pack cellulose	3½” at 3.5–4.0 lbs/cf
7	Drywall	Gypsum board	5/8” gypsum board

Source: J. Lstiburek, “The Perfect Wall,” ASHRAE Journal 49, no. 5 (2007), **https://search.proquest.com/docview/220446314?accountid=28112**; and Chrissi A. Antonopoulos et al., *Wall Upgrades for Energy Retrofits: A Techno-Economic Study*, Pacific Northwest National Laboratory, 2022, **https://doi.org/10.2172/1890229**

Exhibit 53. Detailed Example Wall Layer Information for Package 3: IECC Envelope (Option 2)

Layer	Assembly Layer	Material Type	Market-Available Specification
1	Cladding	Stucco or vinyl lap siding	EIFS finish or lap siding
2	Continuous insulation	Manufactured polyiso, EPS, mineral wool, or fiberglass panel	4” polyiso panel or 5” EPS foam, mineral wool, or fiberglass panel
3	Weather resistive barrier	Spun-bonded polyolefin	House wrap
4	Sheathing	Spruce/pine wood sheathing	1” × 6” (¾” × 5½”) spruce/pine boards
5	Cavity insulation	None	None
6	Drywall	Gypsum board	5/8” gypsum board

Source: Chrissi A. Antonopoulos et al., Wall Upgrades for Energy Retrofits: A Techno-Economic Study, Pacific Northwest National Laboratory, 2022, **https://doi.org/10.2172/1890229**

Package 4: Equipment + Phius Envelope

Package 4 includes a Phius envelope consisting of:

- Envelope aligned with the 2021 Phius prescriptive specification
- Infiltration reduced to 1 ACH50
- ERV/HRV added

Package 4 for Climate Zone 6b would effectively be R-40 to R-56, which is a superinsulated wall. Again, there are two options. One would be R-0+40, which is a wall with 10 inches of EPS, rigid mineral wool, or rigid fiberglass insulation, or eight inches of polyisocyanurate. Much like package 3, this assembly could either be a panelized or site-built insulation retrofit. The exhibit below details an assembly that fits the criteria for package 4.

The second option is an effective R-40, which would be similar to the assembly presented in Exhibit XX, except with six inches of EPS board. Other choices include seven inches of mineral wool board continuous insulation, seven inches of rigid fiberglass board, or four inches of polyisocyanurate board. The polyisocyanurate board is recommended, as it would be the easiest to install while maintaining relatively low EC.

Exhibit 54. Detailed Example Wall Layer Information for Package 4: Phius Envelope (Option 1)

Layer	Assembly Layer	Material Type	Market-Available Specification
1	Cladding	Vinyl lap siding	EIFS finish or lap siding
2	Continuous insulation	Manufactured polyiso, EPS, mineral wool, or fiberglass panel	8” polyiso panel or 10” EPS foam, mineral wool, or fiberglass panel
3	Weather resistive barrier	Spun-bonded polyolefin	House wrap
4	Sheathing	Spruce/pine wood sheathing	1” × 6” (¾” × 5½”) spruce/pine boards
5	Cavity insulation	None	None
6	Drywall	Gypsum board	5/8” gypsum board

Source: Chrissi A. Antonopoulos et al., Wall Upgrades for Energy Retrofits: A Techno-Economic Study, Pacific Northwest National Laboratory, 2022, https://doi.org/10.2172/1890229

Exhibit 55. Detailed Example Wall Layer Information for Package 4: Phius Envelope (Option 2)

Layer	Assembly Layer	Material Type	Market-Available Specification
1	Cladding	Vinyl lap siding	Lap siding
2	Rainscreen	Wood furring strip	1” × 4” (¾” × 3½”) SPF boards at studs
3	Continuous insulation	Polyiso, EPS, mineral wool, or rigid fiberglass board	4” of polyiso, 6” EPS, 7” rigid mineral wool, or 7 “ rigid fiberglass board
4	Weather resistive barrier	Spun-bonded polyolefin	House wrap
5	Sheathing	Spruce/pine wood sheathing	1” × 6” (¾” × 5½”) spruce/pine boards
6	Cavity insulation	Blown-in dense-pack cellulose	3½” at 3.5–4.0 lbs/cf
7	Drywall	Gypsum board	5/8” gypsum board

Source: Chrissi A. Antonopoulos et al., Wall Upgrades for Energy Retrofits: A Techno-Economic Study, Pacific Northwest National Laboratory, 2022, https://doi.org/10.2172/1890229

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