U.S. Building Stock Characterization Study

A National Typology for Decarbonizing U.S. Buildings

Janet Reyna,[1] Eric Wilson,[1] Andrew Parker,[1] Aven Satre-Meloy,[2] Amy Egerter,[3] Carlo Bianchi,[1] Marlena Praprost,[1] Andrew Speake,[1] Lixi Liu,[1] Ry Horsey,[1] Matthew Dahlhausen,[1] Christopher CaraDonna,[1] and Stacey Rothgeb[1]

1 National Renewable Energy Laboratory
2 Lawrence Berkeley National Laboratory
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Revised July 2022

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Errata

This report, originally published in December 2021, has been revised in July 2022 to expand the report scope to include commercial characterization in addition to the residential characterization in the original publication. The majority of these changes are in the new Section 3.2. Additionally, to support this scope expansion, we have included the additional section authors, added two appendences, modified the executive summary and conclusions, and updated text throughout to be inclusive of both the residential and commercial sectors.

List of Acronyms

ABC	Advanced Building Construction
BEM	building energy modeling
BTO	Building Technologies Office
CBECS	Commercial Building Energy Consumption Survey
CBSA	core-based statistical areas
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EUI	energy use intensity
HVAC	heating, ventilating, and air conditioning
MLRA	multiple linear regression analysis
NASEO	National Association of State Energy Officials
NREL	National Renewable Energy Laboratory
RECS	Residential Energy Consumption Survey
RMI	Rocky Mountain Institute
UBEM	urban-scale building energy modeling

Executive Summary

To support the U.S. Department of Energy's (DOE) Advanced Building Construction (ABC) Collaborative, the National Renewable Energy Laboratory (NREL) has been tasked with characterizing the U.S. building stock and developing a national typology of buildings. The potential use cases of such a typology are flexible and evolving, but in this initial phase, the primary intention is to help identify technology requirements and engineering solutions for moving the U.S. building stock toward a zero-carbon future by midcentury. This study was developed by NREL, with input from the ABC Analysis Working Group, which is a subset of the ABC Collaborative led by the Rocky Mountain Institute (RMI).

Using NREL's ResStock™ model, we segment the U.S. housing stock into 165 subgroups based on climate zone, wall structure, housing type, and year of construction. For the commercial building stock, we segment results from NREL's ComStock™ model into 168 subgroups based on climate region, building type, building size, and heating, ventilating, and air-conditioning (HVAC) classification. For each subgroup, we quantify the *thermal energy use* (defined here as energy for HVAC and water heating) by end use and segment. This allows for prioritization of different building segments and technologies for targeted efficiency or electrification upgrades. Typology studies have deep precedence in other countries, particularly in Europe, but a national-level typology study has never been attempted for the United States. Following are several high-level takeaways for U.S. residential energy use:

- **Most residential thermal energy use is in single-family detached homes.** The vast majority of residential buildings in the United States are single-family detached homes; additionally, single-family detached homes have the highest thermal energy end-use intensity with the exception of mobile homes, and they have the largest amount of floor space per unit. The combination of these factors means that any strategy looking to holistically reduce thermal energy use 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.

- **Infiltration drives heating.** Infiltration is the largest contributing component 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 do so while limiting disruption to occupants due to internal modifications—are a priority for further research and development, particularly considering the limited evidence base for how much infiltration can be reduced through envelope improvements such as panelized walls, drill-and-fill insulation, or window retrofits alone. Reduction in air infiltration could also provide co-benefits of reduced moisture infiltration and improved indoor air quality if coupled with mechanical ventilation.

- **Mobile homes are extremely energy-intensive.** Despite accounting for relatively small shares of total housing units in most climate regions (4%–9%), mobile homes typically have much larger thermal energy use intensities than other building types. This is especially the case for older vintage mobile homes in cold or mixed climate regions,

where fossil-fired heating drives higher thermal energy use intensities, but it is also evident in hotter climates, where electric heating and cooling are the primary drivers. These findings highlight the need for retrofit solutions that are applicable to mobile homes, which will likely have larger co-benefits for occupants than solutions for other segments given the energy burdens mobile home occupants face. Being "mobile" and manufactured off-site in the first place, it might be that the solutions include total replacement, although there could be significant nontechnical barriers to this, such as local codes, taxes, and ownership structures, as well as potential equity implications of displacing the occupants.

- **Fossil fuel-based space and water heating must be replaced to achieve decarbonization.** Fossil-fired space and water heating are the largest contributors to thermal end-use energy intensity and total loads in most of the United States, which has clear implications for the scale of electrification needed. Fossil fuel-based space and water heating are most prominent in cold and mixed climate regions but still represent a large share of thermal energy use for single-family segments in hot and humid climate regions where electric heating is more common. These results will help identify segments that can reach carbon neutrality more rapidly through replacement of existing fossil fuel-based heating equipment with electric heating equipment. Furthermore, these findings can inform where existing technology deployment is cost-effective, and where additional research and/or cost reduction is needed. They can also assist in prioritizing deeper envelope retrofits for segments where electric heating adoption may be slower due to technical, economic (e.g., technology cost-effectiveness), market, or regulatory challenges, such as in the very cold Northeast and Mid-Atlantic regions.

- **Solutions are likely transferable between segments.** An important takeaway from this segmentation is that solutions can likely be transferred from one segment to another within the residential sector. Packages developed for single-family detached, midcentury wood frame construction (which is the single-family segment with the highest thermal energy use in three 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, solutions developed for Marine multifamily buildings, where water heating is the predominant thermal energy end use, could potentially be applied broadly to many different multifamily building segments since water heating retrofits are independent of the existing envelope.

For commercial buildings, high-level takeaways are:

- **Upgrading small packaged units presents a significant cross-segment opportunity.** Small packaged units are the most common HVAC classification, serving 55% of the commercial floor area and 73% of the commercial buildings by count[1] in the United States. Furthermore, although they are most common in small buildings, they are also found in much larger buildings as well. The majority of existing small packaged units use fossil fuel (63%), so there is an opportunity to swap these systems with heat pump packaged units, both electrifying the end use and increasing the efficiency. The impact of

[1] Based on the top 14 building types available in ComStock

these systems could be integrating energy recovery ventilation into the same unit. An alternate replacement for this system could involve decoupling ventilation and space conditioning, replacing the central unit with energy recovery ventilation, and using zone-level split heat pumps.

- **Ventilation is a driver of energy use.** Across climate regions, ventilation accounts for a large share of thermal load intensity and total thermal loads in commercial buildings, both as ventilation fan electricity and outdoor air ventilation as a component load for heating and cooling. In all climate regions, ventilation is the component that drives heating and cooling loads due to energy used for conditioning outdoor air that is brought into the building for ventilation. Improvements in ventilation that can be achieved through energy recovery or demand control ventilation could yield benefits in terms of reduced heating and cooling loads in most commercial building segments, indicating the importance of such solutions.

- **Commercial buildings have a high percentage of on-site fossil fuel use.** Across building segments, there is a significant proportion (45%) of thermal end-use energy being met by fossil fuel sources. Depending on the building type and end use, electrification of these loads might be a significant challenge in the commercial sector. For example, some commercial buildings require higher service water heating temperatures than residential buildings, which might not be as easily met with electric heat pumps. Electrification could pose a significant challenge in some commercial building types or applications, and there might not yet be acceptable electric equipment options for all situations. Finding solutions to replace these fossil fuel technologies is essential to achieving full decarbonization.

- **Climate is not a significant driver for commercial thermal energy end uses.** In contrast to the residential sector typologies, the commercial sector has less variation in segments' thermal energy use ranking across climate regions (Appendix B). Instead, general building function is the main driver given the diversity of functions and energy needs of commercial buildings. There is, however, considerable variation in thermal load intensity within identical segments in different climate regions and in the relative contributions of different end uses. This takeaway implies that solution development should focus more on building function and existing HVAC equipment, irrespective of climate region.

- **Solutions are likely transferable between segments.** Similar to the residential sector, solutions can likely be transferred from one segment to another within the commercial building stock. Most of the solutions for reducing thermal energy use and associated carbon emissions in the commercial sector will likely focus on equipment retrofits rather than envelope retrofits. As such, equipment can likely be widely deployed across segments with either similar existing equipment or similar existing system needs.

Accompanying this report is an online dashboard (resstock.nrel.gov/page/typology) that allows for custom segmentation and deeper exploration of building characteristics within a segment. For example, the dashboard could be used to filter results to a specific county, quantify the prevalence of ducted space-conditioning systems within a building segment, examine the contribution of nonthermal energy use in the residential sector, explore detailed HVAC configurations, or create new building segments based on alternate climate zone definitions.

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Introduction

To support the U.S. Department of Energy's (DOE) Advanced Building Construction (ABC) Collaborative, the National Renewable Energy Laboratory (NREL) has been tasked with characterizing the U.S. building stock and developing a national typology of buildings. The potential use cases of such a typology are flexible and evolving, but in this initial phase, the primary intention is to help identify technology requirements and engineering solutions for moving the U.S. building stock toward a zero-carbon future by midcentury. This typology will also support the development of appropriate ABC research goals for existing buildings, such as cost targets for new technology development, and in a later phase, the typology can be used to support the implementation of ABC solutions by informing market aggregation and business model development.

As shown in Figure 1, there are many facets of building decarbonization. In this study, we focus only on operational energy consumption that leads to greenhouse gas emissions. We break down operational energy use by on-site fossil fuel combustion versus electricity consumption, but we do not explicitly calculate associated greenhouse gas emissions. Electric grid greenhouse gas emissions intensity varies by grid region and is changing rapidly; several utilities and states have electricity goals for zero greenhouse gas emissions in the next several decades. Instead of explicitly trying to estimate present-day or future emissions, this report focuses on how buildings can support decarbonization by identifying segments where electrification (or other decarbonization) is necessary. This report does not quantify:

- Buildings' impact on power system costs under a zero-carbon electricity grid.
- The impact of electrification, especially from heating, on systems peaks.
- Embodied emissions across different phases of the building life.
- Non-energy operational emissions (e.g., refrigerant leakage).

At present and for at least the next several decades, emissions from operational energy use will constitute most emissions from the building stock. Although this report does not consider all aspects of building decarbonization, it highlights the primary decarbonization challenges.

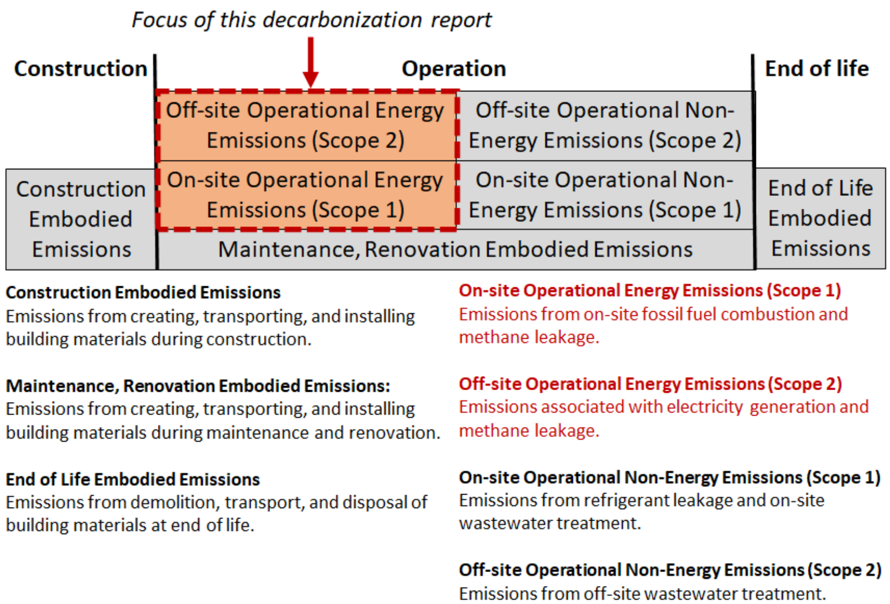

Figure 1. Overview of the elements of building decarbonization

DOE's overarching ABC Initiative[2] invests in new technologies that enable high building performance, can be deployed quickly with minimal on-site construction time, and are affordable and appealing to building owners, investors, and occupants. DOE has funded multiple awardees to advance many innovations, including new building materials, 3D printing, off-site manufacturing, robotics, and digital art-to-part. Although the goals of ABC cover a broad range of objectives around energy, comfort, and health, the primary ABC-related application of this national building characterization study is the development 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 U.S. building stock. Retrofit packages will be determined collaboratively by DOE, NREL, and the ABC Collaborative. We anticipate a range of upgrade packages covering loads related to envelope; heating, ventilating, and air conditioning (HVAC); and water heating.

Given these intentions, this first phase of the national building characterization study aims primarily to inform technology research and development (R&D) activities rather than those related to deployment of ABC solutions or implementation of specific retrofit campaigns. This typology study was developed with collaboration and input from the ABC Analysis Working Group, a subset of the ABC Collaborative. This working group includes members from RMI, the Vermont Energy Investment Corporation (VEIC), DOE, Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, Association for Energy Affordability, and Passive House Institute US (PHIUS). The ABC Collaborative requires analyses to address important questions in each of these areas, and there are other ongoing projects that will, for instance, identify markets to prioritize based on economic or political factors that are relevant to ABC technology deployment opportunities. Some of these nontechnical factors for prioritization are

[2] DOE's ABC Initiative comprises the ABC Collaborative, which is a network of industry stakeholders that is tasked with accelerating ABC adoption. For more information, see: https://www.energy.gov/eere/buildings/abc-collaborative.

covered in the Rocky Mountain Institute's (RMI) report, *Market Opportunities and Challenges for Decarbonizing US Buildings* (Fisler et al. 2021).

In this report, we present a literature review of previous work, the study methodology, and the residential and commercial results of the national characterization study. This work is supplemented by a series of online queryable dashboards. The segmentation approach taken in this study is flexible and can be customized depending on the specific goals of different research efforts; however, this report provides a specific implementation of segmentation, focused on differentiating baseline building characteristics and prospective technology solutions. Further details on the complementary research activities that will support the ABC Collaborative's goals in concert with this characterization study are provided in Section 2.1. To develop the methodology for this national characterization study, we first undertook a comprehensive meta-analysis of existing typology studies both in the United States and abroad. Some studies were similarly focused on deep energy retrofit solutions, while others were more geared toward exploring patterns of energy use in the building stock or developing building stock energy models.

This report is divided into five sections. In Section 1, we summarize identified existing typology studies and discuss applicable methods for our typology work. In Section 2, we detail our methodology for this U.S. national characterization study. In Section 3, we overview the segmentation for residential and commercial buildings and characterize the segments with the highest thermal energy use in each climate zone. In Section 4, we discuss applications for the national characterization study, as well as its limitations. Section 5 concludes with an overview of forthcoming work.

1 Review of Existing Typology Studies

As the first phase in the typology development, NREL undertook a meta-analysis of existing typology studies for the purposes of understanding existing methods and techniques, identifying any existing typologies that might overlap with a U.S. national typology, and identifying elements of existing methodologies that can inform pieces of the typology.

Articles for the meta-analysis were identified in one of three ways: (1) being suggested by (or performed by) members of the ABC Collaborative or DOE's Building Technologies Office (BTO), (2) studies available in the academic literature, identified primarily through a search on Google Scholar, and (3) studies referenced by studies identified by one of the first two methods. Studies were then grouped into multiple categories based on the application of the typology work.

Many of the studies identified in this review follow a similar methodology:

1. Segmentation of the stock based on commonly available characteristics (e.g., vintage, number of units, building type)
2. Sometimes, down-select based on relevant criteria (e.g., building prevalence, percent energy use)
3. Statistical characterization of each down-selected typology segment
4. Building energy modeling (BEM) of each typology segment.

Not all identified typology studies follow this process, or follow it in a less than linear fashion, and deviations are noted. Where this general structure is followed, we discuss the variables used in decision-making at each point in the study.

1.1 Retrofit Deployment Studies

The first class of studies includes typologies performed either to directly support an in-field retrofit deployment or to develop typologies for near-term retrofit prioritization. Two of the most recent studies reviewed were those for REALIZE-CA and RetrofitNY, deep energy retrofit programs for multifamily homes in California and New York, respectively. Relevant characteristics of these and other deployment-focused retrofit studies are catalogued in Table 1.

The REALIZE-CA study (Egerter et al. 2020) focused on low-rise (1- to 3-story) multifamily buildings after previous work showed that low-rise buildings compose more than 82% of the existing multifamily housing stock. The goal of the REALIZE-CA project is to develop standardized retrofit packages for multifamily homes, with an eye toward disadvantaged communities. As such, the goal of the typology was to select prototypes and associated retrofit packages that would be applicable to the largest number of multifamily households, so segment prevalence was the predominant down-select criteria for the study. Initial segmentation was done by the Association for Energy Affordability using number of units, number of stories, and vintage. Three segments, together representing ~62.5% of the multifamily housing stock of California, were selected for analysis. For these three segments, detailed characteristics relevant to the current energy performance and potential for upgrades were compiled using California-specific information, such as historical Title 24 specifications (the California building code), the 2017 American Housing Survey, the 2009 Residential Appliance Saturation Survey, the Low-Income Weatherization Program, and Bay Area Regional Network (BayREN) data. Where these compiled data sources lacked information (for example, on characteristics such as construction types and existing windows), RMI performed a series of interviews with program implementers and technical assistance providers. In these interviews, RMI received feedback on the importance of the existing wall structure for panelized wall upgrades, as many existing walls could not support the weight of panels greater than R-8 without structural upgrades (equivalent to 4 pounds per square foot load-bearing capacity in Title 24 wood-framed multifamily buildings[3]). This information directly influenced the retrofit packages modeled in the building energy modeling (BEM) software, as RMI provided alternate packages when structural upgrades were not feasible, but deeper panelized retrofits could potentially be included for buildings planning to receive seismic structural upgrades. The RMI methodology reviewed for this report was a draft and the study is still ongoing, but the study plans include modeling all three identified typology segments, cost analysis of upgrades, and further study of other potential retrofit installation barriers.

As an earlier part of the REALIZE project, RMI completed a characterization study focused on the northeastern United States (Rocky Mountain Institute, n.d.). The goal of this part of REALIZE was to develop multifamily retrofit solutions that could achieve 50% site energy savings that would be scalable to a large portion of the multifamily housing stock. Initially, RMI performed an analysis of all U.S. multifamily buildings by breaking up multifamily unit count by ASHRAE climate zone. ASHRAE climate zones 4 and 5 (mixed-humid and cold, respectively) were selected as the main focus for the project, due to their large multifamily building populations. For those two climate zones, all of the core-based statistical areas (CBSAs) were ranked based on their multifamily housing populations. Four of the top five CBSAs were located in the northeast: New York City; Chicago; Washington, D.C.; and Boston. Seattle ranked fifth but was excluded from the study due to the geographical distance from the other top cities (potentially limiting the transferability of solution) as well as the milder marine climate subregion that has lower cooling demands. The analysis was expanded to the city with the sixth largest multifamily housing population, Philadelphia, which is also located in the northeast. For these cities, relevant data from the U.S. Energy Information Administration's (EIA) Residential Energy Consumption Survey (RECS) was pulled on HVAC systems and building characteristics to develop typology segments. Three different HVAC system combinations were identified that collectively cover nearly 45% of the multifamily units in the region. The typology segments were also subdivided by building structure: a 15-unit low-rise building and a 50-unit mid-rise building. RMI modeled these six segments in both New York City and Chicago to identify upgrade packages that could achieve the 50% savings mark.

The NYSERDA RetrofitNY Market Characterization Study initially segmented buildings based on the external building shell characteristics, because building envelope retrofits were the main target for upgrades (Brainard et al. 2020). The goal of that work is to help inform the development of standardized whole-building retrofit solutions. The study covers all multifamily buildings in New York State, but the typology segments are not equally distributed. The initial segmentation creates 12 typology segments for the state, based on the number of stories (binned

[3] Although this project was California-specific where seismic constraints are extremely important, other regions throughout the United States would have similar limitations because these requirements are based on the International Building Code.

as low, medium, or high rise) and four major vintage bins, but the high-rise buildings were deemed out of scope for the study, leaving eight remaining segments.

A previous study by another organization had merged 22 different New York State data sources (ICF International 2017), including county assessor databases, to provide a database of building characteristics at the individual building level (where data allowed), although coverage of all characteristics was not comprehensive across the state. Utilizing the state database, the segments were down-selected to four segments that composed ~69% of the multifamily housing stock. Recognizing that building prevalence is not the only relevant characteristic for retrofitting, the authors also explored the floor area, building facade area, and main construction material. Wall material was identified as highly important to the retrofit solutions, so it was added into the segmentation. Notably, data on wall material were not readily available due to low completeness and suspected inaccuracy in the statewide inventory, so envelope material characteristics from the inventory had to be cross-referenced against CoStar commercial real estate data, historical building codes, and photo documentation of sites. Then the types were down-selected again to seven major prototypes based on wall type, vintage, and stories. Given the detailed nature of the data set used for this study, the segmentation and characterization steps were highly iterative, and the typology evolved as the understanding of the stock evolved. Once the seven categories were selected, the RetrofitNY study team worked to understand historical architecture practices by consulting with experts and reviewing a variety of historical sources. Finally, a random sample of 100 buildings across four diverse counties was pulled and checked in detail to ensure a match to the compiled architectural profile. Detailed descriptions of the building construction were compiled for each of the seven types.

Several other typology deployment studies exist, including the Retrofitting Affordability study (Building Energy Exchange 2015) in New York City, which is referenced in the RetrofitNY study (but which provides significantly less detail on the stock opportunities). However, that study is arguably not a deployment-geared study. Additionally, RMI (the lead organization for REALIZE-CA) developed a guide for deep retrofits that utilizes San Francisco as an example case study (Rocky Mountain Institute 2017).

In the Chicago area, Elevate Energy performed typology assessments of the single-family and multifamily housing stocks (Elevate Energy 2017; Spanier et al. 2012). These typology segments were intended to inform retrofit prioritization in the Chicago area, but they were not specifically focused on developing deep energy retrofit packages like the previously mentioned studies. Instead, this typology describes the energy characteristics of the stock by segment, and down-selects to the top segments based on their energy intensity and prevalence in the stock. Some energy modeling was performed for the older single-family segments as part of these segmentations, but it was not comprehensive or as focused on identifying upgrades. These segments are also currently being used in a separate ABC Funding Opportunity Announcement (FOA)[4] award to inform a single-family home retrofit field validation study and an upgrade road map for the City of Chicago.

[4] For more information, see https://www.energy.gov/eere/buildings/downloads/chicago-energy-efficiency-planning-and-analysis-and-integrated-retrofit.

As mentioned in the introduction, the eventual outcome of our meta-analysis is to develop a methodology for identifying a national typology for deep energy retrofits, specifically around thermal energy use. The aforementioned studies provide some examples of typology prioritization, but these results are specific to the locations being studied, and are particularly influenced by the prevalence of different local typologies that vary greatly throughout the country. Furthermore, much of the existing work has focused on residential buildings, especially multifamily residential buildings. To guide our work, colleagues at BTO have taken a preliminary first step in a national typology, highlighting sectors that are either proportionally high consumers or easy targets for standardized retrofits (or both), providing a qualitative assessment of the opportunities and challenges in each sector (Hasz et al. 2020). Similarly, while not quite a typology in its own right, members of the National Association of State Energy Officials (NASEO) highlight the potential of developing deep energy retrofit packages specifically for manufactured houses, highlighting the energy affordability, energy savings, and relative ease of standardized retrofit in that sector, while highlighting financing challenges.

Table 1. Retrofit Deployment Studies

Study	Segments														
	Building Population	Target Population %	Segment Count	Segment Ratio	Sector	Location	Building Type	Stories	Vintage	Units	Heating Fuel	HVAC Type	Climate Zone	Wall Type	Down-Select?
REALIZE-CA (Egerter et al. 2020)	2.6M	62.5%	3	546k	Low-rise multifamily, 5+ units (2.624 million units)	California		X	X	X					Yes: prevalence
NYSERDA RetrofitNY (Brainard et al. 2020)	1M	69%	4	174k	Multifamily	New York State		X	X					X	Yes: prevalence
RMI San Francisco (Rocky Mountain Institute 2017)	5–9 units, 10–19 units, 20+ units	97%	3	N/A	Affordable multifamily	San Francisco				X					Yes: prevalence
REALIZE Northeast (Rocky Mountain Institute n.d.)	27M units	15%	6	675k	Multifamily	United States				X		X			Yes: location, prevalence
Retrofitting Affordability (Building Energy Exchange 2015)	10k	95%	12	840	Multifamily	New York City		X	X		X				Yes: prevalence
Elevate Energy Single Family (Spanier et al. 2012)		100%	15		Single-family	Chicago		X	X					X	No
Elevate Energy Multifamily (Elevate Energy 2017)		93%	3	47k	Multifamily	Chicago		X	X	X				X	Yes: prevalence
DOE Preliminary ABC Typology (Hasz et al. 2020)	~115M	96%	R:4 C:4	R:21 M C:530 k	All buildings	United States	X		X				X		Yes: prevalence, energy use
NASEO Manufactured Homes (Carley et al. 2020)	Manu-factured homes	10%			Residential buildings	United States	X		X						Yes: uniformity of segment, high EUI and energy burden

1.2 National Typology Methodologies

Outside of deployment-focused typologies, there have been several efforts to develop methodologies for creating comprehensive national typologies, with a co-focus on simulating and upgrading the building stock. Mata et al. (2014) present a methodology for Europe that follows the basic process at the beginning of this review paper, but it does not include down-selecting because it is intended to be a comprehensive methodology, and it adds in a validation step to ensure that energy simulation from the typologies falls within an expected range. The Mata protocol specifies that segmentation should be done based on building type/use, vintage, climate zone, and type of heating system,[5] if data are available. Furthermore, this method specifies 23 specific technical characteristics that should be drawn from national data sets to characterize the stock—including parameters such as internal temperature, envelope thermal properties, and ventilation rates. In the four climatically diverse countries tested by Mata et al., it is notable that simulated annual energy consumption only varied between -6% and 2% compared to real data (summarized in Table 2).

The TABULA (Ballarini et al. 2014; Loga et al. 2016) framework is a similar European classification methodology that has been deployed in 21 countries for the residential building stock. TABULA is designed to be flexible enough for country-specific typologies while employing common structures for translating typologies between countries. TABULA follows a similar process, focusing first on segmentation of the stock, then providing detailed statistics on multiple characteristics within each segment (e.g., envelope retrofits, air-conditioning presence, ventilation, solar thermal systems, prevalence of each segment, domestic hot water, central heating). All TABULA countries' typologies are readily available online.[6]

A few other national typology studies exist in Europe, and they use a similar process for developing the typologies as Mata or TABULA, but do not explicitly reference those methodologies. In Greece, Theodoridou et al. (2011a) developed a residential typology based on vintage and climate zone, down-selected to three most common segments, and then developed corresponding energy models. Specific retrofits were not recommended, but the study helped inform the potential for energy savings. Similarly, Streicher et al. (2019) used detailed data based on 25,000 sampled residential buildings for Switzerland to develop and model a typology based on building type, vintage, heating fuel, and the topographical classification (urban/rural/suburban) to examine differences in energy use by segment, but the approach was not targeted at developing upgrade packages.

For the U.S. commercial building sector, DOE—working with three national laboratories—has developed a set of BEMs for 16 common types of commercial buildings (Deru et al. 2011). These 16 building types are further broken down by climate zone and vintage, leading to 768 segments that represent approximately 70% of the U.S. commercial building stock. The down-select of types was based on the prevalence of different building types. The purpose of this typology is primarily to facilitate easier BEM of the commercial sector with consistent assumptions, and these models have been widely used over the past decade. In particular, the reference building models were used to derive sets of commercial prototype building models to facilitate analysis of prospective building energy codes for new construction (ANSI/ASHRAE/IES Standard 90.1 and IECC).[7]

[5] If deployed in a U.S. context, this could also include cooling system. Europe is heating-dominated, with very little cooling, so it is insignificant for a European segmentation but could be highly significant for the United States.
[6] To view the typologies, see https://episcope.eu/building-typology/country/.
[7] For more information, see https://www.energycodes.gov/development/commercial/prototype_models.

Table 2. National Typology Studies

Study	Segments				Sector	Location	Segmentation Variables							Down-Select?
	Building Pop.	Target Pop. %	Segment Count	Segment Ratio			Building Type	Stories	Vintage	Climate Zone	Wall Type	Heating System	Urban/Rural/Sub	
France (Mata et al. 2014)	Res (R): 14.9 M Com (C): 6.1 M	100%	R:54 C:45	R:276k C:136k	Residential and Non-Residential	France	X		X	X		X		No, but combination of segments based on prevalence
Germany (Mata et al. 2014)	18.4 M	100%	122	151k	Residential	Germany	X	X	X	X				No, but combination of segments based on prevalence
Spain (Mata et al. 2014)	R: 9.8 M C: 3 M	100%	R:40 C:80	R: 245k C: 38k	Residential and Non-Residential	Spain	X		X	X				No, but combination of segments based on prevalence
UK (Mata et al. 2014)	R: 20 M C: 7.1 M	100%	R: 168 C:84	R:119k C: 85k	Residential and Non-Residential	UK	X		X	X		X		No, but combination of segments based on prevalence
TABULA		100%	32		Residential	Austria	X		X	X				No
TABULA		100%	24		Residential	Bosnia Herzego-vina	X		X	X				No
TABULA		100%	35		Residential	Belgium	X		X	X				No
TABULA		100%	26		Residential	Bulgaria	X		X	X				No
TABULA		100%	12		Residential	Cyprus	X		X	X				No
TABULA		100%	27		Residential	Czech Republic	X		X	X				No
TABULA		100%	50		Residential	Germany	X		X	X				No
TABULA		100%	30		Residential	Denmark	X		X	X				No
TABULA		100%	24		Residential	Spain	X		X	X				No
TABULA		100%	40		Residential	France	X		X	X				No
TABULA		100%	32		Residential	UK	X		X	X				No
TABULA		100%	32		Residential	Greece	X		X	X				No
TABULA		100%	11		Residential	Hungary	X		X	X				No
TABULA		100%	37		Residential	Ireland	X		X	X				No
TABULA		100%	32		Residential	Italy	X		X	X				No
TABULA		100%	41		Residential	The Nether-lands	X		X	X				No
TABULA		100%	21		Residential	Norway	X		X	X				No
TABULA		100%	26		Residential	Poland	X		X	X				No
TABULA		100%	31		Residential	Serbia	X		X	X				No
TABULA		100%	30		Residential	Sweden	X		X	X				No
TABULA		100%	24		Residential	Slovenia	X		X	X				No
Theodoridou et al. (2011b, 2011a)	3.7 M	71%	3	878k	Multifamily	Greece			X	X				Yes, prevalence
SwissRes (Streicher et al. 2019)			54		Residential	Switzer-land	X		X			X	X	No
DOE Comm. Ref. Bldgs (Deru 2011)	5.6 M	70%	768	7.3k	Commercial	United States	X		X		X			Yes, prevalence

1.3 Data-Driven Segmentations

Beyond the typical approach of segmentation, there are several methods that segment using statistical methods to determine the relative importance of different building characteristics rather than assuming the relevance of certain parameters and manually segmenting. We identified four major studies that attempt alternate segmentation methodologies.

In Ireland, Famuyibo et al. (2012) used a national database and existing literature to select 23 variables that they believed could be influential to energy use in buildings, of which only four were found to be statistically significant via multiple linear regression analysis (MLRA): (1) heating season occupancy schedule, (2) internal temperature, (3) air change rate, and (4) immersion heater weekly frequency. The authors then modified the predictive model, removing all of the significant variables except for air change rate, arguing that occupancy-related information (such as internal temperature) would average out in the long run. This one variable was then manually supplemented with eight additional characteristics that the authors deemed important, and scatter plots were created to visually map clusters of each of the descriptive building characteristics. This typology was still very focused on simulation of energy use, so the MLRA might be applicable for identifying unanticipated significant parameters, but it is unlikely to be as adaptable to a deep retrofit typology.

In New York City, Kontokosta (2015) examined appropriate benchmarking comparisons in office buildings using a multistep statistical approach. First, the author linked the publicly disclosed benchmarking data with CoStar and assessor data and performed a regression analysis to identify the most significant variables. Second, he took all variables significant at the 95% level or higher and developed a predictive regression equation. Real energy use intensity (EUI) values were compared against predicted EUIs. Finally, Kontokosta utilized *k*-means clustering on predicted EUIs to identify four distinct clusters in the data that could be ranked from best to worst energy performing. He argued that an approach such as this would be more appropriate for identifying useful benchmark comparisons for building sectors as opposed to a pure EUI comparison.

In Switzerland, Aksoezen et al. (2015) used a data set from Basel to examine the validity of a priori segmentation of a building stock. They utilized an approach called chi-square automatic interaction detector to identify significant inputs, and then performed clustering based on age and statistical analysis to explore several characteristics of the Swiss building stock. The end result is not a typology in its own right, but it does present some evidence for more closely examining local building characteristics instead of automatically segmenting by building type and vintage.

For two U.S. cities, Los Angeles and New York, Reyna et al. (2016) used max-p clustering to group residential buildings of similar energy use together. For these case studies, max-p clustering endogenously determines the number of clusters of buildings, with the requirement that all clusters are geographically co-located, based on the principle of maximizing the interregional variability of a set of sociotechnical variables for the building stock, which in turn minimizes the intraregional variability. For the study, regression analysis was first performed to find the significant demographic and technical variables of the buildings in each city, and then the significant set (and various variations of significant sets) were used to perform max-p clustering. The energy use homogeneity for each set of each city's clusters were compared to Census tracts, a comparable-sized but predefined geography. In all clustering set ups, the homogeneity within the residential stock was much higher for the max-p clustered sets compared with the Census tracts. Although this study was not a typology itself, it does suggest that data-driven clustering based on stock characteristics can form more similar clusters than by using predefined segmentation for convenience.

One additional analysis relevant to data-driven segmentation of the U.S. building stock was undertaken by Kassel (2017), who used several statistical approaches to identify key features of residential buildings for predicting annual electricity consumption using data from the 2009 EIA RECS. The author applied several machine learning algorithms to quantify variable importance and assess predictive performance on holdout data, finding that the most important variables were ownership of electric space and water heating equipment, number of cooling degree days, number of occupants, and variables related to the size of the dwelling. The approach demonstrates how the application of novel statistical techniques can address challenges inherent to large and varied energy data sets, which are frequently encountered in data-driven segmentation studies.

Table 3. Data-Driven Segmentation Studies

Study	Final Clusters/ Archetypes	Target Stock Percentage	Sector	Location	Clustering/ Segmentation Methodology	Significant Characteristics	Comments
Kontokosta (2015)	4	100%	Office buildings	New York City	Regression, k-means clustering	Number of floors, vintage, inside lot vs. corner lot, floor area to footprint ratio, operating hours, worker density, percent data center, construction type, green labeled (ENERGY STAR®/ LEED)	Focuses on developing appropriate benchmarks for energy performance beyond EUI using NYC LL84 data
Famuyibo et al. (2012)	13	65%	Residenti al	Ireland	MLRA + visual clustering	Air change rate (from MLRA) + wall u-value, roof u-value, window u-value, floor u-value, floor area, heating system, domestic hot water cylinder insulation, building type (manually added by authors)	Does some MLRA to identify one variable, but mostly manually chooses segmentation variables
Aksoezen et al. (2015)	N/A	N/A	All buildings	Basel, Switzerland	Chi-square automatic interaction detector	Building volume, facade area, number of occupants	Seeks to challenge the a priori development of segments on vintage and dwelling type as basis for developing retrofit solutions. Also does statistical analysis and clustering based on vintage, but not a true typology
Reyna et al. (2016)	N/A	100%	Residenti al	Los Angeles, New York City	Max-p clustering	*Los Angeles*: Occupant age, income, ethnicity, rental, building age, and pool *NYC*: Household size, rental, electric heat, number of refrigerators, number of TVs, number of computers, and pool	Focused on creating homogenous neighborhoods for improved energy prediction instead of an explicit typology
(Kassel, 2017)	N/A	N/A	Residenti al	United States	Dimensionality reduction, elastic net regression and gradient boosted machines	Electric heat, dwelling size, household size, cooling degree days, number of refrigerators	Uses several dimensionality reduction and variable selection techniques to identify significant characteristics

1.4 Archetypes for Building Stock Energy Modeling

Another area where typology creation is common is for building stock energy modeling, which simulates the building energy use of a city, region, or country. A subclass of building stock energy modeling, often referred to as physics-simulation, archetype/prototype modeling, or sometimes “UBEM”[8] (see Langevin et al. 2020; Reinhart & Cerezo Davila, 2016; Swan & Ugursal 2009), develops a representative typology, creates BEM for each one, then scales the BEM results to estimate the building stock totals. The goal of this is not necessarily to develop retrofit packages, but rather to develop accurate BEM, so characteristics affecting energy use tend to be prioritized over non-energy-related considerations included in the deployment-focused typologies, such as the structural capacity of walls to support retrofits. Still, these building stock energy modeling typologies are widespread, and already exist for several areas in the United States. Table 4 provides an overview of many existing studies, including their geographic coverage and archetype segmentation.

[8] UBEM stands for “urban” or “urban-scale” BEM.

Table 4. Building Stock Energy Modeling Archetypes

Adapted and expanded from Reinhart & Cerezo Davila (2016)

				Segments			Segmentation Variables												Notable Methods
Study	Scale	Location	Sector	Building Population	Segment Count	Segment Ratio	Building Type	Stories	Vintage	Units	Heating Fuel	Climate Zone/Region	Wall Type	Heating System	Building Code	Hot Water System	Roof Type	Building Geometry	
ResStock (Wilson, 2017)	Country	United States	Residential	133M dwelling units	550k	242	X	X	X	X	X	X	X	X		X	X		Conditional probability distributions + quota sampling
ComStock	Country	United States	Commercial	1.8M	350k	5	X	X	X	X	X	X	X	X	X				Conditional probability distributions + Sobol' sequence sampling, only covers 70% of U.S. commercial floor area
(McKenna et al. 2013)	Country	Germany	Residential	18.4M	80	230k	X		X			X							-
(Siller et al. 2007)	Country	Switzerland	Residential	1.4M	735	1.9k	X							X	X	X			-
CDEM (Firth et al. 2010)	Country	UK	Residential	21M	47	452k	X	X	X										-
(Dascalaki et al. 2011)	Country	Greece	Residential	2.5M	24	105k	X		X			X							Stock model based on TABULA typology
(Fracastoro & Serraino, 2011)	Country	Italy	Residential	877k	3,168	277	X	X	X	X				X					-
(Tuominen et al. 2014)	County	Finland	All	36k	12	3k	X		X										
AutoBEM (New et al. 2018)	Region	Chattanooga (EPB Utility Territory)	All	135k	135k	1	X		X									X	Automatically develops models of all buildings in a region from geometry and DOE prototype buildings, and calibrates to real electricity data
(Filogamo et al. 2014)	Region	Sicily	Residential	171k	84	2k	X		X									X	
(Reyna & Chester 2017)	Region	Los Angeles County	Residential	2.8M	84	33k	X		X	X		X							-

				Segments			Segmentation Variables												Notable Methods
Study	Scale	Location	Sector	Building Population	Segment Count	Segment Ratio	Building Type	Stories	Vintage	Units	Heating Fuel	Climate Zone/Region	Wall Type	Heating System	Building Code	Hot Water System	Roof Type	Building Geometry	
(Reyna & Chester 2015)	Region	Los Angeles County	Residential, Industrial, Commercial	R: 2.8M C:140k I: 58k	R:6 C:8 I:2	R:467k C: 18k I:29k	X												-
SimStock - (Coffey et al. 2015)	City	London (Camden borough)	Commercial	143	143	1	X	X	X				X				X	X	Auto-generated models based on real building geometry up to all buildings in stock, can be used for anywhere in England/Wales
(Pittam et al. 2014)	City	Cork	Social housing	10k	4	2.6k		X					X						Construction type, surface volume, stories
(Sokol et al. 2017)	City	Cambridge, Massachu-setts	Low rise (1-4 unit) residential	2662	8				X					X					Uses typical segmentation and deterministic choice of parameters for most building characteristics, (and some regression selection) but utilizes Bayesian calibration with real electricity data to choose some of the more uncertain parameters in the building model
(Shimoda et al. 2004)	City	Osaka	Residential	1,128	20	56	X												Article includes 10 single-family and 10 multifamily prototypes, but unclear how they were segmented
(Cerezo Davila et al. 2016)	City	Boston	All	84k	52	1607 (but geomet-ries were unique to each building)	X		X									X	Used actual building geometries from GIS databases matched with archetypes or non-geometry characteristics

Study	Scale	Location	Sector	Segments			Segmentation Variables												Notable Methods
				Building Population	Segment Count	Segment Ratio	Building Type	Stories	Vintage	Units	Heating Fuel	Climate Zone/Region	Wall Type	Heating System	Building Code	Hot Water System	Roof Type	Building Geometry	
(Dall'O' et al. 2012)	City	Carugate	Residential	1,320	7	189			X										-
(Caputo et al. 2013)	City	Milan	Residential Commercial	~650k[9]	56	12k	X	X	X									X	
(Gupta & Gregg 2020)	City	Oxford	Residential	431	4	96	X		X									X	Also linked in socio-economic characteristics of households and Energy Performance Certificate data
(Mastrucci et al. 2014)	City	Rotterdam	Residential	300k	26	11k	X		X										
(Heiple & Sailor 2008)	City	Houston	Residential, Commercial	N/A	R: 8 C: 22	N/A	X							X					
Kuwait City (Davila et al. 2017)	City	Kuwait City	Residential	336	A:1 B: 4 C: 4 D: 4	A: 336 B: 84 C: 84 D: 84			X										Utilizes four different characterization methods for the same UBEM, including a Bayesian calibration approach for uncertain parameters
(Österbring et al. 2016)	City	Gothenburg	Multifamily	433	32	14	X		X				X						Modeled actual geometry of every building and matched Energy Performance Certificate Data

[9] Not given in paper; this is estimated from regional population statistics.

1.5 Summary of Meta-Analysis

Throughout this meta-analysis, we identified several common methods for developing building typologies. The most common is a process of segmenting, down-selecting, characterizing, and modeling, as discussed in the introduction. All of the identified studies geared toward deep energy retrofits use a version of this. There was also a lot of commonality in the variables used to segment the building stock: building type and vintage were used in virtually every study, for example, and climate zone, number of stories, wall type, and heating system were also commonly used. Data availability often explicitly or implicitly drove the segmentation. For example, some parameters critical to energy performance, such a surface-to-volume ratio, were not included for segmentation because of the difficulty deriving them from existing data sources.

Several alternate segmentation methodologies were identified as well, which used various versions of data-driven clustering and segmentation, although they were often combined with some level of manual segmentation by some of the most common segmentation variables. Although these alternate methods did provide some insights into critical variables for modeling the building stock, the overall performance of models utilizing these alternate methods did not appear to have any improvement in energy prediction (and many of the clustering studies were not actually used for building stock energy modeling development).

In the identified studies, there is a wide range of building populations represented, as well as the number of buildings represented by each segment ("segmentation ratio")—spanning from tens of buildings represented by segment all the way up to hundreds of thousands represented. There does not seem to be any sort of standard or norm for establishing this segmentation ratio. The choice seems to be driven by the size of the target population (with smaller target populations, such as cities, having generally lower buildings represented by segment), data availability, and perhaps indirectly by a need to keep computation times reasonable. ResStock™ and ComStock™, two U.S. building stock energy models developed by NREL, have some of the lowest segmentation ratios of any model, and by far the lowest of any national typologies.

There have been several key building stock characterization studies done in the United States, mostly on a local level. More frequently, the national-level studies have been done in Europe. There are many challenges of adapting the national-level methodologies from Europe to the United States, primarily the wide diversity of construction methods, climate zones, and building policies throughout the United States, which are not all documented in a centralized database. However, there is still significant insight that can be gained by developing a national typology with the data available, as it can be a springboard for detailed regional work. Furthermore, the level of data availability varies throughout the United States, whereas many European countries have centralized data on buildings, particularly for the residential sector, through Energy Performance Certificates reporting. Still, we believe there are many techniques from previous work that can be adapted for the U.S. context.

2 Study Methodology

2.1 Overview

In this section, we discuss the proposed methodology for the building stock characterization study. Building on the work discussed in the first section of this report, we propose a methodology for creating a set of national U.S. building typology segments focused on deep energy retrofits as a first step in targeting a zero-carbon building stock. The focus of this report is the initial typology segments; NREL will next model potential upgrade packages for the highest-priority typology segments. The ABC Collaborative (in particular, RMI) includes several parallel efforts that complement this characterization study, and we will work closely with RMI to align our deliverables. There are several ongoing complementary activities within the ABC Collaborative that aim to address questions that are relevant to ABC goals but that are outside the scope of this building characterization study. An overview of these analysis activities is presented in Figure 2. The main related activity is an assessment of market opportunities and solutions relevant to the implementation of ABC technologies.[10]

This national characterization study and the Market Opportunities and Challenges for Decarbonizing US Buildings report (Fisler et al. 2021) will support the initial prioritization of ABC activities—the characterization study informing the technology context of national building segments and the white paper informing the prioritization of market segments for deployment. As shown in Figure 2, both deliverables will support future analysis activities, such as the development of ABC performance standards and cost targets. Finally, RMI will publish an ABC Industry Guidance Report that summarizes the findings of these various activities. Section 4 presents more information on these activities and how the characterization study will inform them.

As with the earlier typology studies, this one is constrained by data availability. Even apart from the nontechnical factors such as owner/tenant arrangements and financing (to be addressed in the Market Insights paper), there are a number of technical factors not addressed here. Many of these factors fall into a category of "existing deficiencies" as viewed by the Federal Emergency Management Agency (FEMA) or the Environmental Protection Agency (EPA)—for example, vulnerabilities to flood, high wind, or earthquake, and conditions detrimental to indoor air quality, such as radon, asbestos, and mold. In order to prioritize segments more equitably, it may be necessary to develop a building-by-building assessment protocol. This could also incorporate assessment for the detailed applicability requirements of selected new technologies and would involve sampling at most scales.

[10] This analysis work incorporates both qualitative stakeholder interviews to solicit information on barriers and challenges to adoption from a range of industry participants, as well as quantitative analyses of geographic variability in important adoption-related attributes, such as utility and labor costs, availability of incentives, political atmosphere, and others.

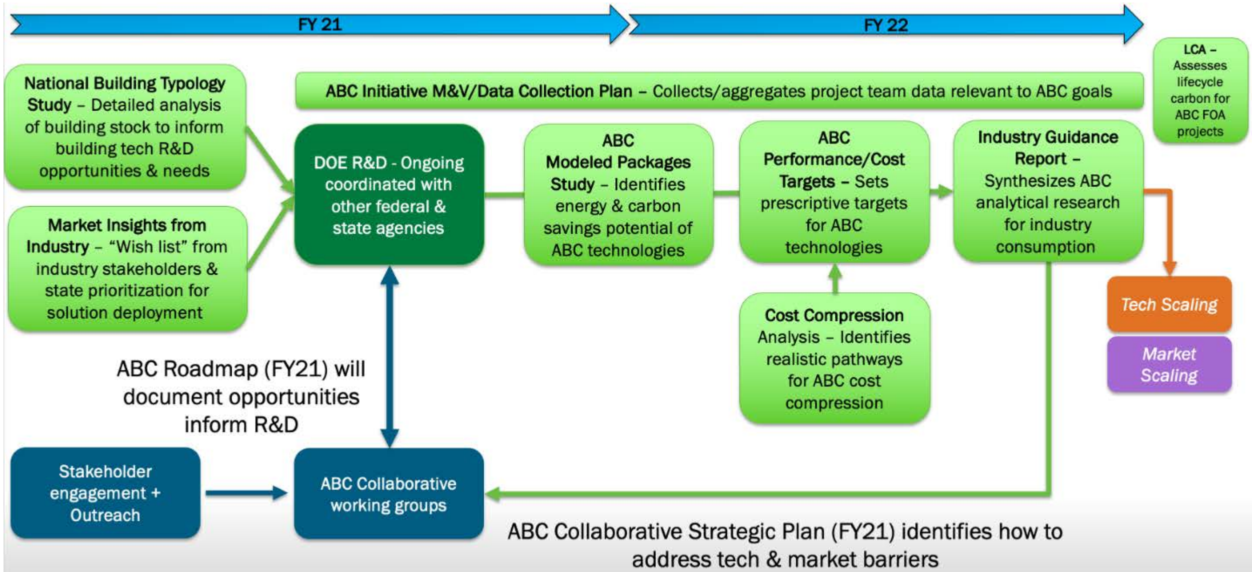

Figure 2. Overview of all primary ABC analysis activities

2.2 Background on Building Stock Segmentation Approaches

In the studies reviewed in Section 1, the vast majority linked the typology development with physics-based BEMs to represent building stock segment energy consumption. In generic classification of building stock energy models, these all would be considered bottom-up/white-box models (Langevin et al. 2020). There are many reasons these types of models are well-suited to typology studies, primarily that they are able to link energy consumption to building-level technologies and processes and capture the energy implications of building-level changes.

There are many ways to develop bottom-up/white-box building stock energy models, but the most common one is an *archetype* approach, where a typical, predominant, or average building is selected to represent a segment of the building stock, and then a single BEM is developed for that archetype. These models can oversimplify the stock representation by eliminating building characteristic combinations that might not be predominant but are still influential to the stock segment and the impact of upgrades. On the other end of the spectrum, there is the approach to model every building within the stock—a "population" modeling approach. This is not common given the computational intensity and the difficulty obtaining data on every single building within a stock, but there are a few notable examples of this approach being used (New et al. 2021). For this project, we propose an intermediate approach where we develop a large set of representative BEMs for each typology segment in the stock using NREL's ResStock and ComStock models. Both models represent the building stock with conditional probability distributions of building characteristics, and then sample from the probability space to create hundreds of thousands of representative BEMs. These models are described in more detail in the next section.

2.3 ResStock and ComStock

ResStock[11] and ComStock[12] are physics-based simulation models developed to represent the energy use and energy saving potential of residential and commercial building stocks with high granularity at national, regional, and local scales. ResStock and ComStock are DOE models that have been developed and maintained by NREL since 2014 and 2016, respectively.

Table 5. Major Data Sources Used in ResStock

Data Sources	ResStock Inputs
EIA Residential Energy Consumption Survey (RECS) 2009, 2015	Foundation type, number of stories, attached garages, wall material, HVAC type and age, refrigerator number/age, pool/spa presence/fuel type, window panes, dishwasher presence/age
American Community Survey (ACS) Public Use Microdata Sample (PUMS), 2016 5-yr, 2017 5-yr	Building type, vintage, heating fuel, vacancy status
American Housing Survey (AHS) microdata, 2017	Floor area, number of bedrooms, number of occupants, clothes washer/dryer presence
U.S. Census 2010 spatial definitions	Geospatial mapping between different resolutions
Residential Diagnostics Database (ResDB), http://resdb.lbl.gov/	Envelope air leakage
Home Innovation Research Labs, Builder Practice Surveys, selected years 1980–2010	As-built insulation levels (walls, attics, foundations)
2012 NEEA Residential Building Stock Assessment (RBSA) I microdata	Insulation levels (walls, attics)
2016–17 NEEA Residential Building Stock Assessment (RBSA) II microdata	Window areas
Nettleton, G., Edwards, J. 2012. *Data Collection-Data Characterization Summary*, NorthernSTAR Building America Partnership, Building Technologies Program. Washington, D.C.: U.S. Department of Energy.	Insulation levels (walls, attics)
Navigant Consulting. 2015. *U.S. Lighting Market Characterization*. DOE Office of EERE.	Lighting types
Lucas and Cole. 2009. “Impacts of the 2009 IECC for Residential Buildings at State Level.”	Duct leakage

Compared to other building stock models, ResStock and ComStock use a large number of representative models—close to 1,000,000 for the contiguous United States—to represent the building stock with high fidelity. Unlike many urban BEM approaches, ResStock and ComStock do not attempt to generate a physics model for every building, but rather use a relatively large number of statistically sampled models to represent the building stock with a realistic diversity of

[11] For more information on ResStock, see https://www.nrel.gov/buildings/resstock.html.
[12] For more information on ComStock, see https://www.nrel.gov/buildings/comstock.html.

building characteristics. The major data sources for ResStock and ComStock are listed in Table 5 and Table 6, respectively.

Table 6. Major Data Sources Used in ComStock

Data Sources	ComStock Inputs
Commercially purchased, proprietary end-use submeter data	Loads, efficiency, occupancy
California Energy Commission Reports	Loads, efficiency, occupancy
ASHRAE 62.1	Loads, efficiency, occupancy
ASHRAE 90.1	Loads, efficiency, occupancy
CoStar real estate data	Building type, floor area, year built
EIA Commercial Building Energy Consumption Survey (CBECS) 2012	Aspect ratio, HVAC system type, and window-to-wall ratio
Homeland Security Infrastructure Plan (HSIP)	Building type, floor area, year built
DOE Commercial Prototype Buildings	Loads, efficiency, occupancy, space type ratio and zone definition

A complete description of the ResStock and ComStock methodologies is beyond the scope of this document, but they will be summarized here. For further details on ResStock see Wilson et al. (2017), which reflects an older set of data sources, but the methodology is largely the same, and see Mims Frick et al. (2019) for ComStock and some updates on ResStock. Results presented here are consistent with the state of ResStock used to produce the End-Use Load Profiles (EULP) dataset v1.0; the output correction model discussed in the EULP report has not been applied to these results (Wilson et al. 2021).

For both ResStock and ComStock, the general methodology is as follows:

1. **Stock characterization.** Conditional probability distributions for building stock characteristics are queried from data sources (e.g., distribution of "year structure built" as a function of location and "building type"). Parameters common across data sources, such as geographic location, building type, and vintage are used to combine and map between the disparate data sources. Geographic resolution for queried distributions varies in scale—for example, from counties (~3,000) to climate zones (16)—so various geospatial data sources are used to map between geographic resolutions. The conditional probability distributions take the form of a hierarchical tree of dependencies.

2. **Sampling.** The parameter space defined by the conditional probability distributions is sampled. ResStock currently uses deterministic quota sampling, with probabilistic combination of noncorrelated parameters. ComStock currently uses quasi-random sampling using Sobol' sequences. At the U.S. national scale, ResStock uses 550,000 samples to represent 133,172,057 dwelling units (approximately 1:242), and ComStock

currently uses 350,000 samples to represent 1.8 million commercial buildings (approximately 1:5). The appropriate ratio of samples to buildings or dwelling units was initially determined through convergence testing (Wilson et al. 2017) for national-scale applications; however, the appropriate ratio for different application and scales is the subject of ongoing research.

3. **Physics simulation.** The samples are used to construct physics simulation models using a simulation engine of choice. NREL typically uses the EnergyPlus® simulation engine for this purpose. Model construction and articulation is facilitated by the OpenStudio® software development kit and associated commercial and residential modeling workflows (e.g., OpenStudio-Standards and OpenStudio-HPXML).

4. **Calibration and validation.** ResStock received an initial calibration/validation process in 2015. Annual electricity and natural gas consumption were validated against EIA RECS 2009 data for various cohorts of single-family detached homes. Calibration involved numerous improvements to model input data and refinement of probability distribution dependencies. An initial ComStock validation was completed in 2019. ResStock and ComStock validation, with a focus on end-use load profiles, was completed under the DOE project End-Use Load Profiles for the U.S. Building Stock (Mims Frick et al. 2019; Wilson et al. 2021).

5. **Model outputs and post-processing.** Model outputs include both annual and hourly or subhourly timeseries energy use outputs for each sample for major and minor end uses (electricity and on-site natural gas, propane, and fuel oil use). Outputs for each sample also include HVAC system capacities and hours the heating and cooling setpoints were not met. Optional outputs also include timeseries indoor zone temperatures (e.g., for analyzing thermal comfort and resilience; see Murphy et al. 2020). Additional model outputs being integrated for this characterization study include estimates of annual heating and cooling loads by component (opaque walls, ceilings, foundations, window conduction, window solar gain, infiltration, mechanical ventilation, and internal gains).

ResStock and ComStock also include post-processing scripts to calculate additional output metrics, including utility bills, primary energy use, and carbon emissions. A parallel effort is currently underway to integrate hourly marginal emissions rates and hourly avoided costs for future electric grid scenarios from NREL's Cambium data set (Hale 2019).

Timeseries outputs from the millions of simulations can be extremely large and difficult to work with, so NREL has been developing a stack of technologies to facilitate processing, aggregation, and analysis of ResStock and ComStock timeseries and non-timeseries outputs.

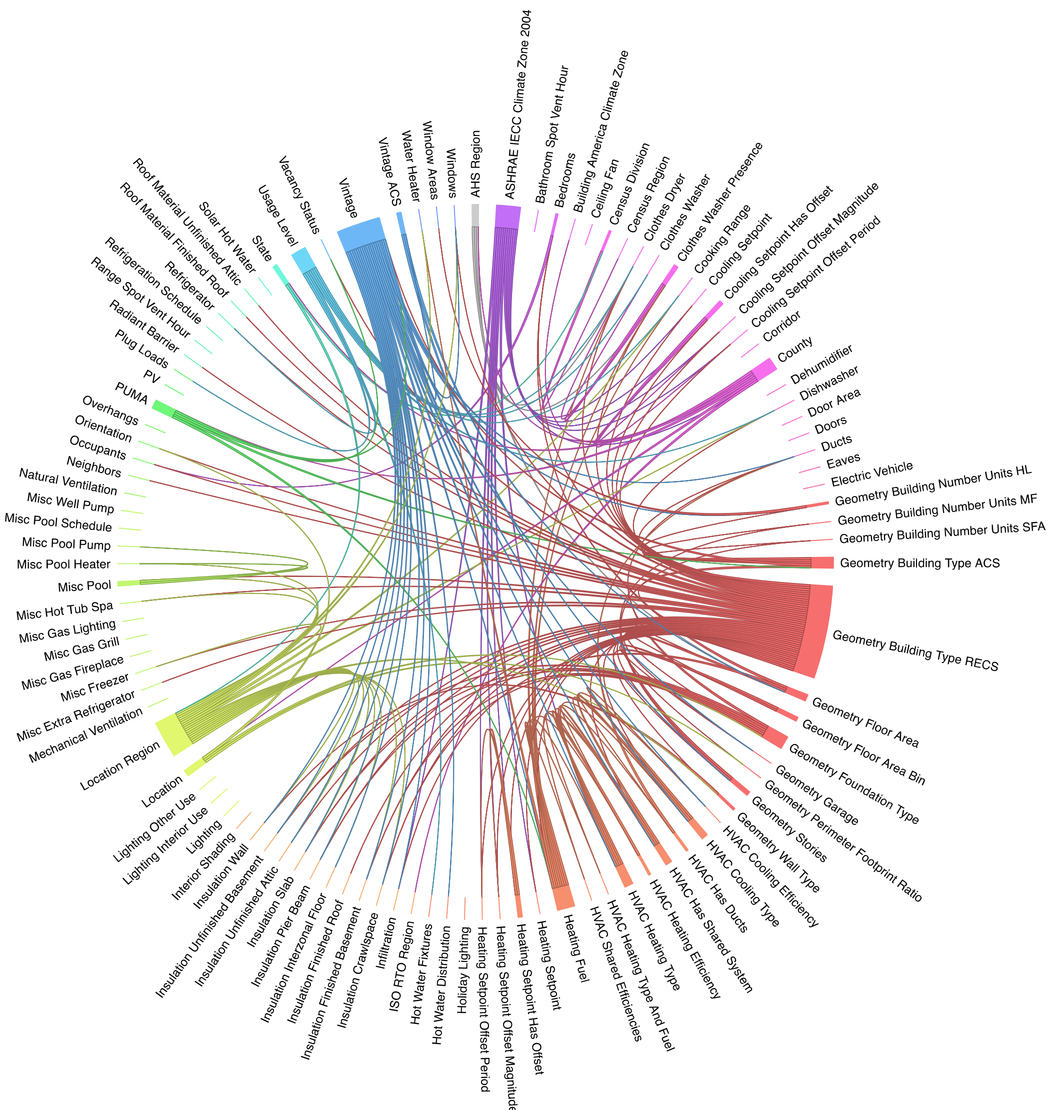

Figure 3. Sample structure of parameter dependencies in ResStock

Each housing characteristic has a set of dependencies and dependents. In this dependency wheel, each chord in the disc represents a dependency. The thin part of the chord represents a dependency to the thicker part of the chord. This illustrates the relationship between conditional probability distributions for ResStock.[13]

2.4 Description of Methodology Steps

Our characterization study methodology builds on the work of previous studies while leveraging the compiled databases of ResStock and ComStock as well as the detailed simulation results (Figure 4). As described in the introduction to this report, a typical approach to building stock typology is to (1) segment the stock, (2) prioritize and/or down-select segments, (3) characterize

[13] An interactive version of this figure can be found at https://htmlpreview.github.io/?https://github.com/NREL/OpenStudio-BuildStock/blob/master/project_national/util/dependency_wheel/dep_wheel.html.

(all parameters necessary for BEM) the top segments, and (4) model the selected segments, including upgrades.

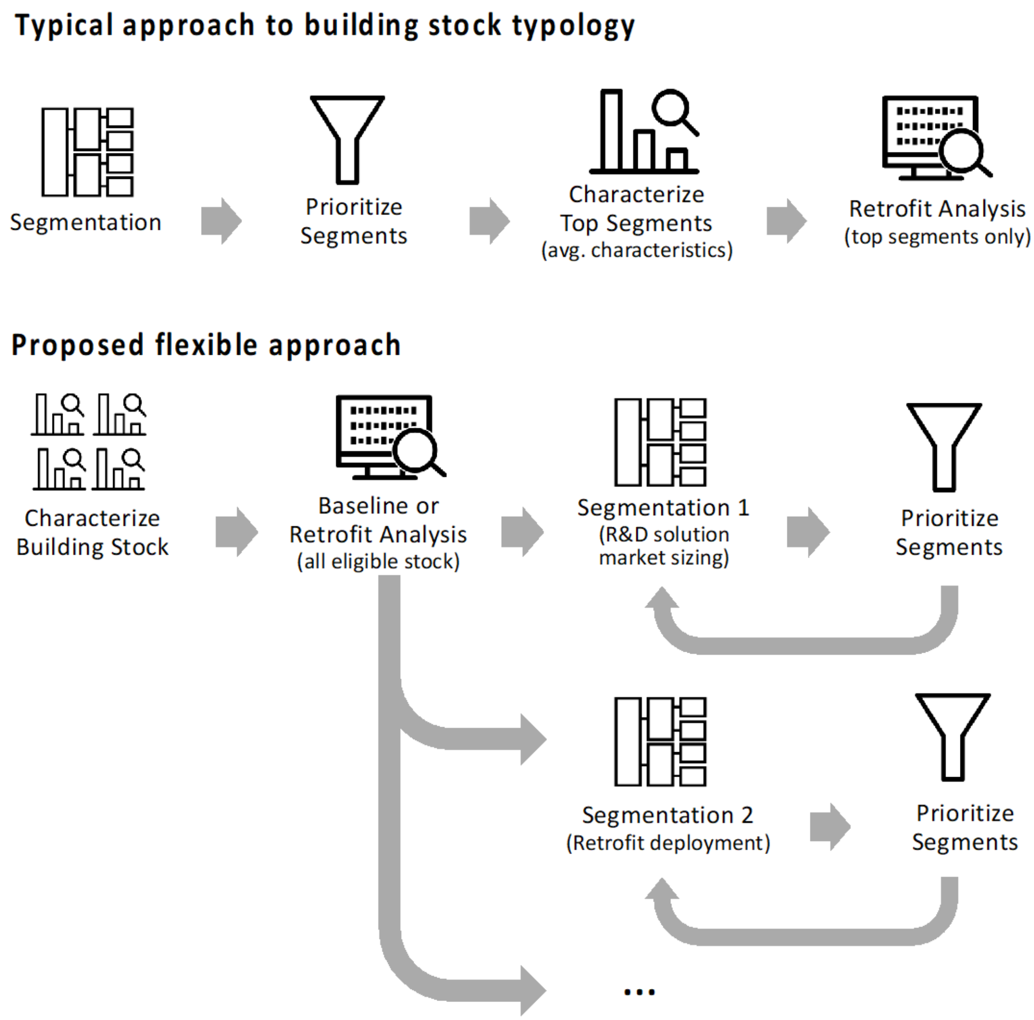

Figure 4. Methodological overview

For our study, we use a similar approach, with some modification. We begin with characterization (all parameters necessary for BEM) of the entire building stock at the beginning of the study using ResStock and ComStock, because these characteristics are already compiled. With initial ResStock and ComStock baseline results, we then segment on variables important for ABC and begin an iterative process of prioritizing via ABC-relevant metrics and re-segmenting results based on the prioritization. This also informs retrofit options in the forthcoming Industry Guidance Report from RMI. We detail each of these steps in the following sections.

2.4.1 Characterize Stock With National ResStock and ComStock Runs

Characterize the building stock. The first step in our process is to characterize the national building stock. As described in Section 2.3, ResStock and ComStock already characterize the diversity of the building stock through the use of a network of conditional probability distributions. Specifically for this project, we made some additional improvements to the input specification, notably around wall type characterization. In the original ResStock model, wall type was derived from the RECS 2009 survey, but it was impossible to differentiate between structural masonry walls and masonry facades. Our approach for improving this distinction and other updates are further described in Section 4.2.

For this characterization study, we performed national scale runs of ResStock and ComStock with typical reporting of end uses at the building level by fuel type. For ComStock, we used an additional reporting measure to report additional details on building equipment, such as the size of the HVAC system, which was determined during the model articulation process. Additionally, we layered on post-processing aggregations, such as summing up the thermal energy use end uses that are the focus of ABC (heating, cooling, ventilating, and water heating) within the building. We also performed an analysis to break down the component loads of space conditioning (similar to Huang, Franconi, et al. 1999 and Huang, Hanford, et al. 1999), so we could identify the relevant contributors to space conditioning loads (e.g., walls, roof, ventilation). These results are especially useful when identifying upgrade packages. The results of the national runs contain full energy outputs by simulated building, as well as all of the sampled building characteristics. This full set of 550,000 residential models and 350,000 commercial models is the baseline synthetic stock to be used throughout the typology process.

2.4.2 Initial Segmentation

Segment the building stock. With the synthetic stock simulated, we initially segmented the building stock based on commonly observed segmentation variables in the literature. We then went through an iterative process with the ABC Analysis Working Group to identify additional segmentation parameters and to aggregate different variables. For residential buildings, our segmentation parameters are climate zone, building type (single-family detached, mobile home, etc.), wall structure, and vintage. In reality, this segmentation will not capture every building characteristic significant for ABC, but based on the literature and our own modeling experience, we have confidence that these are characteristics that are highly important for building energy use, because our chosen parameters appear frequently in other studies and are also highly correlated to many other important building characteristics. This method also has the advantage that we can revisit the segmentation as needed without rerunning models, and external stakeholders can perform custom segmentation via the online dashboard.

2.4.3 Assessment Metrics

Calculate metrics for the initial segments. Initially, NREL and the ABC Analysis Working Group developed a list of potential metrics to be used for comparative assessment of the segments (Table 7). Although all of these are potentially important for ABC, we focus primarily on thermal energy intensity and total thermal energy use. However, we also present many of the other metrics in the results (e.g., prevalence of typology segment, total floor area, thermal component EUI), and we anticipate that we will include additional metrics (e.g., carbon intensity, present and future) as part of the upgrade packages.

Table 7. Typology Assessment Metrics

Metric	Description
Site EUI (kBtu/ft^2)	Includes all end uses, both electricity and on-site fuels, per square foot of building conditioned floor area.
Thermal energy use intensity (kBtu/ft^2)	A subset of site EUI, including only the loads that are the main focus of ABC (thermal end uses: HVAC and water heating).
Total thermal energy use (kBtu)	Total thermal energy use that are the focus of ABC (heating, cooling, ventilating, and water heating) for a segment of the stock. Could potentially be expanded to cover commercial refrigeration and refrigerated spaces.
On-site fossil fuel use intensity (kBtu/ft^2)	To assist in identifying electrification potential, this metric excludes electricity use and only includes fossil fuels combusted on-site. Wood use for heating may optionally be included.
Carbon intensity (kg/ft^2)	Carbon intensity of on-site fuel combustion (with or without upstream emissions) and electricity generation. Options for electricity emissions rates include using annual average carbon emissions rates (e.g., using EPA eGRID) or hourly (*short-run*—i.e., operational dispatch, or *long-run*—i.e., capacity expansion/retirement) marginal emissions rates, using either recent historical data (WattTime) or future grid scenarios (Cambium).
Prevalence of typology segment	Number of buildings, number of dwelling units.
Total floor area (ft^2)	Total conditioned floor area of typology.
Building size (floor area per building)	To prioritize large projects for implementation efficiency.
Thermal component EUI (kBtu/ft^2)	Thermal components include opaque walls, ceilings, foundations, window conduction, window solar gain, infiltration, mechanical ventilation, and internal gains. This metric can assist in prioritizing and aggregating segments for specific ABC R&D solutions (e.g., panelized wall retrofits).

2.4.4 Iterate to Down-Select Final Segments

Iterate on segmentation and append characteristics as necessary. Using the metrics from the preliminary segmentation, we collaborated closely with the ABC Analysis Working Group to finalize the typology segments in a highly iterative process. One of the benefits of using ResStock and ComStock is that they have nearly 1 million building energy models between them that we aggregate to create our typology segments. This is in contrast to other typology studies where only one building energy model might exist per segment. This detailed modeling approach precludes the need for additional model runs if the typology segmentation might change; we can simply reaggregate the large pool of existing building energy model runs results into new segments as necessary. Upgrade packages will similarly be aggregated by these segments, but additional segments might also need to be developed after the upgrade runs are complete.

3 Development of a U.S. Building Typology

This section provides an overview of the U.S. national building typology developed from ResStock and ComStock. The goal of this typology is to present a nationwide, comprehensive breakdown of all U.S. buildings by climate zone, segmenting by technical characteristics relevant for designing retrofit strategies. It is anticipated that this national characterization study will evolve and adapt to serve many use cases based upon new data. As such, we will maintain an accompanying online dashboard—available at resstock.nrel.gov/page/typology—that provides the most up-to-date data as well as custom query capabilities down to a county level. The results we present here in this report are consistent with the state of ResStock used to produce the End-Use Load Profiles dataset v1.0; the output correction model discussed in the End-Use Load Profiles report has not been applied to these results (Wilson et al. 2021).

In this characterization study, we divide the building stock into distinct segments than can be used for further analysis. We also provide additional characteristics and commentary for some segments to provide further characterization.

For the residential typology segmentation, we report segments by climate zone. In consultation with the ABC Analysis Working Group, we have selected Building America climate zones (Figure 5).[14] For commercial buildings, we do not report findings by climate zone for the final segmentation; we found climate zone to be much less influential for commercial compared to residential buildings. However, in the accompanying online dashboards, users can segment commercial results by the ASHRAE 90.1-2013 climate zones (Figure 6).

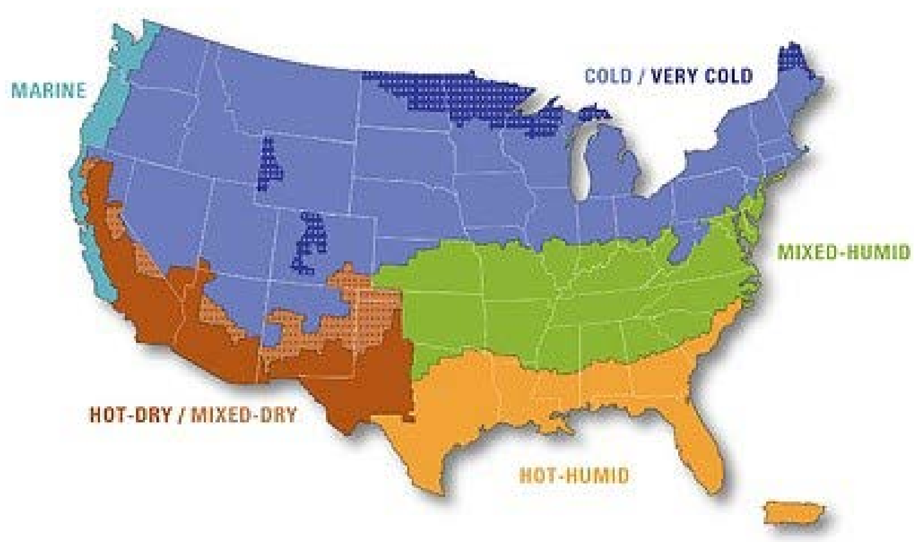

Figure 5. Building America climate zones.

Image from Baechler et al. (2015)

[14] The online dashboard accompanying this study allows for alternate climate zone aggregations, including ASHRAE/IECC.

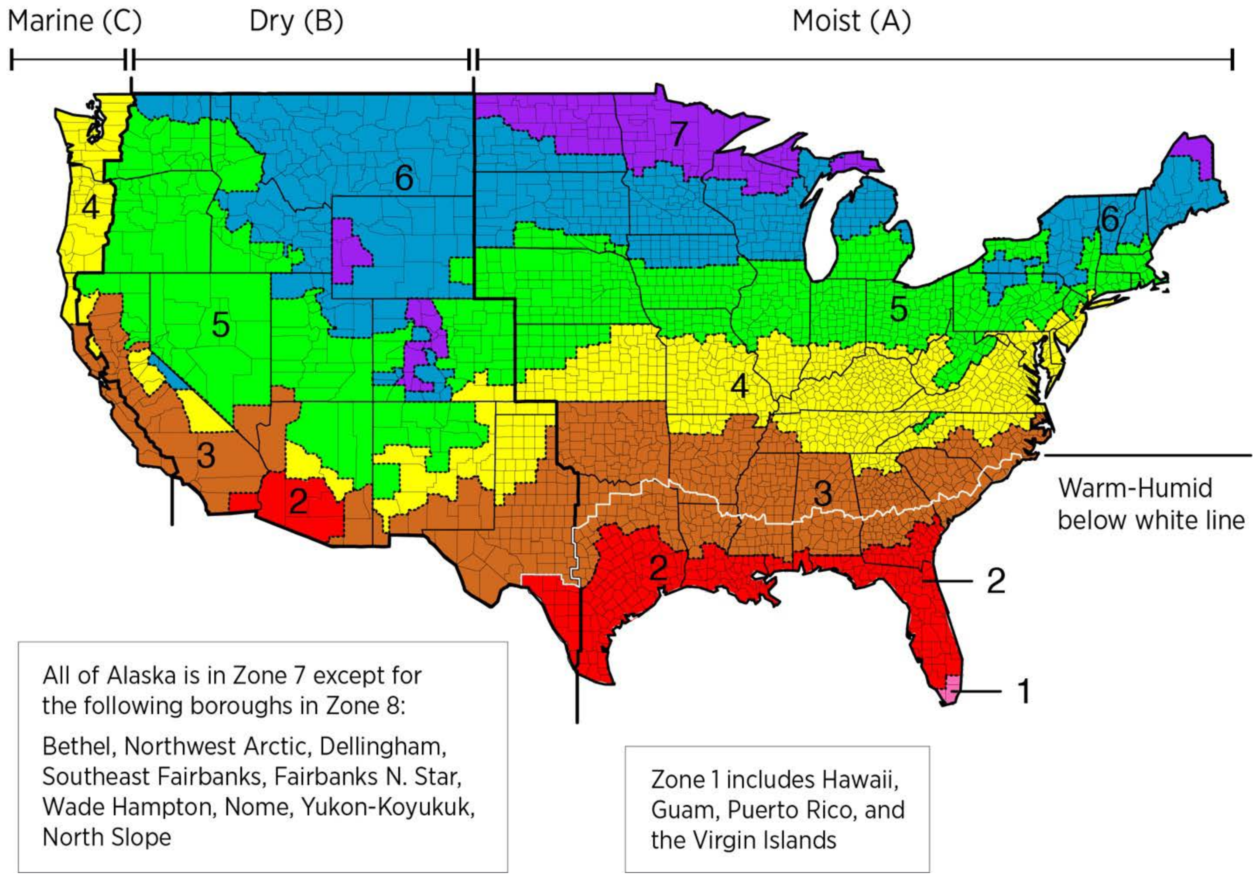

Figure 6. IECC/ASHRAE 90.1-2013 climate zones[15]

We also provide a preliminary component loads analysis by dividing up the relative contribution of different building components to heating or cooling loads as normalized energy per square foot. Processing these load components out of EnergyPlus for each underlying ResStock building energy model is an ongoing research effort that the NREL team continues to refine. The process involves using hourly EnergyPlus outputs to determine the contribution of thermal gains or losses to heating or cooling loads in each hour of the year. For the purposes of this report, we use smaller ResStock and ComStock runs reporting out the component loads to start exploring this approach. The sample for ResStock uses 5,000 buildings nationally, and the sample for ComStock uses 1,000 buildings nationally. We anticipate that these reporting measures will be fully completed and able to run for the full national samples during the next phase of the project.

3.1 Residential Segments

For residential buildings, we segment ResStock results based on six building types, five climate regions, two wall types,[16] and three vintage bins, for a total of 165 residential building segments nationally (Table 8).

[15] https://basc.pnnl.gov/images/iecc-climate-zone-map

[16] This does not apply to mobile homes. Wall structure type is an area of ongoing improvement in ResStock. Notably, we are working to improve the representation of structural steel buildings in the ResStock characteristics database for high-rise buildings.

We chose not to segment by HVAC parameters (heating fuel, presence of ducts, or building shared heating/cooling) because they are less related to the building structure, and we wanted to maintain a reasonable number of typology segments. Further characterization details can be explored on the online typology dashboard. These HVAC parameters can still be used to determine applicability of retrofits and could be used to define subsegments within the characterization study as necessary.

We discuss the segmentation climate zone by climate zone, including major segment characteristics. We then highlight the segment with the highest total thermal energy use for both single-family and multifamily housing and discuss major contributors to that segment's thermal energy use.

Table 8. Residential Segmentation Parameters

Segmentation Parameter	Levels
Building America Climate Zone	Cold/Very-Cold; Mixed-Humid; Marine; Hot-Dry Mixed; Hot-Humid
Building Type	Single-Family Detached; Mobile Home[17]; Single-Family Attached; Multifamily 2–4 Units; Multifamily 5+ Units (1–3 stories); Multifamily 5+ Units (4+ stories)
Wall Structure	Masonry or Steel Frame; Wood Frame
Vintage	Pre-1940; 1940–1979; Post-1980

3.1.1 Residential Climate Area 1: Cold/Very Cold

The Cold/Very-Cold climate region covers the Northeast, Midwest, and Mountain West regions of the United States, as well as Alaska,[18] in total representing 34.5% of the U.S. housing stock by unit (35.3% by building count) and 49% of the national residential thermal energy use. Figure 7 shows the 34 segments in the Cold/Very Cold region, with the number of buildings, average building size, average thermal energy use intensity, and annual thermal energy used in each segment.

Single-family detached is the most prevalent housing type, composing 82% of the region's residential buildings and 66% of the housing units. Correspondingly, single-family detached homes are responsible for 80% of the cold climate zone's thermal energy use. Although numerous, the average floor area of single-family homes (1,846 ft^2) is much smaller than the average multifamily building (38,932 ft^2); additionally, many single-family homes are owner-occupied or owned by smaller companies, meaning that significant energy reductions in this segment of the stock will involve aggregating many small projects and interacting with many different decision makers.

Although they represent only 4% of the housing units in the Cold/Very-Cold climate region, mobile homes in this area are notable for being the most energy-intensive housing type in the United States, especially units built before 1980. The thermal energy use for these building

[17] In this report, we use the term "mobile home" to align with the EIA RECS survey that provides much of the inputs to ResStock. The term "manufactured housing" is also commonly used for this building type.
[18] Although included in this region, Alaska is currently not modeled in ResStock.

segments are primarily driven by space heating. Addressing ABC goals in these cold-climate pre-1980 mobile homes could also help address the energy burden faced by the occupants of these housing units.

All building segments show a strong correlation with age, with post-1980 homes across building types utilizing approximately half of the thermal end-use energy per square foot of their pre-1940 counterparts. Despite being thermal energy intense, pre-1940 homes might also have some additional considerations in retrofitting because of the building age; specifically, they might have historic preservation restrictions or occupant facade preference that could hinder external retrofits. It is unclear what percentage of the stock might have these formal restrictions, but it could pose specific localized challenges city-to-city. To retrofit this segment of the stock, strategies should be developed that can improve the envelope without external modifications, or in the case of windows either closely replicate the exterior appearance or provide acceptable modifications (e.g., storm windows or attachments). Internal strategies to reduce infiltration might be especially effective, although internal strategies may be disruptive to current occupants. Furthermore, from an energy and safety perspective alone, for some portions of this segment, it might be better to replace older homes rather than to renovate them, although there are certainly numerous other important considerations in turning over existing building stock.

Across residential building types, space heating (particularly from natural gas) dominates thermal energy use. For homes in rural areas without piped gas distribution, fuel oil heating is common in the Northeast and Mid-Atlantic, and propane heating is common in other rural areas. Although there are challenges in electrifying space heating in cold climates, to approach carbon neutrality in this climate region, heating loads must be reduced through envelope improvements while electrifying the load.[19]

Breaking down the contributors to heating loads in the Cold/Very-Cold climate region across building types, infiltration is the highest for all building types (see Figure 8). Based on current ResStock modeling of multifamily buildings, infiltration is particularly significant, contributing approximately two-thirds of the envelope heat transfer. In single-family buildings, infiltration is still the main contributor, with walls next, followed by floors and ceilings in similar proportions.

[19] In theory, there might be other strategies beyond electrification for achieving a carbon-neutral building stock, such as “renewable” natural gas, green hydrogen, or carbon credits. For the purposes of this report, we focus on electrification and efficiency as the main supporting components from the building sector toward decarbonization, although in practicality other approaches might supplement for difficult-to-electrify loads.

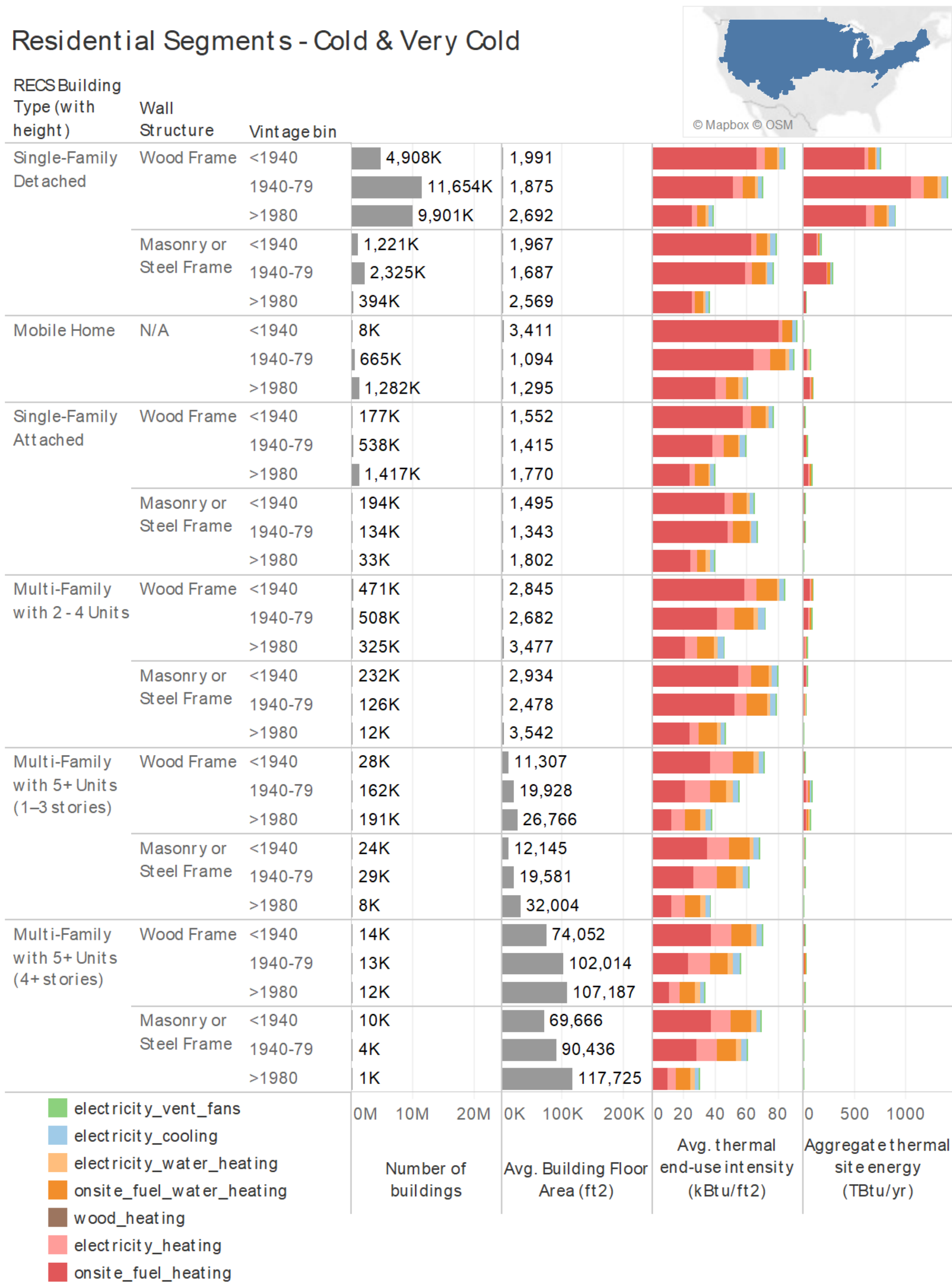

Figure 7. Residential Cold/Very-Cold typology segments

3.1.1.1 Cold/Very-Cold: Highest Thermal Energy Use Segments

Single-Family: Detached, 1940–1979, Wood Frame. This segment has the highest thermal energy use in the climate region, as well as in the entire country. Loads in this segment are dominated by heating, especially heating from fossil fuel sources such as natural gas. Infiltration is a key concern for reducing this end use, as is electrification and increased efficiency of the heating equipment. The component loads analysis (Figure 8) indicates that envelope upgrades to the walls and roof/ceiling could also significantly reduce the loads in this segment. Solutions developed for this segment could also potentially be applied to other Cold/Very-Cold typology segments such as other wood frame vintages and low-rise wood frame multifamily.
Cold/Very-Cold Prevalence: 25% of housing units / 31% of residential buildings / 32% of residential thermal energy use.

Multifamily: 2–4 Unit, Pre-1940, Wood Frame. Among Cold/Very-Cold multifamily segments, this segment has the largest total thermal energy use as well as one of the largest intensities of thermal energy use. Like all homes in this climate region, the segment is dominated by heating, especially fossil-fuel heating. Similar to the highest single-family segment, infiltration, roof, and wall upgrades are most likely to reduce heating loads. Solutions could potentially be shared between this segment and the single-family segment for this climate region given the similar height, size, and wall construction.
Cold/Very-Cold Prevalence: 2% of housing units / 1% of residential buildings / 2% of residential thermal energy use.

3.1.1.2 Introduction to Component Loads

Figures 8 and 9 present the component loads breakdown for heating and cooling for the Cold/Very-Cold climate region. The component loads are the specific contributors to heat gains and losses that comprise the heating and cooling loads. Summing across the row for a segment will sum to the total heating or cooling load of the segment. The largest number within a row will be the largest contributor of the component loads for that segment. In the heating figure, Figure 8, positive numbers are heat losses (i.e., increase heating load) and represented by the color blue. In the cooling figure, Figure 9, positive numbers are heat gains (i.e., increase cooling loads) and are represented by the color orange. The same sign convention and color scheme are present in all subsequent component load diagrams.

Annual heating load per square foot of building floor area
Cold & Very Cold Climate Zone

RECS Building Type (with height)	Wall Structure	Vintage bin	infiltration	walls	other	roof / ceiling	floor	equipment	windows - conduction	foundation walls	ground	doors	lighting	people	windows - solar
Single-Family Detached	Masonry or Steel	<1940	23.2	7.7	6.1	4.1	4.4	3.2	2.9	0.7	0.4	0.1	-0.2	-0.5	-3.4
		1940-79	20.8	6.3	4.7	4.3	3.5	3.4	2.5	1.2	0.9	0.1	-0.2	-0.5	-2.9
		>1980	10.1	2.2	2.6	2.4	2.0	2.4	1.7	0.4	0.6	0.1	-0.2	-0.3	-1.9
	Wood Frame	<1940	24.2	9.4	6.9	4.5	4.5	3.3	3.1	0.7	0.4	0.1	-0.2	-0.5	-3.4
		1940-79	20.4	6.9	5.0	4.6	3.5	3.3	2.5	1.3	0.9	0.1	-0.2	-0.5	-2.8
		>1980	9.5	2.6	2.8	2.5	2.1	2.3	1.7	0.4	0.7	0.1	-0.2	-0.3	-2.0
Mobile Home	N/A	<1940	15.3	7.2	10.1	10.4	12.0	9.7	2.4	0.0	0.0	0.1	-0.2	-0.2	-2.8
		1940-79	17.7	8.5	7.9	7.9	11.7	6.0	3.4	0.0	0.0	0.2	-0.2	-0.6	-4.0
		>1980	11.5	4.4	4.7	4.9	7.2	5.2	2.5	0.0	0.0	0.2	-0.2	-0.5	-3.0
Single-Family Attached	Masonry or Steel	<1940	30.3	4.4	3.1	2.5	2.1	1.9	1.5	0.3	0.2	0.1	-0.2	-0.5	-2.0
		1940-79	24.1	3.0	2.2	2.4	1.6	2.3	1.2	0.5	0.6	0.1	-0.2	-0.5	-1.6
		>1980	14.4	1.3	1.3	1.7	0.7	1.9	1.0	0.3	0.6	0.1	-0.2	-0.4	-1.2
	Wood Frame	<1940	29.0	5.3	3.9	3.1	2.3	2.6	1.4	0.3	0.2	0.1	-0.2	-0.5	-1.9
		1940-79	23.6	3.1	2.4	2.8	1.3	2.2	1.2	0.7	0.6	0.1	-0.2	-0.5	-1.6
		>1980	14.2	1.5	1.5	1.6	1.0	2.0	1.0	0.2	0.6	0.1	-0.2	-0.4	-1.3
Multi-Family with 2 - 4 Units	Masonry or Steel	<1940	25.0	7.6	4.7	4.9	5.8	-0.4	3.4	0.0	0.2	0.2	-0.3	-0.7	-3.4
		1940-79	22.0	6.6	3.9	4.1	4.6	-0.8	3.5	0.0	0.7	0.2	-0.3	-0.7	-3.4
		>1980	14.2	2.6	2.1	2.5	2.9	-0.6	2.7	0.0	0.6	0.2	-0.2	-0.5	-2.5
	Wood Frame	<1940	24.9	9.4	5.3	5.4	6.0	-0.4	3.5	0.0	0.2	0.2	-0.3	-0.7	-3.4
		1940-79	23.1	8.3	4.5	4.6	5.1	-1.1	3.9	0.0	0.8	0.3	-0.3	-0.7	-3.7
		>1980	12.2	3.0	2.4	3.0	2.9	-0.7	2.6	0.0	0.6	0.2	-0.2	-0.5	-2.5
Multi-Family with 5+ Units (1–3 stories)	Masonry or Steel	<1940	25.1	5.0	3.2	3.4	4.5	-2.2	2.8	0.0	0.1	0.1	-0.3	-0.6	-2.8
		1940-79	21.1	3.3	2.3	2.7	3.1	-1.7	2.5	0.0	0.5	0.1	-0.2	-0.6	-2.3
		>1980	13.3	1.4	1.2	1.7	1.8	-1.1	1.8	0.0	0.3	0.0	-0.2	-0.5	-1.6
	Wood Frame	<1940	23.9	5.6	3.3	3.5	4.2	-2.0	2.7	0.0	0.1	0.1	-0.2	-0.6	-2.5
		1940-79	20.8	3.8	2.4	2.8	3.1	-2.0	2.6	0.0	0.4	0.1	-0.2	-0.6	-2.3
		>1980	12.7	1.7	1.4	1.9	1.8	-1.1	1.8	0.0	0.3	0.0	-0.2	-0.5	-1.6
Multi-Family with 5+ Units (4+ stories)	Masonry or Steel	<1940	27.3	4.0	2.4	2.2	3.9	-3.0	3.7	0.0	0.1	0.1	-0.2	-0.6	-3.0
		1940-79	22.8	2.6	1.6	1.5	3.0	-2.8	3.4	0.0	0.1	0.0	-0.2	-0.6	-2.5
		>1980	12.2	0.9	0.7	0.8	1.5	-1.8	2.0	0.0	0.1	0.0	-0.2	-0.4	-1.4
	Wood Frame	<1940	23.9	5.4	3.2	2.9	4.5	-2.9	3.6	0.0	0.1	0.1	-0.3	-0.6	-3.0
		1940-79	23.3	3.6	2.1	2.1	3.2	-2.5	3.1	0.0	0.2	0.1	-0.2	-0.6	-2.5
		>1980	11.6	1.0	0.8	1.0	1.3	-1.5	1.4	0.0	0.2	0.0	-0.2	-0.4	-1.2
Average by component			19.6	4.5	3.4	3.4	3.7	0.7	2.5	0.2	0.4	0.1	-0.2	-0.5	-2.5

Thermal load component

Annual heating load intensity (kBtu/ft2/yr)

-4.0 30.3

Figure 8. Residential Cold/Very-Cold heating component loads

1. The wall, floor, roof/ceiling, window, and foundation wall conduction categories only include conduction through those components; all air envelope leakage is accounted for in the infiltration category.
2. “Other” includes time-lagged heat transfer with internal partition wall and furniture mass.
3. “Equipment” includes duct losses (leakage and conduction) as positive contributions to heating load, as well as heat gain from major appliances, water heaters, hot water pipes, and hot water draws as negative contributions to heating load.

Annual cooling load per square foot of building floor area
Cold & Very Cold Climate Zone

RECS Building Type (with height)	Wall Structure	Vintage bin	windows - solar	equipment	other	walls	roof / ceiling	people	windows - conduction	foundation walls	infiltration	lighting	doors	ground	floor
			Thermal load component												
Single-Family Detached	Masonry or Steel	<1940	2.4	1.7	1.8	1.1	0.5	0.2	0.2	0.1	0.2	0.1	0.0	-0.1	-1.5
		1940-79	2.3	2.4	1.4	0.9	0.6	0.2	0.1	0.2	0.2	0.1	0.0	-0.4	-1.2
		>1980	2.1	2.0	1.2	0.6	0.4	0.2	0.1	0.1	0.0	0.1	0.0	-0.3	-1.3
	Wood Frame	<1940	2.5	1.7	1.7	1.3	0.5	0.2	0.2	0.1	0.2	0.1	0.0	-0.1	-1.6
		1940-79	2.1	2.1	1.3	1.0	0.6	0.2	0.1	0.2	0.2	0.1	0.0	-0.3	-1.1
		>1980	2.1	1.9	1.2	0.6	0.5	0.2	0.1	0.1	0.0	0.1	0.0	-0.3	-1.1
Mobile Home	N/A	<1940	1.3	1.6	1.1	0.7	0.8	0.1	0.1	0.0	0.3	0.1	0.0	0.0	-0.4
		1940-79	2.4	2.0	1.2	1.0	0.7	0.2	0.1	0.0	0.1	0.1	0.0	0.0	-1.5
		>1980	2.7	3.0	1.3	0.8	0.7	0.2	0.1	0.0	0.0	0.1	0.0	0.0	-1.7
Single-Family Attached	Masonry or Steel	<1940	1.7	2.4	1.7	1.4	0.4	0.3	0.1	0.0	0.4	0.1	0.0	-0.1	-0.9
		1940-79	1.4	3.2	1.2	1.0	0.4	0.3	0.1	0.1	0.3	0.1	0.0	-0.3	-0.6
		>1980	1.6	3.1	1.3	0.8	0.5	0.3	0.1	0.1	0.0	0.1	0.0	-0.3	-0.8
	Wood Frame	<1940	1.3	2.1	1.3	1.1	0.3	0.2	0.1	0.0	0.4	0.1	0.0	-0.1	-0.8
		1940-79	1.2	2.7	1.0	0.8	0.3	0.2	0.1	0.1	0.2	0.1	0.0	-0.2	-0.5
		>1980	1.5	2.8	1.1	0.7	0.3	0.3	0.1	0.1	0.0	0.1	0.0	-0.3	-0.7
Multi-Family with 2 - 4 Units	Masonry or Steel	<1940	2.3	1.7	1.4	1.1	0.8	0.3	0.2	0.0	0.2	0.1	0.0	-0.1	-0.9
		1940-79	3.0	2.6	1.6	1.2	0.9	0.3	0.2	0.0	0.2	0.1	0.0	-0.4	-1.1
		>1980	3.4	3.5	1.6	1.1	0.9	0.4	0.1	0.0	-0.1	0.2	0.0	-0.5	-1.5
	Wood Frame	<1940	2.0	1.5	1.2	1.0	0.7	0.2	0.1	0.0	0.1	0.1	0.0	-0.1	-0.8
		1940-79	3.2	2.6	1.5	1.2	0.9	0.3	0.2	0.0	0.1	0.1	0.0	-0.5	-1.4
		>1980	3.2	3.0	1.5	1.0	0.9	0.3	0.1	0.0	-0.2	0.1	0.0	-0.6	-1.3
Multi-Family with 5+ Units (1–3 stories)	Masonry or Steel	<1940	2.4	2.3	1.3	1.1	0.7	0.3	0.1	0.0	0.1	0.1	0.0	-0.1	-1.1
		1940-79	2.7	3.0	1.3	1.1	0.8	0.4	0.1	0.0	-0.1	0.2	0.0	-0.4	-1.1
		>1980	2.7	3.5	1.3	1.0	0.8	0.4	0.1	0.0	-0.3	0.2	0.0	-0.4	-1.1
	Wood Frame	<1940	2.0	1.9	1.1	0.9	0.6	0.2	0.1	0.0	0.0	0.1	0.0	-0.1	-0.9
		1940-79	2.6	3.0	1.3	1.1	0.7	0.4	0.1	0.0	-0.1	0.1	0.0	-0.4	-1.1
		>1980	2.6	3.3	1.3	1.0	0.7	0.4	0.0	0.0	-0.3	0.2	0.0	-0.4	-1.0
Multi-Family with 5+ Units (4+ stories)	Masonry or Steel	<1940	2.9	2.2	1.2	1.0	0.6	0.3	0.2	0.0	0.0	0.1	0.0	0.0	-1.5
		1940-79	3.5	2.9	1.4	1.1	0.7	0.4	0.1	0.0	-0.3	0.2	0.0	-0.1	-1.9
		>1980	3.2	3.3	1.5	1.0	0.7	0.4	0.0	0.0	-0.6	0.2	0.0	-0.1	-1.6
	Wood Frame	<1940	2.6	1.8	1.1	0.9	0.6	0.2	0.2	0.0	0.0	0.1	0.0	0.0	-1.4
		1940-79	3.2	3.0	1.4	1.2	0.7	0.4	0.1	0.0	-0.1	0.2	0.0	-0.2	-1.6
		>1980	2.5	3.2	1.3	0.9	0.7	0.4	0.0	0.0	-0.5	0.2	0.0	-0.2	-1.0
Average by component			2.4	2.5	1.3	1.0	0.6	0.3	0.1	0.0	0.0	0.1	0.0	-0.2	-1.2

Annual cooling load intensity (kBtu/ft2/yr)

-1.9 3.5

Figure 9. Residential Cold/Very-Cold cooling component loads

3.1.2 Residential Climate Area 2: Mixed-Humid

The Mixed-Humid climate region covers the mid-Atlantic as well as the non-coastal south and south-central United States. Homes in this area represent 30% of the U.S. housing units and residential buildings, and 32% of the residential thermal energy uses. Figure 10 shows the 34 segments in the Mixed-Humid region, with the number of buildings, average building size, average thermal energy use intensity, and annual thermal energy use energy used in each segment.

Similar to the Cold/Very-Cold climate region, single-family detached housing composes the majority of homes both by building and unit counts (at 77% and 60%, respectively). Compared to Cold/Very-Cold, the Mixed-Humid climate region also has a higher proportion of housing units in multifamily 5+ buildings (18% versus 15%), which is primarily because it contains large urban areas like New York City. From a retrofit perspective, larger buildings offer some advantages in that each project has more floor area, is able to reduce more thermal energy use per project, and has fewer stakeholders (e.g., building owners, zoning regulations) to interact with.

Although lower than in the Cold/Very-Cold climate region, energy used for space heating is still significant (71% of thermal energy use), and the majority of heating loads are met with fossil fuels. Additionally, the Mixed-Humid climate region has a more substantial portion of the thermal energy use driven by cooling. Water heating makes up a larger portion of the thermal energy use than in the Cold/Very-Cold climate region, and for post-1980 multifamily buildings water heating loads are approximately on par with heating.

In the Mixed-Humid climate region, there is a strong correlation between vintage and thermal energy use intensity, but the load intensity is relatively similar across all building types, with the exception of mobile homes. This region has a higher proportion of mobile homes than the Cold/Very-Cold climate region at 7% of the housing units, but the thermal energy use intensity of these mobile homes is more similar to single-family detached than in the Cold/Very-Cold climate region. The component load breakdown for Mixed-Humid heating (Figure 11) shows a similar pattern to the Cold/Very-Cold climate region. The majority of the load is driven by infiltration, followed by walls and ceiling. The exception to this is mobile homes, where infiltration is still the majority contributor, but where thermal conduction through floors, walls, and ceiling each contribute in almost equal measure.

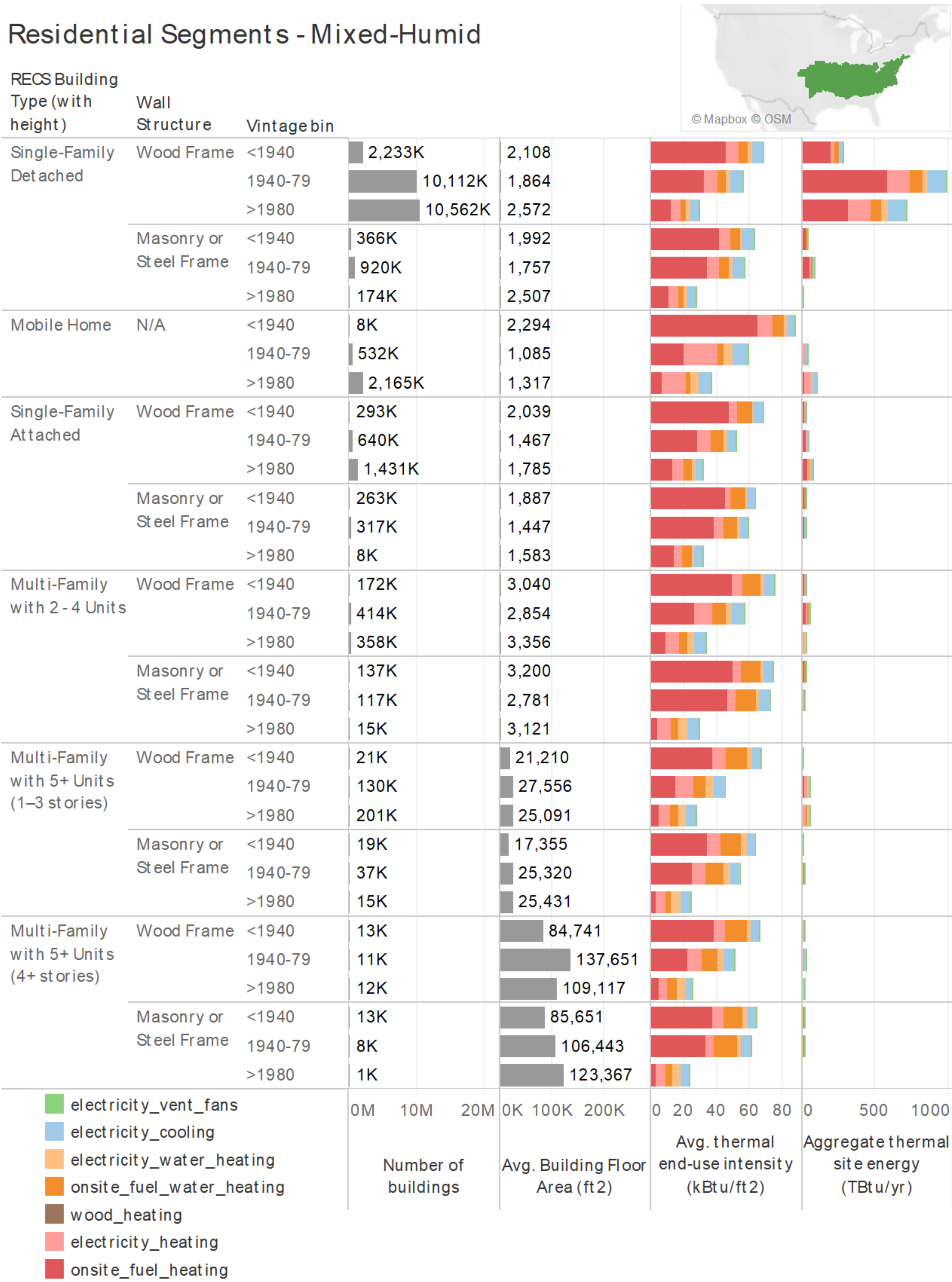

Figure 10. Residential Mixed-Humid typology segments

3.1.2.1 Mixed-Humid: Highest Thermal Energy Use Segments

Single Family: Detached, 1940-1979 Wood Frame. As in the Cold/Very-Cold climate region, this typology segment has the largest contribution to total thermal energy use, and this is driven primarily by heating. This typology segment diverges from its cold-climate counterpart in that a larger portion of the heating demand is met by electricity, and cooling is a more significant contributor to the overall thermal demand; however, fossil fuel space heating still makes up the majority of thermal energy use energy use in this segment. Like in the Cold/Very-Cold climate region, infiltration drives most of the heating loads.
Mixed-Humid Prevalence: 25% of housing units / 32% of residential buildings / 34% of residential thermal energy use.

Multifamily: 5+ Units, Post-1980, Wood Frame, 1–3 stories. For the Mixed-Humid climate region, this segment has the highest total thermal energy use of any multifamily typology segment. Heating is the dominant thermal end use for this segment, but this is a lower thermal end-use intensity segment in space heating, so water heating and cooling are also non-negligible contributors. The component load breakdown indicates that infiltration is the largest driver of heating loads for this segment. Cost- and time-effective upgrades to reduce infiltration are still a substantial research need.
Mixed-Humid Prevalence: 6% of housing units / 1% of residential buildings / 2% of residential thermal energy use.

Annual heating load per square foot of building floor area
Mixed-Humid Climate Zone

RECS Building Type (with height)	Wall Structure	Vintage bin	Thermal load component: infiltration	walls	other	roof / ceiling	floor	equipment	windows - conduction	ground	foundation walls	doors	lighting	people	windows - solar
Single-Family Detached	Masonry or Steel	<1940	17.7	5.4	4.4	3.0	3.8	1.1	2.2	0.4	0.2	0.1	-0.2	-0.4	-3.1
		1940-79	14.0	4.0	3.1	3.2	2.8	3.3	1.8	0.8	0.3	0.1	-0.2	-0.4	-2.6
		>1980	6.6	1.3	1.5	1.4	1.2	2.3	1.2	0.8	0.1	0.0	-0.1	-0.3	-1.7
	Wood Frame	<1940	18.8	7.2	5.3	3.6	3.7	1.3	2.3	0.4	0.2	0.1	-0.2	-0.4	-3.0
		1940-79	15.6	5.6	3.8	3.5	3.1	3.4	2.0	0.8	0.4	0.1	-0.2	-0.4	-2.7
		>1980	7.4	1.8	1.8	1.7	1.4	2.6	1.3	0.8	0.1	0.0	-0.1	-0.3	-1.8
Mobile Home	N/A	<1940	14.7	6.8	7.2	7.2	9.1	-0.2	1.9	0.0	0.0	0.1	-0.2	-0.3	-2.7
		1940-79	11.7	6.1	5.2	5.5	8.1	5.1	2.3	0.0	0.0	0.2	-0.2	-0.5	-3.4
		>1980	6.8	2.6	2.7	2.9	4.6	4.3	1.6	0.0	0.0	0.1	-0.1	-0.4	-2.3
Single-Family Attached	Masonry or Steel	<1940	23.3	3.0	2.6	2.3	2.1	1.0	1.1	0.2	0.1	0.1	-0.2	-0.4	-1.7
		1940-79	22.4	2.7	2.1	2.3	1.7	2.1	1.0	0.5	0.3	0.1	-0.2	-0.5	-1.6
		>1980	11.5	0.8	0.8	1.1	0.6	2.4	0.7	0.6	0.1	0.1	-0.2	-0.3	-1.2
	Wood Frame	<1940	21.5	3.5	3.0	2.6	2.1	0.9	1.0	0.2	0.1	0.1	-0.2	-0.4	-1.6
		1940-79	20.1	2.9	2.0	2.2	1.5	2.5	1.0	0.5	0.3	0.1	-0.2	-0.5	-1.6
		>1980	11.8	1.1	1.0	1.6	0.4	2.4	0.8	0.6	0.1	0.1	-0.2	-0.3	-1.2
Multi-Family with 2 - 4 Units	Masonry or Steel	<1940	22.1	5.6	3.5	3.7	5.0	-1.6	2.9	0.3	0.0	0.1	-0.2	-0.6	-3.4
		1940-79	18.6	5.1	3.0	3.1	4.1	-0.7	2.8	0.6	0.0	0.2	-0.2	-0.6	-3.3
		>1980	7.8	1.4	1.1	1.4	1.6	-0.6	1.5	0.5	0.0	0.1	-0.2	-0.4	-1.7
	Wood Frame	<1940	23.4	7.4	4.1	4.1	5.3	-1.3	3.0	0.3	0.0	0.2	-0.2	-0.7	-3.5
		1940-79	18.0	6.0	3.2	3.2	4.1	-0.5	2.8	0.5	0.0	0.2	-0.2	-0.6	-3.2
		>1980	9.1	2.0	1.4	1.8	2.0	-0.2	1.8	0.5	0.0	0.1	-0.2	-0.4	-2.0
Multi-Family with 5+ Units (1–3 stories)	Masonry or Steel	<1940	25.1	3.4	2.0	2.3	3.3	-1.9	2.2	0.2	0.0	0.1	-0.2	-0.7	-2.5
		1940-79	19.0	2.3	1.5	1.8	2.4	-1.1	1.7	0.4	0.0	0.0	-0.2	-0.6	-2.0
		>1980	8.9	0.8	0.7	1.1	1.2	-0.8	1.2	0.3	0.0	0.0	-0.1	-0.4	-1.2
	Wood Frame	<1940	25.2	4.4	2.5	2.6	3.7	-2.3	2.3	0.1	0.0	0.1	-0.2	-0.7	-2.6
		1940-79	14.4	2.7	1.5	1.8	2.3	-0.8	1.7	0.3	0.0	0.0	-0.2	-0.5	-1.9
		>1980	8.5	1.0	0.8	1.1	1.2	-0.5	1.1	0.3	0.0	0.0	-0.1	-0.4	-1.2
Multi-Family with 5+ Units (4+ stories)	Masonry or Steel	<1940	25.6	2.9	1.7	1.6	3.4	-2.8	2.9	0.1	0.0	0.0	-0.2	-0.6	-2.9
		1940-79	23.1	2.2	1.2	1.2	2.7	-2.4	2.6	0.1	0.0	0.0	-0.2	-0.6	-2.5
		>1980	9.5	0.6	0.4	0.5	1.2	-1.2	1.3	0.1	0.0	0.0	-0.1	-0.3	-1.2
	Wood Frame	<1940	24.7	3.6	1.9	1.8	3.4	-2.2	2.7	0.1	0.0	0.1	-0.2	-0.7	-2.7
		1940-79	19.2	2.7	1.5	1.5	2.6	-2.1	2.3	0.2	0.0	0.0	-0.2	-0.6	-2.2
		>1980	8.8	0.6	0.4	0.6	0.9	-1.3	0.9	0.1	0.0	0.0	-0.1	-0.3	-1.0
Average by component			16.2	3.3	2.4	2.4	2.9	0.3	1.8	0.4	0.1	0.1	-0.2	-0.5	-2.2

Annual heating load intensity (kBtu/ft2/yr)

-3.5 25.6

1. The wall, floor, ceiling, window, and foundation wall conduction categories only include conduction through those components; all air envelope leakage is accounted for in the infiltration category.
2. "Other" includes time-lagged heat transfer with internal partition wall and furniture mass.
3. "Equipment" includes duct losses (leakage and conduction) as positive contributions to heating load, as well as heat gain from major appliances, water heaters, hot water pipes, and hot water draws as negative contributions to heating load.

Figure 11. Residential Mixed-Humid heating component loads

Annual cooling load per square foot of building floor area
Mixed-Humid Climate Zone

RECS Building Type (with height)	Wall Structure	Vintage bin	equipment	windows - solar	other	walls	roof / ceiling	infiltration	people	windows - conduction	lighting	foundation walls	doors	ground	floor
			Thermal load component												
Single-Family Detached	Masonry or Steel	<1940	2.9	4.0	3.7	2.6	1.2	0.9	0.3	0.4	0.1	0.2	0.0	-0.4	-2.0
		1940-79	5.0	4.1	3.1	2.3	1.4	0.9	0.4	0.4	0.1	0.2	0.0	-0.9	-1.5
		>1980	4.3	3.9	2.6	1.4	1.0	0.4	0.3	0.3	0.2	0.1	0.0	-1.3	-1.2
	Wood Frame	<1940	3.0	4.0	3.7	2.8	1.2	1.0	0.3	0.4	0.1	0.1	0.0	-0.4	-2.0
		1940-79	4.7	4.0	3.1	2.5	1.5	1.0	0.3	0.4	0.1	0.2	0.0	-0.8	-1.6
		>1980	4.1	3.6	2.5	1.4	1.0	0.4	0.3	0.3	0.2	0.1	0.0	-1.1	-1.3
Mobile Home	N/A	<1940	1.8	1.4	1.3	0.9	0.8	0.4	0.1	0.1	0.0	0.0	0.0	0.0	-0.2
		1940-79	6.8	5.5	3.8	3.2	2.3	1.0	0.5	0.5	0.2	0.0	0.1	0.0	-2.3
		>1980	6.8	5.1	3.1	2.0	1.7	0.5	0.5	0.4	0.2	0.0	0.0	0.0	-2.6
Single-Family Attached	Masonry or Steel	<1940	2.5	1.7	2.2	1.6	0.6	1.0	0.3	0.1	0.1	0.0	0.0	-0.1	-0.7
		1940-79	4.1	1.8	1.9	1.5	1.0	1.0	0.4	0.1	0.2	0.1	0.0	-0.3	-0.9
		>1980	4.1	2.0	1.7	1.1	0.6	0.3	0.3	0.1	0.2	0.1	0.0	-0.6	-0.8
	Wood Frame	<1940	2.5	1.7	2.4	1.8	0.8	1.1	0.3	0.2	0.1	0.1	0.0	-0.1	-0.6
		1940-79	4.6	2.1	2.1	1.8	0.8	1.1	0.4	0.2	0.2	0.1	0.0	-0.5	-0.7
		>1980	4.4	2.1	1.9	1.2	0.8	0.5	0.4	0.1	0.2	0.1	0.0	-0.6	-0.9
Multi-Family with 2 - 4 Units	Masonry or Steel	<1940	2.2	3.1	2.2	1.7	1.2	0.7	0.4	0.3	0.1	0.0	0.0	-0.2	-0.9
		1940-79	4.2	4.5	2.8	2.3	1.6	0.8	0.5	0.4	0.2	0.0	0.0	-0.6	-1.5
		>1980	4.8	4.6	2.7	1.9	1.6	0.3	0.5	0.3	0.2	0.0	0.0	-0.9	-1.4
	Wood Frame	<1940	2.3	3.3	2.3	1.9	1.3	0.8	0.4	0.3	0.1	0.0	0.0	-0.2	-0.9
		1940-79	4.1	4.5	2.7	2.4	1.5	0.8	0.5	0.4	0.2	0.0	0.0	-0.6	-1.6
		>1980	4.3	4.3	2.4	1.7	1.4	0.3	0.5	0.3	0.2	0.0	0.0	-0.8	-1.4
Multi-Family with 5+ Units (1-3 stories)	Masonry or Steel	<1940	2.9	2.7	1.8	1.6	1.0	0.5	0.5	0.2	0.1	0.0	0.0	-0.2	-0.8
		1940-79	4.1	3.1	2.0	1.7	1.1	0.5	0.5	0.2	0.2	0.0	0.0	-0.4	-1.0
		>1980	4.6	3.6	2.2	1.6	1.3	0.0	0.6	0.2	0.3	0.0	0.0	-0.7	-1.0
	Wood Frame	<1940	2.7	2.7	1.8	1.6	1.0	0.6	0.4	0.2	0.1	0.0	0.0	-0.1	-0.9
		1940-79	4.8	4.2	2.5	2.3	1.4	0.7	0.6	0.3	0.2	0.0	0.0	-0.6	-1.4
		>1980	4.8	3.5	2.2	1.6	1.3	0.1	0.6	0.2	0.3	0.0	0.0	-0.6	-1.0
Multi-Family with 5+ Units (4+ stories)	Masonry or Steel	<1940	2.8	3.6	1.8	1.4	0.9	0.4	0.4	0.2	0.2	0.0	0.0	-0.1	-1.8
		1940-79	3.7	4.4	2.1	1.6	1.0	0.4	0.5	0.3	0.2	0.0	0.0	-0.1	-2.1
		>1980	4.5	4.2	2.3	1.6	1.1	-0.3	0.7	0.2	0.3	0.0	0.0	-0.3	-1.7
	Wood Frame	<1940	2.9	3.5	1.8	1.5	0.9	0.5	0.5	0.3	0.2	0.0	0.0	-0.1	-1.5
		1940-79	4.3	4.7	2.4	2.1	1.3	0.6	0.6	0.3	0.2	0.0	0.0	-0.2	-2.0
		>1980	4.5	3.4	2.1	1.6	1.1	-0.3	0.7	0.2	0.3	0.0	0.0	-0.3	-1.2
Average by component			3.9	3.5	2.4	1.8	1.2	0.6	0.4	0.3	0.2	0.0	0.0	-0.4	-1.3

Annual cooling load intensity (kBtu/ft2/yr)

-2.6 6.8

Figure 12. Residential Mixed-Humid cooling component loads

3.1.3 Residential Climate Area 3: Marine

The Marine climate region covers the California coast starting north of Los Angeles, and up through Oregon and Washington west of the Cascades. Homes in this area represent 5% of U.S. housing units and residential buildings and 3% of the residential thermal energy use. Figure 13 shows the 34 segments in the Marine region, with the number of buildings, average building size, average thermal energy use intensity, and annual thermal energy used in each segment.

Loads in the Marine climate region differ substantially from the Cold/Very-Cold and Mixed-Humid regions. Thermal energy use intensity is much lower in this region, and water heating is a much more substantial contributor to total thermal energy use (both due to the comparably milder climate). This is especially true across multifamily typology segments where water heating is generally the dominant thermal end use. The Marine climate region also has a much higher proportion of electric heating than previously discussed regions, especially in mobile homes and large (5+ unit) multifamily homes. Cooling loads in the Marine climate region are lower than in any other area of the country; this is because of the mild, coastal climate where relatively few housing units (~33%) have cooling systems.

Across typology segments in the Marine climate region, there is less sensitivity to vintage in comparison to other climate regions, partially due to the lower space-conditioning loads, but the typical trend of older vintages having higher thermal energy use intensity holds true. This indicates that if solutions for the Marine climate region are more dependent upon equipment rather than envelope modifications, they could likely be applied widely, irrespective of vintage. Exceptions to this include wood-framed single-family detached homes and mobile homes, both of which make significant heating contributions to the thermal energy use intensity with a strong vintage dependency.

The Marine climate region has the lowest percentage of single-family detached homes nationally at just 59% of housing units and the highest percentage of multifamily 5+ unit homes at 22%, a non-negligible portion of which (7% of Marine housing units) are in buildings 4+ stories tall. This higher percentage of large multifamily buildings could present an opportunity to deploy large-building retrofits in this region. Mobile homes compose just 5% of the housing units but have the highest heating load intensity of all building types of comparable vintage.

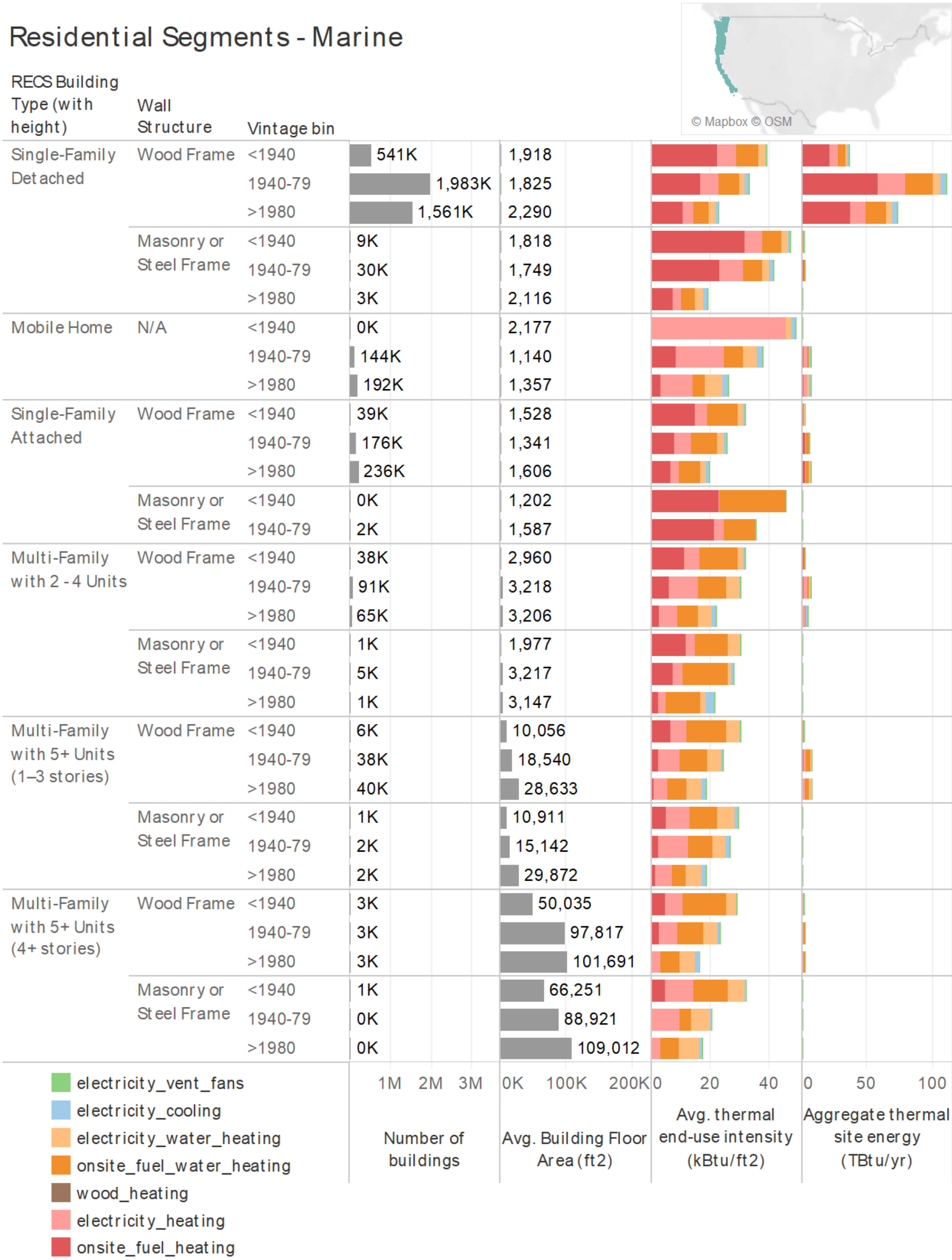

Figure 13. Residential Marine typology segments

3.1.3.1 Marine: Highest Thermal Energy Use Segments

Single-Family: Detached, 1940–1979, Wood Frame. Similar to the Cold/Very-Cold and Mixed-Humid climate regions, midcentury detached wood homes are the typology segment with the largest overall thermal energy use. Loads are once again driven primarily by heating, the majority of which comes from fossil fuels. Infiltration and walls are the main component loads contributors. Cooling is not a significant contributor to thermal energy use.
Marine Prevalence: 28% of housing units / 38% of residential buildings / 39% of residential thermal end-use energy.

Multifamily: Post-1980, 5+ Units, Wood-Framed, 1–3 Stories. In this segment, space conditioning is not the dominant thermal end use; instead, water heating makes up more than half of the thermal energy use, with a significant portion from electric equipment. This suggests that significant thermal energy savings could be obtained through upgrading water heating equipment; of buildings with electric water heating, more than 95% are currently using electric resistance technologies. Water heating retrofits for this segment could likely be applied more broadly across many different types of multifamily buildings because these retrofit solutions are independent of envelope.
Marine Prevalence: 7% of housing units / 1% of residential buildings / 3% of residential thermal end-use energy.

Annual heating load per square foot of building floor area
Marine Climate Zone

RECS Building Type (with height)	Wall Structure	Vintage bin	infiltration	walls	other	floor	roof / ceiling	equipment	windows - conduction	ground	foundation walls	doors	lighting	people	windows - solar
Single-Family Detached	Masonry or Steel	<1940	13.5	5.2	4.7	3.5	2.8	2.4	1.8	0.5	0.3	0.1	-0.2	-0.5	-2.8
		1940-79	9.3	3.7	3.1	2.7	3.0	2.6	1.3	0.7	0.2	0.1	-0.2	-0.5	-2.2
		>1980	6.3	1.5	1.4	1.9	1.3	1.8	1.2	0.4	0.0	0.1	-0.1	-0.3	-1.8
	Wood Frame	<1940	9.4	4.5	3.4	2.7	2.4	2.0	1.5	0.4	0.2	0.1	-0.1	-0.4	-2.2
		1940-79	7.1	3.6	2.6	2.3	2.5	1.6	1.2	0.6	0.1	0.1	-0.1	-0.4	-1.8
		>1980	4.7	1.5	1.6	1.6	1.4	2.0	1.0	0.4	0.0	0.0	-0.1	-0.3	-1.4
Mobile Home	N/A	<1940	8.3	8.8	10.2	11.1	11.0	-2.3	2.1	0.0	0.0	0.1	-0.2	-0.3	-2.5
		1940-79	6.7	4.6	4.0	6.3	4.3	0.7	1.6	0.0	0.0	0.1	-0.1	-0.6	-2.6
		>1980	4.7	2.2	2.5	4.0	2.6	1.7	1.3	0.0	0.0	0.1	-0.1	-0.4	-1.9
Single-Family Attached	Masonry or Steel	<1940	2.8	0.6	0.3	0.1	0.4	-0.1	0.2	0.3	0.1	0.0	-0.1	-0.2	-0.4
		1940-79	6.5	1.1	1.1	1.1	1.3	0.3	0.5	0.3	0.0	0.0	-0.2	-0.3	-1.0
		>1980	7.7	0.8	0.8	0.7	1.5	1.0	0.7	1.1	0.0	0.0	-0.1	-0.3	-1.7
	Wood Frame	<1940	8.7	1.8	1.4	1.3	1.2	0.6	0.6	0.2	0.0	0.0	-0.1	-0.4	-1.2
		1940-79	6.8	1.7	1.3	1.2	1.5	0.8	0.5	0.4	0.0	0.1	-0.1	-0.4	-1.0
		>1980	4.5	0.7	0.7	0.6	0.7	0.9	0.4	0.3	0.0	0.0	-0.1	-0.3	-0.7
Multi-Family with 2 - 4 Units	Masonry or Steel	<1940	6.9	3.4	2.0	2.5	1.9	-0.7	1.6	0.9	0.0	0.1	-0.2	-0.4	-2.6
		1940-79	3.4	1.6	0.9	1.2	1.0	-1.1	0.9	0.5	0.0	0.0	-0.1	-0.4	-1.3
		>1980	2.1	0.5	0.4	0.5	0.6	-0.7	0.7	0.5	0.0	0.0	-0.1	-0.2	-0.8
	Wood Frame	<1940	6.4	2.9	1.5	2.4	1.6	-0.9	1.2	0.1	0.0	0.1	-0.1	-0.5	-1.8
		1940-79	6.1	3.1	1.9	2.5	1.9	-1.2	1.5	0.3	0.0	0.1	-0.1	-0.5	-1.8
		>1980	4.5	1.3	1.1	1.5	1.3	-0.4	1.1	0.3	0.0	0.1	-0.1	-0.4	-1.2
Multi-Family with 5+ Units (1–3 stories)	Masonry or Steel	<1940	6.5	1.8	0.9	1.4	0.9	-1.7	0.9	0.1	0.0	0.0	-0.1	-0.4	-1.1
		1940-79	6.7	2.0	1.3	1.8	1.4	-1.0	1.0	0.2	0.0	0.0	-0.1	-0.4	-1.2
		>1980	5.3	0.9	0.8	1.2	1.1	-1.0	0.8	0.2	0.0	0.0	-0.1	-0.3	-0.9
	Wood Frame	<1940	5.5	1.6	0.8	1.4	0.9	-1.6	0.9	0.2	0.0	0.0	-0.1	-0.4	-1.2
		1940-79	5.5	1.7	1.1	1.5	1.2	-1.1	1.0	0.2	0.0	0.0	-0.1	-0.4	-1.1
		>1980	3.7	0.7	0.6	0.8	0.7	-0.7	0.6	0.1	0.0	0.0	-0.1	-0.3	-0.7
Multi-Family with 5+ Units (4+ stories)	Masonry or Steel	<1940	7.4	1.8	1.0	2.1	0.9	-2.0	1.9	0.2	0.0	0.0	-0.1	-0.4	-1.9
		1940-79	6.1	1.2	0.6	1.4	0.6	-1.4	1.4	0.0	0.0	0.0	-0.1	-0.4	-1.2
		>1980	3.2	0.3	0.3	0.6	0.3	-0.8	0.7	0.0	0.0	0.0	-0.1	-0.2	-0.6
	Wood Frame	<1940	6.7	1.9	0.9	1.8	0.8	-1.8	1.4	0.0	0.0	0.0	-0.1	-0.4	-1.5
		1940-79	5.6	1.4	0.9	1.5	0.8	-1.3	1.1	0.1	0.0	0.0	-0.1	-0.3	-1.1
		>1980	2.4	0.3	0.2	0.4	0.3	-0.6	0.4	0.0	0.0	0.0	0.0	-0.2	-0.3
Average by component			6.1	2.1	1.7	2.1	1.7	-0.1	1.1	0.3	0.0	0.0	-0.1	-0.4	-1.4

Annual heating load intensity (kBtu/ft2/yr)
-2.8 … 13.5

1. The wall, floor, ceiling, window, and foundation wall conduction categories only include conduction through those components; all air envelope leakage is accounted for in the infiltration category.
2. “Other” includes time-lagged heat transfer with internal partition wall and furniture mass.
3. “Equipment” includes duct losses (leakage and conduction) as positive contributions to heating load, as well as heat gain from major appliances, water heaters, hot water pipes, and hot water draws as negative contributions to heating load.

Figure 14. Residential Marine heating component loads

Annual cooling load per square foot of building floor area
Marine Climate Zone

RECS Building Type (with height)	Wall Structure	Vintage bin	windows - solar	equipment	other	walls	roof / ceiling	people	lighting	windows - conduction	doors	foundation walls	infiltration	ground	floor
			Thermal load component												
Single-Family Detached	Masonry or Steel	<1940	0.3	0.2	0.3	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
		1940-79	1.3	1.0	0.6	0.4	0.3	0.1	0.0	0.0	0.0	0.0	-0.2	-0.3	-0.7
		>1980	0.9	0.9	0.4	0.3	0.2	0.1	0.0	0.0	0.0	0.0	-0.2	-0.2	-0.4
	Wood Frame	<1940	1.0	0.5	0.5	0.4	0.2	0.1	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.6
		1940-79	1.4	1.1	0.6	0.6	0.3	0.1	0.0	0.0	0.0	0.0	-0.1	-0.4	-0.7
		>1980	1.4	1.0	0.6	0.4	0.3	0.1	0.0	0.0	0.0	0.0	-0.2	-0.4	-0.8
Mobile Home	N/A	<1940	0.1	0.1	0.2	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		1940-79	2.5	1.7	0.9	0.9	0.6	0.2	0.1	0.1	0.0	0.0	-0.2	0.0	-1.9
		>1980	2.3	2.0	0.9	0.6	0.5	0.2	0.1	0.0	0.0	0.0	-0.3	0.0	-1.7
Single-Family Attached	Masonry or Steel	<1940	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		1940-79	0.6	0.5	0.2	0.2	0.2	0.1	0.0	0.0	0.0	0.0	0.0	-0.1	-0.4
		>1980	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Wood Frame	<1940	0.6	0.5	0.4	0.3	0.1	0.1	0.0	0.0	0.0	0.0	-0.2	0.0	-0.5
		1940-79	0.8	1.1	0.4	0.4	0.2	0.1	0.0	0.0	0.0	0.0	-0.2	-0.3	-0.4
		>1980	1.0	1.4	0.6	0.4	0.2	0.2	0.1	0.0	0.0	0.0	-0.3	-0.5	-0.4
Multi-Family with 2 - 4 Units	Masonry or Steel	<1940	0.8	0.4	0.2	0.2	0.1	0.0	0.0	0.0	0.0	0.0	-0.2	0.0	-0.7
		1940-79	0.9	0.6	0.3	0.2	0.2	0.1	0.0	0.0	0.0	0.0	-0.2	-0.4	-0.3
		>1980	2.7	1.6	0.8	0.4	0.5	0.2	0.1	-0.1	0.0	0.0	-0.5	-1.4	-0.6
	Wood Frame	<1940	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
		1940-79	0.8	0.5	0.3	0.3	0.2	0.1	0.0	0.0	0.0	0.0	-0.2	-0.2	-0.4
		>1980	1.8	1.6	0.6	0.4	0.4	0.2	0.1	-0.1	0.0	0.0	-0.4	-0.4	-0.8
Multi-Family with 5+ Units (1-3 stories)	Masonry or Steel	<1940	0.4	0.5	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	-0.2	0.0	-0.2
		1940-79	0.5	0.6	0.2	0.2	0.1	0.1	0.0	0.0	0.0	0.0	-0.2	0.0	-0.3
		>1980	1.2	1.6	0.5	0.3	0.2	0.2	0.1	-0.1	0.0	0.0	-0.5	-0.2	-0.6
	Wood Frame	<1940	0.2	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
		1940-79	0.9	0.9	0.3	0.3	0.2	0.1	0.0	0.0	0.0	0.0	-0.3	-0.2	-0.5
		>1980	1.6	2.0	0.7	0.5	0.4	0.3	0.1	-0.1	0.0	0.0	-0.7	-0.3	-0.7
Multi-Family with 5+ Units (4+ stories)	Masonry or Steel	<1940	0.9	0.7	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	-0.2	-0.1	-0.6
		1940-79	1.5	0.9	0.4	0.3	0.2	0.1	0.0	0.0	0.0	0.0	-0.4	0.0	-0.9
		>1980	2.1	1.9	0.8	0.6	0.4	0.3	0.1	-0.1	0.0	0.0	-0.8	-0.1	-1.1
	Wood Frame	<1940	0.3	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	-0.2
		1940-79	1.0	0.6	0.3	0.2	0.2	0.1	0.0	0.0	0.0	0.0	-0.2	-0.1	-0.6
		>1980	1.5	1.8	0.7	0.5	0.4	0.3	0.1	0.0	0.0	0.0	-0.8	-0.1	-0.6
Average by component			1.0	0.9	0.4	0.3	0.2	0.1	0.0	0.0	0.0	0.0	-0.2	-0.2	-0.5

Annual cooling load intensity (kBtu/ft2/yr)

-1.9 2.7

Figure 15. Residential Marine cooling component loads

3.1.4 Residential Climate Area 4: Hot-Dry/Mixed-Dry

The Hot-Dry/Mixed-Dry climate region covers southern California, the California Central Valley, southern Nevada, southern Arizona, southern New Mexico, and west Texas. Homes in this area represent 12% of U.S. housing units and residential buildings, and 6% of the residential thermal end-use energy. Figure 16 shows the 33 segments in the Hot-Dry/Mixed-Dry region, with the number of buildings, average building size, average thermal end-use intensity, and annual thermal end-use energy used in each segment.

As in other climate regions, the majority of housing units in the Hot-Dry/Mixed-Dry climate region are single-family detached houses, composing 62% of the housing units. This climate region is notable in that the housing stock is newer than any other region, with few homes (~6%) built before 1940. Furthermore, with a few exceptions, thermal energy use intensity does not vary much across building or wall types, generally only fluctuating with vintage, although the end-use drivers within that total does vary by building type. In single-family building types, heating end-use energy is substantial, whereas for many multifamily typology segments, both water heating and space cooling contribute more significantly to the thermal energy use intensity compared to space heating. The component load breakdown indicates that floors drive most of the load in mobile homes (followed closely by ceiling, walls, and infiltration), indicating an area of significant potential improvement. Across building types, fossil fuels are used to meet the majority of space and water heating loads.

In the Hot-Dry/Mixed-Dry climate region, the multifamily 5+ units, 1–3 stories, masonry segment contributes a larger portion of the region's total thermal energy use than in other areas. Partly this is due to the higher proportion of housing units in multifamily 5+ buildings more broadly (20% of the housing units), and partly this is due to the relative parity in thermal end-use intensity with the single-family segments.

The Hot-Dry/Mixed-Dry climate region might benefit from additional subsegmentation. Two-thirds of the housing units in this region are in California, which uses its own building energy code (Title 24) that is distinct from the IECC-based energy codes used in other states. Furthermore, there are areas of this region that experience extreme heat, and the relative importance of reducing cooling loads in these homes might be less apparent when they are aggregated with homes in more temperate areas.

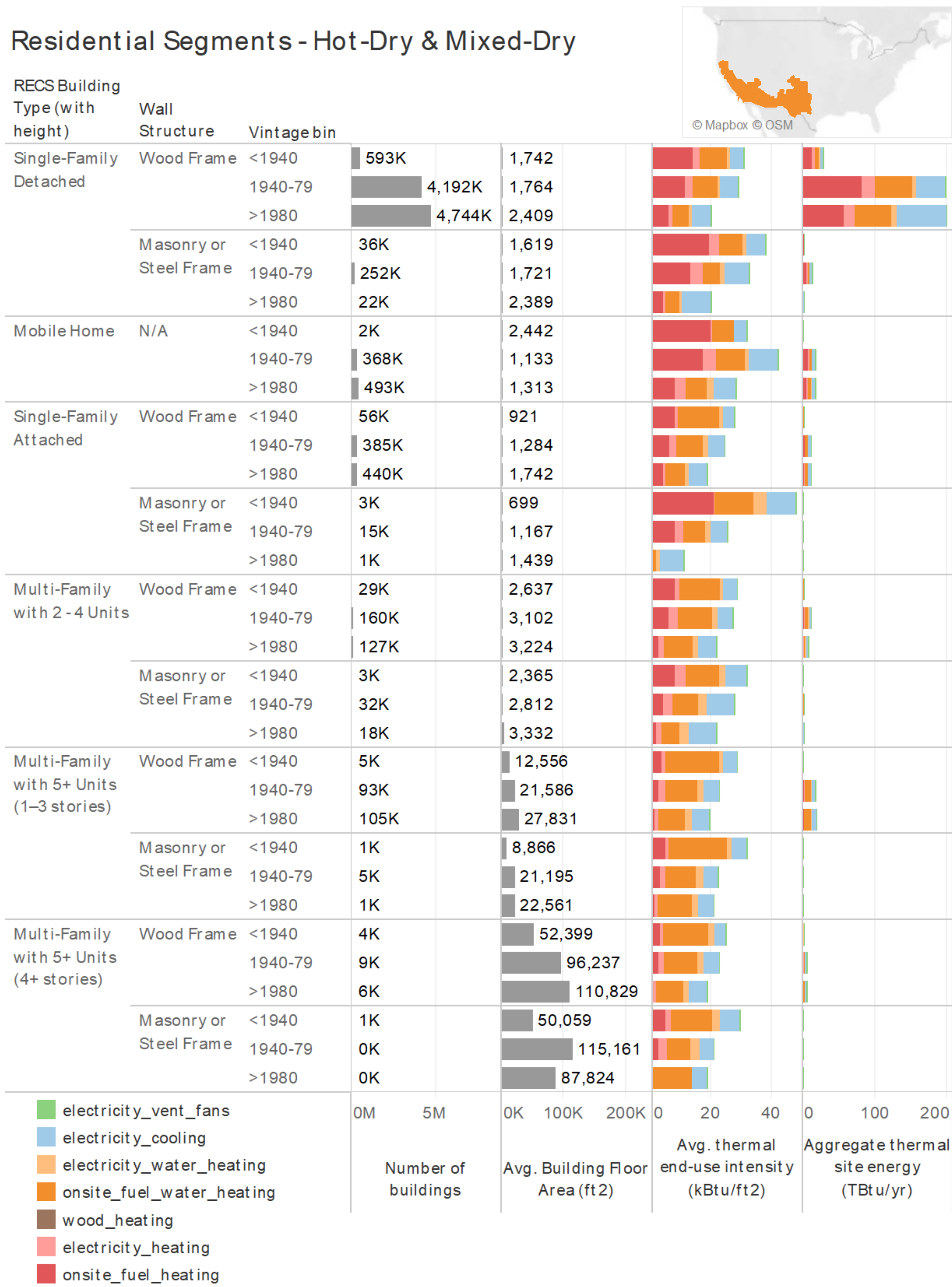

Figure 16. Residential Hot-Dry/Mixed-Dry typology segments

3.1.4.1 Hot-Dry/Mixed-Dry: Highest Thermal Energy Use Segments

Single-Family: Detached, Post-1980, Wood Frame. Unlike all previously discussed regions, the segment with the highest thermal end-use energy for single-family homes is from the post-1980 construction era, which like all other climate regions has wood frame construction. This segment's thermal energy use is about a third space heating, most of which is from fossil fuel sources. This segment also has a significant amount of cooling energy use. From the component loads, infiltration and wall losses are the main contributors to heating and cooling loads.
Hot-Dry/Mixed-Dry Prevalence: 30% of housing units / 39% of residential buildings / 35% of residential thermal end-use energy.

Multifamily: Post-1980, 5+ Units, Wood Frame, 1–3 Stories. This typology segment has the largest thermal energy use of all multifamily building segments but is virtually tied with the same category one vintage period earlier (1940–1979, 5+ units, wood frame, 1–3). This segment is driven almost entirely by water heating, with some amount of cooling and minimal heating. Water heating in this segment is mostly from on-site fossil fuels, but the heating systems in this building type are predominately electric.
Hot-Dry/Mixed-Dry Prevalence: 8% of housing units / 1% of residential buildings / 3% of residential thermal energy use.

Annual heating load per square foot of building floor area
Hot-Dry & Mixed-Dry Climate Zone

Thermal load component

RECS Building Type (with height)	Wall Structure	Vintage bin	infiltration	walls	roof / ceiling	floor	other	equipment	windows - conduction	ground	doors	foundation walls	lighting	people	windows - solar
Single-Family Detached	Masonry or Steel	<1940	7.0	2.9	2.4	2.5	2.5	1.1	1.4	0.6	0.0	0.0	-0.1	-0.3	-2.6
		1940-79	5.9	2.3	2.0	1.5	1.6	1.5	1.3	1.1	0.0	0.0	-0.1	-0.3	-2.2
		>1980	3.1	0.8	0.9	0.6	0.8	1.2	0.9	1.0	0.0	0.0	-0.1	-0.2	-1.4
	Wood Frame	<1940	4.3	2.7	1.5	2.0	1.8	0.9	1.0	0.3	0.0	0.0	-0.1	-0.4	-1.6
		1940-79	3.9	2.3	1.7	1.1	1.4	1.2	0.9	0.7	0.0	0.0	-0.1	-0.3	-1.4
		>1980	2.0	0.6	0.5	0.6	0.6	1.0	0.7	0.6	0.0	0.0	-0.1	-0.2	-1.0
Mobile Home	N/A	<1940	4.4	2.8	4.2	4.6	3.3	3.0	0.8	0.0	0.0	0.0	-0.2	-0.3	-1.8
		1940-79	4.1	3.3	3.3	4.7	2.7	1.8	1.3	0.0	0.1	0.0	-0.1	-0.4	-2.3
		>1980	2.6	1.3	1.5	2.6	1.3	1.5	0.9	0.0	0.0	0.0	-0.1	-0.2	-1.5
Single-Family Attached	Masonry or Steel	<1940	6.6	2.1	3.5	1.0	1.7	-0.5	0.7	0.7	0.1	0.0	-0.1	-0.4	-1.5
		1940-79	6.6	1.0	1.2	0.4	0.6	0.4	0.7	0.8	0.1	0.0	-0.1	-0.3	-1.2
		>1980	4.0	0.4	0.4	0.3	0.4	0.3	0.6	0.5	0.0	0.0	-0.1	-0.2	-0.8
	Wood Frame	<1940	4.5	1.4	1.0	0.9	0.8	0.4	0.4	0.1	0.0	0.0	-0.1	-0.4	-0.8
		1940-79	3.7	1.0	1.0	0.4	0.6	0.7	0.4	0.4	0.0	0.0	-0.1	-0.3	-0.7
		>1980	2.2	0.3	0.4	0.1	0.3	0.7	0.3	0.4	0.0	0.0	0.0	-0.2	-0.5
Multi-Family with 2 - 4 Units	Masonry or Steel	<1940	5.1	1.8	1.1	2.2	1.0	-0.9	1.4	0.3	0.1	0.0	-0.1	-0.3	-2.1
		1940-79	3.4	1.6	0.9	1.1	0.8	-0.7	1.0	0.4	0.0	0.0	-0.1	-0.3	-1.3
		>1980	2.0	0.4	0.4	0.6	0.3	-0.5	0.7	0.4	0.0	0.0	-0.1	-0.2	-0.8
	Wood Frame	<1940	3.2	1.8	1.0	1.4	0.8	-0.8	0.8	0.1	0.0	0.0	-0.1	-0.5	-1.1
		1940-79	3.4	1.9	1.0	1.2	0.9	-0.9	1.0	0.3	0.1	0.0	-0.1	-0.4	-1.2
		>1980	2.4	0.7	0.7	0.7	0.5	-0.8	0.7	0.4	0.0	0.0	-0.1	-0.3	-0.9
Multi-Family with 5+ Units (1–3 stories)	Masonry or Steel	<1940	2.3	0.6	0.4	0.8	0.4	-0.8	0.4	0.1	0.0	0.0	-0.1	-0.2	-0.7
		1940-79	4.1	0.8	0.6	0.9	0.4	-0.4	0.7	0.3	0.0	0.0	-0.1	-0.2	-0.9
		>1980	3.1	0.4	0.5	0.5	0.3	-0.6	0.7	0.3	0.0	0.0	-0.1	-0.2	-0.7
	Wood Frame	<1940	2.2	0.9	0.4	0.8	0.4	-0.7	0.5	0.1	0.0	0.0	-0.1	-0.3	-0.6
		1940-79	2.3	0.7	0.5	0.6	0.3	-0.6	0.5	0.1	0.0	0.0	0.0	-0.2	-0.6
		>1980	1.6	0.3	0.3	0.3	0.2	-0.5	0.4	0.2	0.0	0.0	0.0	-0.2	-0.4
Multi-Family with 5+ Units (4+ stories)	Masonry or Steel	<1940	2.6	0.5	0.2	0.7	0.2	-0.7	0.5	0.0	0.0	0.0	0.0	-0.2	-0.7
		1940-79	2.7	0.5	0.3	0.8	0.3	-0.8	0.7	0.0	0.0	0.0	0.0	-0.2	-0.7
		>1980	1.5	0.2	0.2	0.4	0.1	-0.5	0.4	0.0	0.0	0.0	0.0	-0.1	-0.4
	Wood Frame	<1940	2.2	0.8	0.3	0.9	0.4	-0.6	0.6	0.0	0.0	0.0	0.0	-0.3	-0.7
		1940-79	2.6	0.7	0.4	0.7	0.3	-0.8	0.6	0.1	0.0	0.0	0.0	-0.2	-0.6
		>1980	1.2	0.1	0.2	0.2	0.1	-0.4	0.2	0.0	0.0	0.0	0.0	-0.1	-0.2
Average by component			3.4	1.2	1.1	1.2	0.9	0.1	0.7	0.3	0.0	0.0	-0.1	-0.3	-1.1

Annual heating load intensity (kBtu/ft2/yr)

-2.6 — 7.0

1. The wall, floor, ceiling, window, and foundation wall conduction categories only include conduction through those components; all air envelope leakage is accounted for in the infiltration category.
2. "Other" includes time-lagged heat transfer with internal partition wall and furniture mass.
3. "Equipment" includes duct losses (leakage and conduction) as positive contributions to heating load, as well as heat gain from major appliances, water heaters, hot water pipes, and hot water draws as negative contributions to heating load.

Figure 17. Residential Hot-Dry/Mixed-Dry heating component loads

Annual cooling load per square foot of building floor area
Hot-Dry & Mixed-Dry Climate Zone

RECS Building Type (with height)	Wall Structure	Vintage bin	windows - solar	equipment	other	walls	roof / ceiling	infiltration	people	windows - conduction	lighting	doors	foundation walls	floor	ground
			Thermal load component												
Single-Family Detached	Masonry or Steel	<1940	4.4	3.7	3.5	2.6	1.5	0.8	0.3	0.4	0.1	0.0	0.0	-1.4	-1.3
		1940-79	5.2	5.1	3.5	2.8	1.8	1.2	0.4	0.4	0.1	0.0	0.0	-0.9	-2.3
		>1980	5.2	5.1	3.1	1.8	1.3	0.6	0.4	0.4	0.2	0.0	0.0	-0.7	-2.6
	Wood Frame	<1940	4.3	2.9	2.9	2.5	1.1	-0.1	0.3	0.2	0.1	0.0	0.0	-2.3	-0.8
		1940-79	4.9	4.4	2.9	2.9	1.5	0.3	0.3	0.2	0.1	0.0	0.0	-1.2	-2.2
		>1980	5.6	4.9	3.4	2.2	1.3	0.7	0.4	0.4	0.1	0.0	0.0	-1.0	-2.6
Mobile Home	N/A	<1940	2.7	2.8	1.7	1.5	1.5	-0.5	0.1	0.0	0.1	0.0	0.0	-1.8	0.0
		1940-79	6.1	6.0	4.1	3.6	2.7	1.0	0.3	0.5	0.1	0.1	0.0	-2.4	0.0
		>1980	5.1	5.9	3.2	2.2	1.8	0.7	0.4	0.4	0.1	0.0	0.0	-2.3	0.0
Single-Family Attached	Masonry or Steel	<1940	2.3	3.5	2.6	2.4	1.6	1.4	0.3	0.2	0.1	0.0	0.0	-0.3	-1.3
		1940-79	3.4	5.3	2.6	2.3	1.1	1.8	0.4	0.3	0.2	0.0	0.0	-0.5	-1.9
		>1980	4.5	7.1	2.9	2.1	0.9	0.7	0.5	0.2	0.2	0.0	0.0	-0.5	-2.9
	Wood Frame	<1940	3.1	4.6	2.4	2.4	0.8	-0.8	0.5	0.0	0.1	0.0	0.0	-2.1	-0.4
		1940-79	3.3	5.2	2.4	2.3	1.1	0.3	0.5	0.1	0.2	0.0	0.0	-0.6	-1.9
		>1980	3.4	5.4	2.4	1.6	0.8	0.3	0.5	0.1	0.2	0.0	0.0	-0.4	-2.2
Multi-Family with 2 - 4 Units	Masonry or Steel	<1940	7.6	4.4	3.9	3.8	2.2	1.6	0.5	0.7	0.2	0.1	0.0	-3.0	-0.8
		1940-79	6.5	3.9	3.4	3.3	2.0	1.0	0.6	0.5	0.2	0.1	0.0	-1.4	-2.0
		>1980	7.9	5.3	4.1	3.2	2.3	1.0	0.8	0.7	0.3	0.1	0.0	-1.6	-2.3
	Wood Frame	<1940	4.3	3.4	1.7	1.7	1.0	-0.8	0.5	0.0	0.1	0.0	0.0	-2.4	-0.4
		1940-79	5.1	3.6	2.3	2.5	1.3	-0.2	0.5	0.1	0.2	0.0	0.0	-1.8	-1.1
		>1980	6.2	4.5	3.0	2.4	1.8	0.1	0.7	0.3	0.2	0.0	0.0	-1.6	-1.8
Multi-Family with 5+ Units (1–3 stories)	Masonry or Steel	<1940	5.0	5.4	2.4	2.2	1.2	-0.2	0.7	0.0	0.2	0.0	0.0	-2.2	-0.6
		1940-79	4.4	4.3	2.2	1.9	1.2	0.1	0.6	0.1	0.3	0.0	0.0	-1.1	-1.3
		>1980	5.0	4.6	2.6	2.0	1.5	0.0	0.7	0.2	0.3	0.0	0.0	-1.4	-1.1
	Wood Frame	<1940	4.3	4.7	1.8	1.9	1.0	-1.0	0.6	0.0	0.2	0.0	0.0	-2.1	-0.5
		1940-79	4.3	4.0	2.1	2.1	1.2	-0.5	0.6	0.0	0.2	0.0	0.0	-1.4	-1.0
		>1980	4.9	4.7	2.6	2.2	1.5	0.0	0.8	0.2	0.3	0.0	0.0	-1.1	-1.4
Multi-Family with 5+ Units (4+ stories)	Masonry or Steel	<1940	5.4	4.3	1.9	1.6	1.0	-1.2	0.7	0.0	0.2	0.0	0.0	-3.0	-0.2
		1940-79	6.0	3.7	2.3	1.8	1.2	-0.5	0.6	0.1	0.2	0.0	0.0	-3.2	-0.2
		>1980	6.9	5.0	3.1	2.2	1.6	-0.6	0.9	0.2	0.3	0.0	0.0	-3.0	-0.5
	Wood Frame	<1940	4.7	3.7	1.7	1.6	0.9	-0.9	0.6	0.0	0.2	0.0	0.0	-2.7	-0.1
		1940-79	5.2	4.0	2.2	2.0	1.2	-0.8	0.7	0.0	0.2	0.0	0.0	-2.4	-0.4
		>1980	4.8	5.2	2.7	2.1	1.4	-0.7	0.9	0.1	0.3	0.0	0.0	-1.4	-0.7
Average by component			4.9	4.6	2.7	2.3	1.4	0.2	0.5	0.2	0.2	0.0	0.0	-1.7	-1.2

Annual cooling load intensity (kBtu/ft2/yr)

-3.2 … 7.9

1. The wall, floor, ceiling, window, and foundation wall conduction categories only include conduction through those components; all air envelope leakage is accounted for in the infiltration category.
2. “Other” includes time-lagged heat transfer with internal partition wall and furniture mass.
3. “Equipment” includes duct losses (leakage and conduction), as well as heat gain from major appliances, water heaters, hot water pipes, and hot water draws, as contributions to cooling load.

Figure 18. Residential Hot-Dry/Mixed-Dry cooling component loads

3.1.5 Residential Climate Area 5: Hot-Humid

The Hot-Humid climate region covers the coastal South from Texas to North Carolina. Homes in this area represent 18% of U.S. housing units and buildings, and 10% of the residential thermal end-use energy. Figure 19 shows the 34 segments in the Hot-Humid region, with the number of buildings, average building size, average thermal energy use intensity, and annual thermal energy used in each segment.

Across all typology segments in the Hot-Humid climate region, cooling loads dominate the thermal end-use energy intensity. Furthermore, the heating loads that do exist are predominately electric, and most segments have majority electric water heating as well. Whereas in other regions, on-site fossil fuel combustion serves the majority of thermal energy use, in the Hot-Humid region only 25% of residential thermal energy use are served by on-site fuel combustion. In the multifamily segments, especially, buildings are nearly 100% electric.

The Hot-Humid climate region has the highest proportion of mobile homes of any region, making up 9% of housing units, which account for just below 8% of the residential thermal end-use energy consumption in the region. Similar to the results of other regions, mobile homes in the Hot-Humid climate region have higher thermal energy use intensity compared to commensurate (i.e., same vintage) units in every other typology segment. This is also a region where thermal end-use energy intensity is correlated strongly with age but is otherwise fairly equal across building types.

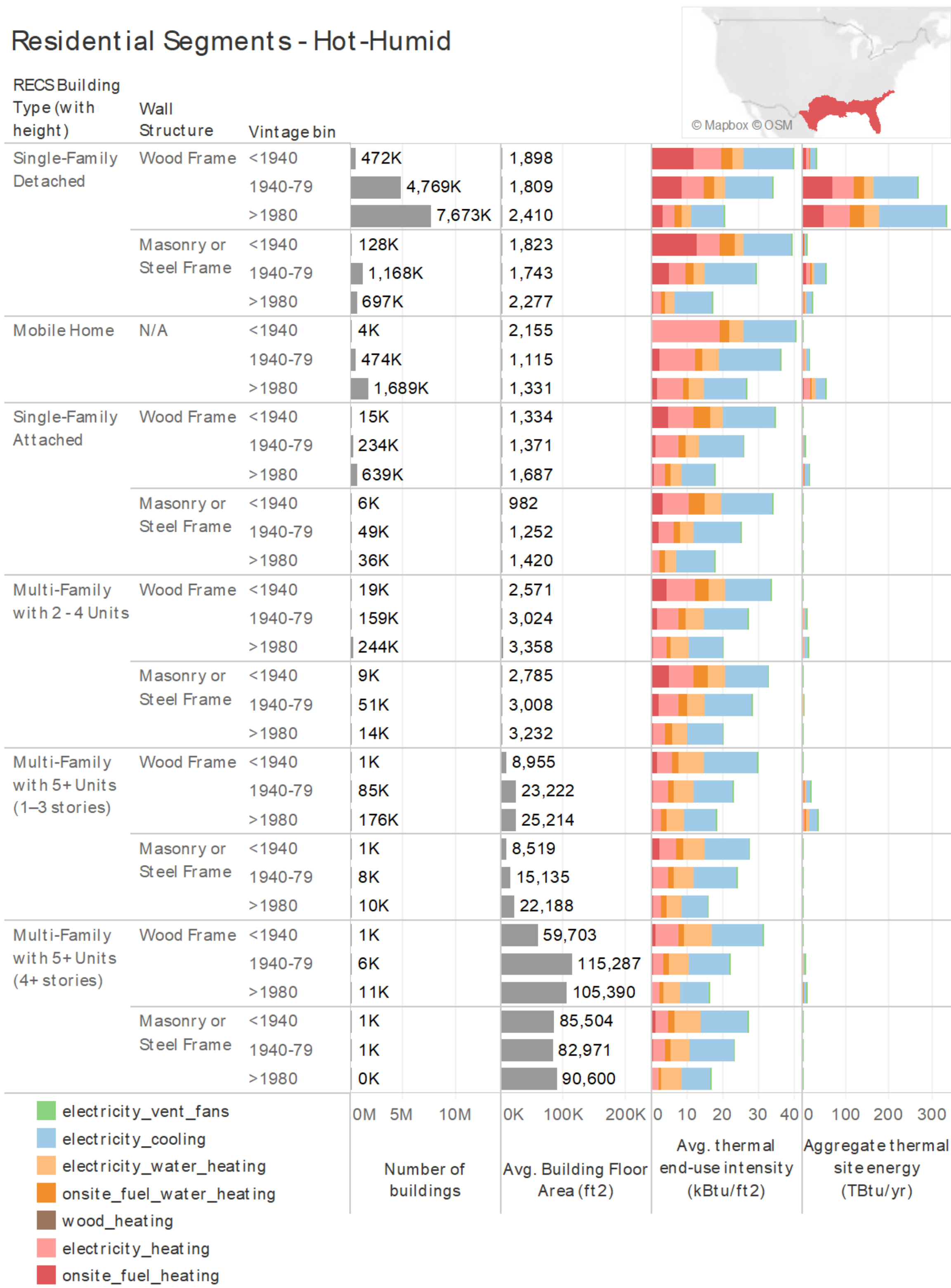

Figure 19. Residential Hot-Humid typology segments

3.1.5.1 Hot-Humid: Highest Thermal End-Use Energy Segments

Single-Family: Detached, Post-1980, Wood Frame. This is one of only two climate regions (along with Hot-Dry/Mixed-Dry) where post-1980 single-family homes are the highest contributing segment. This segment is dominated by cooling loads, but also has significant heating loads that are majority electric. Equipment gains, duct leakage, and solar gain through windows are the main drivers of cooling load in this segment.
Hot-Humid Prevalence: 32% of housing units / 41% of residential buildings / 36% of residential thermal end-use energy.

Multifamily: 5+ Units, Post-1980, Wood Frame, 1–3 Stories. This segment is the only top multifamily buildings segment across climate regions that has masonry construction. The predominant load is cooling, and the heating that exists is mostly electric. Equipment gain is the main driver of load, followed by duct leakage, walls, solar heat gain from windows, and infiltration, all in about equal measure.
Hot-Humid Prevalence: 9% of housing units / 1% of residential buildings / 4% of residential thermal end-use energy.

Annual heating load per square foot of building floor area
Hot-Humid Climate Zone

RECS Building Type (with height)	Wall Structure	Vintage bin	infiltration	equipment	walls	floor	roof / ceiling	windows - conduction	other	ground	doors	foundation walls	lighting	people	windows - solar
			Thermal load component												
Single-Family Detached	Masonry or Steel	<1940	7.8	1.3	2.4	2.2	1.7	1.3	1.8	0.3	0.0	0.0	-0.1	-0.3	-2.1
		1940-79	4.4	1.2	1.1	0.9	1.0	0.8	0.8	0.5	0.0	0.0	-0.1	-0.2	-1.2
		>1980	2.5	0.8	0.4	0.4	0.5	0.6	0.4	0.4	0.0	0.0	-0.1	-0.1	-0.8
	Wood Frame	<1940	6.6	1.6	2.9	1.9	1.8	1.1	2.0	0.3	0.0	0.0	-0.1	-0.3	-1.7
		1940-79	6.3	1.9	2.3	1.3	1.7	1.1	1.4	0.7	0.0	0.0	-0.1	-0.3	-1.7
		>1980	3.0	1.0	0.7	0.6	0.6	0.7	0.5	0.5	0.0	0.0	-0.1	-0.2	-1.0
Mobile Home	N/A	<1940	2.4	0.4	1.9	3.2	2.6	0.7	2.3	0.0	0.0	0.0	-0.1	-0.2	-1.2
		1940-79	3.8	1.8	2.2	3.2	2.1	1.0	1.8	0.0	0.1	0.0	-0.1	-0.3	-1.7
		>1980	3.0	1.6	1.1	2.3	1.3	0.9	1.1	0.0	0.0	0.0	-0.1	-0.2	-1.4
Single-Family Attached	Masonry or Steel	<1940	10.9	1.2	2.2	1.7	1.9	1.1	1.4	0.3	0.1	0.0	-0.2	-0.4	-1.7
		1940-79	4.0	1.0	0.4	0.2	0.5	0.3	0.3	0.3	0.0	0.0	-0.1	-0.1	-0.6
		>1980	2.2	0.4	0.1	0.1	0.2	0.2	0.1	0.3	0.0	0.0	0.0	-0.1	-0.4
	Wood Frame	<1940	7.9	2.1	1.4	1.0	0.9	0.5	0.8	0.2	0.0	0.0	-0.1	-0.3	-0.9
		1940-79	6.3	1.4	1.0	0.3	1.1	0.5	0.6	0.5	0.0	0.0	-0.1	-0.2	-0.9
		>1980	3.5	0.7	0.3	0.2	0.4	0.4	0.2	0.4	0.0	0.0	-0.1	-0.1	-0.6
Multi-Family with 2 - 4 Units	Masonry or Steel	<1940	5.3	-0.3	1.5	1.5	0.8	0.9	0.8	0.2	0.0	0.0	-0.1	-0.3	-1.3
		1940-79	3.6	-0.5	1.0	0.8	0.6	0.7	0.5	0.3	0.0	0.0	-0.1	-0.2	-1.0
		>1980	2.0	-0.4	0.3	0.4	0.3	0.5	0.2	0.2	0.0	0.0	-0.1	-0.1	-0.6
	Wood Frame	<1940	5.4	-1.0	2.5	1.9	1.3	1.1	1.2	0.1	0.1	0.0	-0.1	-0.3	-1.5
		1940-79	5.3	-0.6	1.9	1.3	1.0	1.1	0.9	0.4	0.1	0.0	-0.1	-0.3	-1.4
		>1980	3.7	-0.7	0.7	0.8	0.6	1.0	0.4	0.4	0.0	0.0	-0.1	-0.2	-1.1
Multi-Family with 5+ Units (1–3 stories)	Masonry or Steel	<1940	5.4	-0.3	0.9	1.1	0.5	0.8	0.5	0.0	0.0	0.0	-0.1	-0.2	-0.9
		1940-79	3.7	-0.5	0.4	0.5	0.3	0.5	0.2	0.2	0.0	0.0	-0.1	-0.2	-0.6
		>1980	2.4	-0.4	0.2	0.3	0.3	0.4	0.1	0.1	0.0	0.0	-0.1	-0.1	-0.4
	Wood Frame	<1940	5.5	-0.9	1.2	0.8	0.6	0.7	0.6	0.1	0.0	0.0	-0.1	-0.2	-0.7
		1940-79	4.3	-0.6	0.8	0.7	0.5	0.7	0.4	0.1	0.0	0.0	-0.1	-0.2	-0.8
		>1980	2.6	-0.5	0.3	0.4	0.3	0.5	0.2	0.2	0.0	0.0	-0.1	-0.2	-0.5
Multi-Family with 5+ Units (4+ stories)	Masonry or Steel	<1940	4.7	-0.7	0.9	1.2	0.4	1.2	0.5	0.1	0.0	0.0	-0.1	-0.3	-1.1
		1940-79	2.8	-0.5	0.4	0.5	0.2	0.6	0.2	0.0	0.0	0.0	0.0	-0.1	-0.5
		>1980	2.0	-0.4	0.1	0.3	0.1	0.4	0.1	0.0	0.0	0.0	0.0	-0.1	-0.3
	Wood Frame	<1940	6.1	-1.0	1.5	1.5	0.7	1.2	0.8	0.0	0.0	0.0	-0.1	-0.3	-1.2
		1940-79	3.2	-0.3	0.7	0.7	0.3	0.6	0.3	0.0	0.0	0.0	-0.1	-0.1	-0.6
		>1980	2.1	-0.4	0.2	0.3	0.2	0.4	0.1	0.1	0.0	0.0	0.0	-0.1	-0.4
Average by component			4.4	0.2	1.1	1.0	0.8	0.7	0.7	0.2	0.0	0.0	-0.1	-0.2	-1.0

Annual heating load intensity (kBtu/ft2/yr)
-2.1 10.9

1. The wall, floor, ceiling, window, and foundation wall conduction categories only include conduction through those components; all air envelope leakage is accounted for in the infiltration category.
2. “Other” includes time-lagged heat transfer with internal partition wall and furniture mass.
3. “Equipment” includes duct losses (leakage and conduction) as positive contributions to heating load, as well as heat gain from major appliances, water heaters, hot water pipes, and hot water draws as negative contributions to heating load.

Figure 20. Residential Hot-Humid heating component loads

Annual cooling load per square foot of building floor area
Hot-Humid Climate Zone

			Thermal load component												
RECS Building Type (with height)	Wall Structure	Vintage bin	equipment	windows - solar	other	walls	roof / ceiling	infiltration	people	windows - conduction	lighting	doors	foundation walls	floor	ground
Single-Family Detached	Masonry or Steel	<1940	7.7	7.3	6.7	5.0	2.5	2.3	0.5	0.9	0.2	0.1	0.0	-3.4	-1.1
		1940-79	9.0	7.3	5.5	4.1	2.5	2.1	0.6	0.7	0.2	0.1	0.0	-1.3	-3.0
		>1980	7.1	6.6	4.4	2.5	1.6	1.2	0.5	0.5	0.2	0.0	0.0	-1.3	-2.9
	Wood Frame	<1940	7.5	7.1	6.9	5.3	2.5	2.2	0.5	0.8	0.2	0.1	0.0	-3.2	-1.2
		1940-79	8.5	6.9	5.4	4.5	2.6	2.2	0.6	0.7	0.2	0.1	0.0	-1.4	-2.5
		>1980	6.7	6.1	4.1	2.5	1.5	1.1	0.5	0.5	0.2	0.0	0.0	-1.2	-2.6
Mobile Home	N/A	<1940	4.2	4.4	5.5	3.6	3.3	1.3	0.3	0.7	0.2	0.0	0.0	1.0	0.0
		1940-79	11.7	8.6	6.3	5.0	3.8	1.9	0.7	0.8	0.2	0.1	0.0	-3.1	0.0
		>1980	10.0	7.6	4.7	3.0	2.6	1.1	0.7	0.6	0.2	0.1	0.0	-3.6	0.0
Single-Family Attached	Masonry or Steel	<1940	10.4	6.3	5.8	5.7	1.9	2.9	0.8	0.6	0.4	0.1	0.0	-3.5	-1.2
		1940-79	9.4	4.2	3.9	3.0	1.6	2.6	0.7	0.4	0.3	0.1	0.0	-0.5	-2.4
		>1980	8.6	4.7	3.7	2.4	1.2	1.8	0.6	0.4	0.3	0.0	0.0	-0.3	-3.1
	Wood Frame	<1940	10.7	5.4	5.5	5.0	1.9	3.4	0.7	0.6	0.3	0.1	0.0	-2.6	-1.2
		1940-79	8.7	3.9	3.9	3.3	1.7	2.5	0.6	0.4	0.3	0.1	0.0	-0.5	-2.1
		>1980	7.5	3.9	3.3	2.2	1.1	1.5	0.5	0.3	0.3	0.0	0.0	-0.4	-2.4
Multi-Family with 2 - 4 Units	Masonry or Steel	<1940	5.2	5.5	4.2	3.8	2.4	2.0	0.6	0.7	0.3	0.1	0.0	-1.3	-0.4
		1940-79	5.7	7.6	4.7	4.2	2.7	2.2	0.8	0.8	0.4	0.1	0.0	-1.6	-1.9
		>1980	5.1	7.3	4.2	3.0	2.4	1.2	0.8	0.6	0.4	0.1	0.0	-1.5	-2.1
	Wood Frame	<1940	5.0	6.4	4.6	4.2	2.6	1.9	0.6	0.8	0.3	0.1	0.0	-1.6	-0.4
		1940-79	5.1	6.5	4.3	4.0	2.4	1.7	0.7	0.7	0.3	0.1	0.0	-1.3	-1.5
		>1980	5.8	7.4	4.2	3.3	2.3	1.2	0.8	0.6	0.4	0.1	0.0	-1.7	-2.0
Multi-Family with 5+ Units (1-3 stories)	Masonry or Steel	<1940	7.8	6.1	4.1	4.3	2.1	2.2	0.8	0.8	0.4	0.0	0.0	-2.2	-0.3
		1940-79	6.2	5.9	3.9	3.5	2.2	2.3	0.9	0.6	0.4	0.0	0.0	-1.1	-1.4
		>1980	5.5	5.6	3.4	2.6	2.0	1.3	0.8	0.4	0.4	0.0	0.0	-1.1	-1.5
	Wood Frame	<1940	6.6	5.5	3.9	4.0	2.1	2.0	0.9	0.6	0.4	0.0	0.0	-1.6	-0.4
		1940-79	6.1	5.9	3.9	3.6	2.2	2.1	0.9	0.5	0.4	0.0	0.0	-1.2	-1.3
		>1980	5.2	5.3	3.3	2.5	1.9	1.1	0.8	0.4	0.4	0.0	0.0	-1.0	-1.5
Multi-Family with 5+ Units (4+ stories)	Masonry or Steel	<1940	7.2	9.7	4.9	4.2	2.5	2.1	1.0	1.2	0.4	0.0	0.0	-4.4	-0.6
		1940-79	5.9	8.0	4.3	3.5	2.1	2.1	0.9	0.8	0.4	0.0	0.0	-3.3	-0.5
		>1980	5.3	6.2	3.6	2.6	1.8	1.0	0.8	0.5	0.4	0.0	0.0	-2.1	-0.7
	Wood Frame	<1940	7.3	8.8	4.9	5.0	2.6	2.7	0.9	1.1	0.3	0.1	0.0	-3.7	-0.4
		1940-79	5.6	6.8	4.0	3.6	2.1	2.5	0.8	0.8	0.4	0.0	0.0	-2.4	-0.6
		>1980	4.9	5.2	3.2	2.4	1.7	0.8	0.8	0.4	0.4	0.0	0.0	-1.4	-0.9
Average by component			7.1	6.4	4.5	3.7	2.2	1.9	0.7	0.6	0.3	0.0	0.0	-1.8	-1.3

Annual cooling load intensity (kBtu/ft2/yr)

-4.4 11.7

1. The wall, floor, ceiling, window, and foundation wall conduction categories only include conduction through those components; all air envelope leakage is accounted for in the infiltration category.
2. “Other” includes time-lagged heat transfer with internal partition wall and furniture mass.
3. “Equipment” includes duct losses (leakage and conduction), as well as heat gain from major appliances, water heaters, hot water pipes, and hot water draws, as contributions to cooling load.

Figure 21. Residential Hot-Humid cooling component loads

3.1.6 Conclusions for Residential Typology Segmentation

The highest thermal end-use energy segments from each climate region are summarized in Table 9.

Table 9. Residential Highest Thermal End-Use Energy Segments by Climate Region and National Prevalence

	Single-Family	Multifamily
Cold/Very-Cold	Detached, 1940–1979, Wood Frame *Housing Unit Proportion: 9%* *Residential Building Proportion: 11.1%* *National Thermal End-Use Energy Proportion: 16%*	2–4 Unit, Pre-1940, Wood Frame *Housing Unit Proportion: 1%* *Residential Building Proportion: 0.5%* *National Thermal End-Use Energy Proportion: 1%*
Mixed-Humid	Detached, 1940–1979, Wood Frame *Housing Unit Proportion: 8%* *Residential Building Proportion: 10%* *National Thermal End-Use Energy Proportion: 11%*	5+ Units, Post-1980, Wood Frame, 1–3 stories *Housing Unit Proportion: 2%* *Residential Building Proportion: 0.2%* *National Thermal End-Use Energy Proportion: 0.6%*
Marine	Detached, 1940–1979, Wood Frame *Housing Unit Proportion: 1%* *Residential Building Proportion: 2%* *National Thermal End-Use Energy Proportion: 1%*	5+ Units, Post-1980, Wood Frame, 1–3 Stories *Housing Unit Proportion: 0.4%* *Residential Building Proportion: 0.04%* *National Thermal End-Use Energy Proportion: 0.08%*
Hot-Dry/Mixed-Dry	Detached, Post-1980, Wood Frame *Housing Unit Proportion: 4%* *Residential Building Proportion: 5%* *National Thermal End-Use Energy Proportion: 2%*	5+ Units, Post-1980, Wood Frame, 1–3 Stories *Housing Unit Proportion: 1%* *Residential Building Proportion: 0.1%* *National Thermal End-Use Energy Proportion: 0.2%*
Hot-Humid	Detached, Post-1980, Wood Frame *Housing Unit Proportion: 6%* *Residential Building Proportion: 7%* *National Thermal End-Use Energy Proportion: 4%*	5+ Units, Post-1980, Wood Frame, 1–3 Stories *Housing Unit Proportion: 2%* *Residential Building Proportion: 0.2%* *National Thermal End-Use Energy Proportion: 0.4%*

There are several major takeaways from the residential typology segmentation:

- **Most residential thermal end-use energy is in single-family detached homes.** The vast majority of residential buildings in the United States are single-family detached homes; additionally, single-family detached homes have the highest thermal end-use intensity with the exception of mobile homes, and they have the largest amount of floor space per unit. The combination of these factors means that any strategy looking to holistically reduce thermal energy use 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.

- **Infiltration drives heating.** Infiltration is the largest contributing component 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 do so while limiting disruption to occupants due to internal modifications—are a priority for further research and development, particularly considering the limited evidence base for how much infiltration can be reduced through envelope improvements such as panelized walls, drill-and-fill insulation, or window retrofits alone. Reduction in air infiltration could also provide co-benefits of reduced moisture infiltration and improved indoor air quality if coupled with mechanical ventilation.

- **Mobile homes are extremely energy-intensive.** Despite accounting for relatively small shares of total housing units in most climate regions (4%–9%), mobile homes typically have much larger thermal energy use intensities than other building types. This is especially the case for older vintage mobile homes in cold or mixed climate regions, where fossil-fired heating drives higher thermal energy use intensities, but it is also evident in hotter climates, where electric heating and cooling are the primary drivers. These findings highlight the need for retrofit solutions that are applicable to mobile homes, which will likely have larger co-benefits for occupants than solutions for other segments given the energy burdens mobile home occupants face. Being "mobile," and manufactured off-site in the first place, it might be that the solutions include total replacement, although there could be significant nontechnical barriers to this such as local codes, taxes, and ownership structures as well as potential equity implications of displacing the occupants.

- **Fossil fuel-based space and water heating must be replaced to achieve decarbonization.** Fossil-fired space and water heating are the largest contributors to thermal end-use energy intensity and total loads in most of the United States, which has clear implications for the scale of electrification needed. Fossil fuel-based space and water heating are most prominent in cold and mixed climate regions but still represent a large share of thermal energy use for single-family segments in hot and humid climate regions where electric heating is more common. These results will help identify segments that can reach carbon neutrality more rapidly through replacement of existing fossil fuel-based heating equipment with electric heating equipment. Furthermore, these findings can inform where existing technology deployment is cost-effective, and where additional research and/or cost reduction is needed. They can also assist in prioritizing deeper envelope retrofits for segments where electric heating adoption may be slower due to technical, economic (e.g., technology cost-effectiveness), market, or regulatory challenges, such as in the very cold Northeast and Mid-Atlantic regions.

- **Solutions are likely transferable between segments.** An important takeaway from this segmentation is that solutions can likely be transferred from one segment to another within the residential sector. Packages developed for single-family detached, midcentury wood frame construction (which is the single-family segment with the highest thermal energy use in three 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, solutions developed for Marine multifamily buildings, where water heating is the predominant thermal energy end use, could potentially be applied broadly to many different multifamily building segments since water heating retrofits are independent of the existing envelope.

3.2 Commercial Segments

For commercial buildings, we segment ComStock results based on seven building types, three building size bins, and three HVAC classifications, for a total of 57 commercial building segments nationally (Table 10).[20] Unlike the residential segmentation, we do not include climate zone as an official segmentation parameter in this report. However, climate zone, in addition to other characteristics, is available as a parameter for custom segmentation in the online dashboard. When we segmented by climate zone, we found that it does influence the heating and cooling loads in different regions to some extent, but it is not a substantial differentiator compared to other commercial building characteristics. Furthermore, segmenting by climate regions yields virtually identical rankings of top building segments across climate regions.

ComStock covers 66% of the commercial floor area, as reported in CBECS, by modeling the 14 most common commercial building types in the United States by floor area. For this segmentation, we aggregate the 14 ComStock building types to seven categories based on basic building function: education, mercantile, healthcare, food service, lodging, office, and warehouse. For each of these building types, we further segment based on the general size of the building: <25,000 ft^2, 25,000–200,000 ft^2, and >200,000 ft^2.

Commercial buildings have a wide variety of HVAC configurations. ComStock uses the HVAC equipment reported in CBECS 2012 to inform the HVAC configurations by building type.[21] We aggregate the 45 different HVAC configurations found in ComStock to three general categories:

[20] Not all HVAC classifications are found in all building types and not all building types have permutations in all size bins.

[21] Commercial HVAC systems can be complex and difficult to access, so there is some uncertainty in what a building owner/operator might report in CBECS. The ComStock analysts interpreting CBECS have found survey responses with combinations of pieces of equipment that are difficult or impossible to classify into a real system type, so we have made assumptions regarding the system type mapping. Additionally, for small packaged units, many buildings self-identified as having electric heating but no heat pump. In this case, we assume an electric

1) **Small packaged unit**: Factory-built units that typically contain a fan, gas heating coil, direct expansion condenser and evaporator coils, and an outdoor air intake. Often rooftop-mounted, they are sometimes called "rooftop units" or "gas packs," and they typically have less than 10-ton cooling capacity, although multiple units might service a single building. In this category, we also include residential-style central systems, which typically include a fan, gas heating coil, and direct expansion condenser coil inside the building and a direct expansion evaporator coil outside the building, connected by a thin refrigerant line. Residential-style systems typically don't provide mechanical ventilation. Small packaged unit systems service 55% of commercial floor area.

2) **Central multizone systems:** Forced air systems that simultaneously serve multiple thermal zones in the building, each of which has different heating and cooling needs using either constant or variable air volumes. Typically, these systems include either pieces of large rooftop equipment or a custom-engineered system designed specifically for a building. These HVAC systems service 29% of commercial floor area as modeled in ComStock.

3) **Zone-by-zone:** Heating and cooling systems that use small individual pieces of equipment to heat or cool each zone in the building, such as through-the-wall packaged terminal air conditioners (PTAC) or fan coil units found in hotels and less common systems like zone-level water-to-air heat pumps. In this category, ventilation air can be conditioned and supplied to the zone by a separate system, is brought in directly to each zone via the small individual equipment in each zone, or is not provided at all. This category also contains any other type of system not covered by the previous two categories. Zone-by-zone systems service 16% of commercial floor area.

The detailed mapping of all the ComStock HVAC systems to the aggregated typology classifications can be found in Appendix A. Furthermore, additional levels of HVAC detail can be explored on the online dashboard. As will be discussed in the subsequent sections, HVAC types are heavily correlated to building type and size, and identifying existing equipment is important for determining retrofit options.

In the following sections, we discuss the segmentation of the commercial building stock, including major segment characteristics. We then highlight the top segments with the highest total thermal energy use and discuss major contributors to that segment's thermal energy use. For the commercial sector, we currently exclude refrigeration and refrigerated spaces (e.g., walk-in freezers, refrigerated warehouses) from our definition of thermal loads. However, these end uses have potentially significant emissions impacts due to both electricity use and refrigerant leaks (Francis et al., 2017).

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resistance heating system, but the amount of air-source heat pumps might be undercounted if CBECS survey respondents weren't able to identify a heat pump. Despite these caveats, we think this HVAC classification is broadly correct and suitable for drawing big-picture conclusions.

Table 10. Commercial Segmentation Parameters

Segmentation Parameter	Levels
Building type	Mercantile; Education; Food Service; Healthcare; Lodging; Office; Warehouse
Building size	<25,000 ft^2; 25,000–20,000 ft^2; >200,000 ft^2
HVAC category	Small packaged unit; central multizone system; zone-by-zone

3.2.1 Commercial Segmentation Overview

Figure 22 shows the 57 segments in the commercial segmentation, with the total floor area, average building size, average thermal energy use intensity, and annual thermal energy used in each segment.

Within the commercial building sector, there is wide variability in the prevalence of building segments, and there are strong correlations between building type, size bin, and typical HVAC equipment. For example, most mercantile, warehouse, and education buildings are in the middle size bin (25,000–200,000 ft^2), whereas food service buildings mostly fall within the smallest size bin (<25,000 ft^2), and healthcare buildings are typically greater than 200,000 ft^2. Lodging is split between the two larger size bins (25,000–200,000 and >200,000 ft^2), and offices are more equally split across all three size bins. Office buildings are the most prevalent building type at 28% of the floor area (22% of thermal energy use), followed by education spaces at 21% of the region floor area (23% of thermal energy use) and warehouses at 19% of the floor area (6% of thermal energy use).

Like residential buildings, heating is the leading thermal energy end use for most commercial building segments, with a few notable exceptions such as several food service and lodging segments where water heating or fans use a higher proportion of thermal energy use. In segments with zone-by-zone HVAC systems, having other end uses besides heating dominate seems especially common. Commercial buildings also have forced mechanical ventilation more frequently than in residential buildings, and this is reflected in a more substantial portion of thermal energy use going to fan energy. Overall, 45% of thermal energy use is in the form of on-site fossil fuel use, 80% of which is for space heating. Commercial buildings also have a lot of variation in thermal energy use intensity and end-use breakdown between segments due to the heterogeneity of building functions in the commercial sector. For example, food service segments use between 100–190 kBtu/ft^2 across a variety of end uses (water heating, fans, space heating/cooling), whereas warehouse segments use between 3–41 kBtu/ft^2, primarily just for space heating. The building size and category of HVAC equipment also strongly influence the thermal energy use intensity of the segments. Of the three HVAC categories, the central multizone systems tend to be the most energy-intensive, followed by small packaged units and the zone-by-zone categories.

Breaking down the contributors to thermal heating loads in the commercial sector, ventilation is the highest for most building types, with a few building segments (i.e., some warehouses and lodging) having infiltration as the highest contributor (see Figure 28). These building segments are less likely to have mechanical ventilation to contribute to thermal loads.

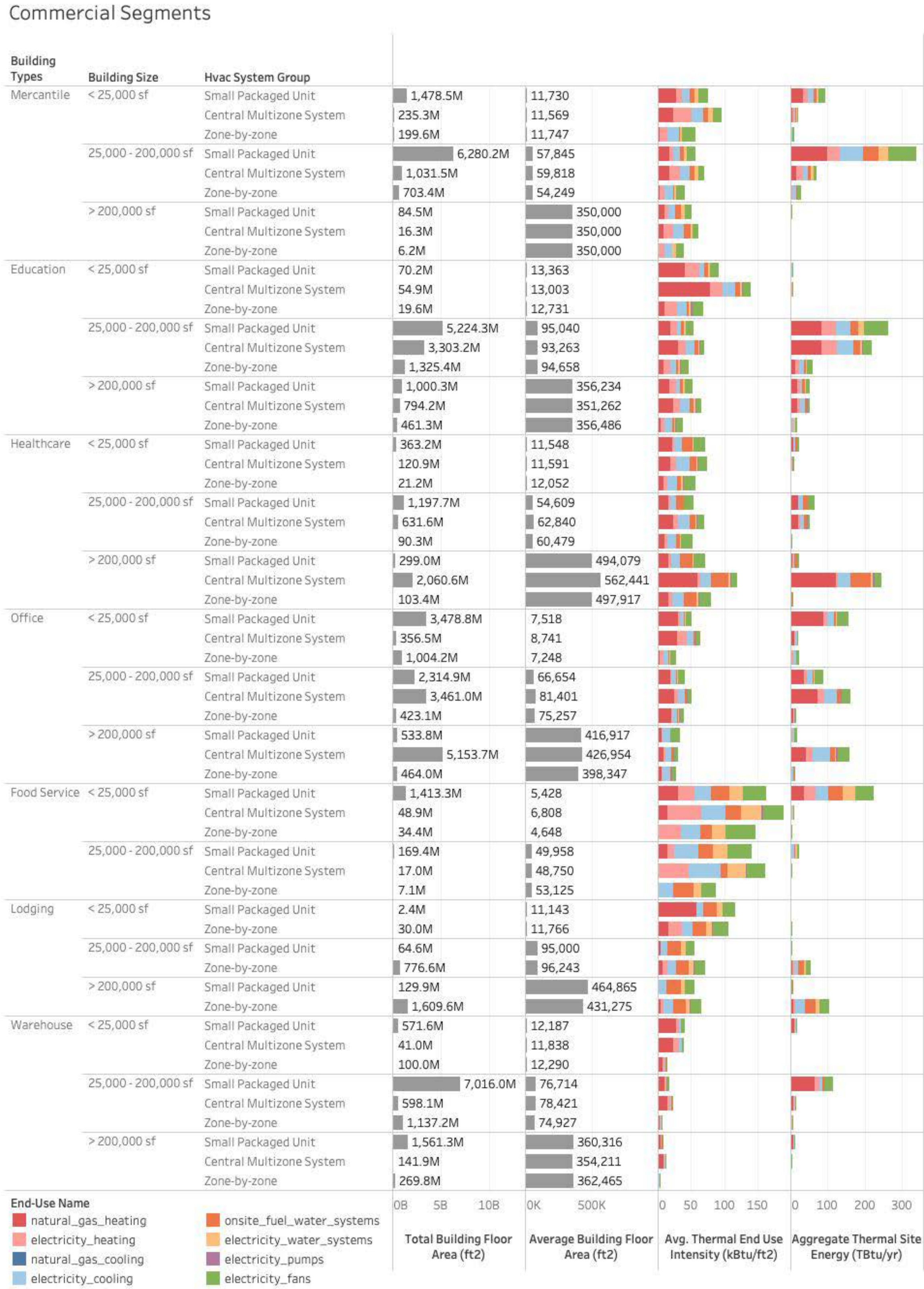


Figure 22. Commercial typology segments

3.2.1.1 Highest Thermal Energy Use Segments

From the results in Figure 22, we highlight the "top" five segments that contribute the most to national total thermal end-use energy consumption. As discussed earlier, this is not a definitive prioritization, and different use cases might segment or prioritize differently. The highest thermal end-use energy segments for commercial buildings are summarized in Table 11.

Table 11. Highest Commercial Thermal End-Use Energy Segments

	Prevalence	Energy Use
Segment 1: **Mercantile, 25,000–200,000 ft^2, Small Packaged Unit**	*ComStock Floor Area Proportion: 10%* *ComStock Building Proportion: 6%*	*ComStock Thermal End-Use Energy Proportion: 12%* *Thermal End-Use Energy Intensity: 59 kBtu/ft^2*
Segment 2: **Education, 25,000–200,000 ft^2, Small Packaged Unit**	*ComStock Floor Area Proportion: 9%* *ComStock Building Proportion: 3%*	*ComStock Thermal End-Use Energy Proportion: 9%* *Thermal End-Use Energy Intensity: 54 kBtu/ft^2*
Segment 3: **Healthcare, >200,000 ft^2, Central Multizone System**	*ComStock Floor Area Proportion: 3%* *ComStock Building Proportion: <1%*	*ComStock Thermal End-Use Energy Proportion: 8%* *Thermal End-Use Energy Intensity: 120 kBtu/ft^2*
Segment 4: **Food Service, <25,000 ft^2, Small Packaged Unit**	*ComStock Floor Area Proportion: 2%* *ComStock Building Proportion: 15%*	*ComStock Thermal End-Use Energy Proportion: 8%* *Thermal End-Use Energy Intensity: 164 kBtu/ft^2*
Segment 5: **Education, 25,000–200,000 ft^2, Central Multizone System**	*ComStock Floor Area Proportion: 5%* *ComStock Building Proportion: 2%*	*ComStock Thermal End-Use Energy Proportion: 7%* *Thermal End-Use Energy Intensity: 71 kBtu/ft^2*

SEGMENT 1. ***Mercantile, 25,000–200,000 ft², Small Packaged Unit***

This segment includes strip malls and other retail spaces and has the highest total thermal end-use energy consumption, driven by heating, which is 40% of the total thermal energy use, about 74% of which is in the form of fossil fuels burned on-site (mostly natural gas). Water heating comprises 20% of thermal energy use, 18% is cooling, and 22% is used to power fans for HVAC. In addition to the direct energy use of fans for HVAC, conditioning the outdoor ventilation air itself is the main driver of the component loads for heating (Figure 28) and cooling (Figure 29) of this segment, with wall/roof envelope losses also contributing in lesser proportion to heating, and occupant and lighting gains somewhat to cooling. This indicates that improvements to ventilation, both in the direct electricity used to power the fans and the heat or energy recovery from ventilation, could significantly reduce thermal energy use. Equipment-focused solutions such as heat pump rooftop units, rooftop units with integrated energy recovery, or decoupled rooftop ventilation with split-system heat pumps for space conditioning could reduce the heating and ventilation energy use in this segment as well as other segments with similar HVAC configurations.

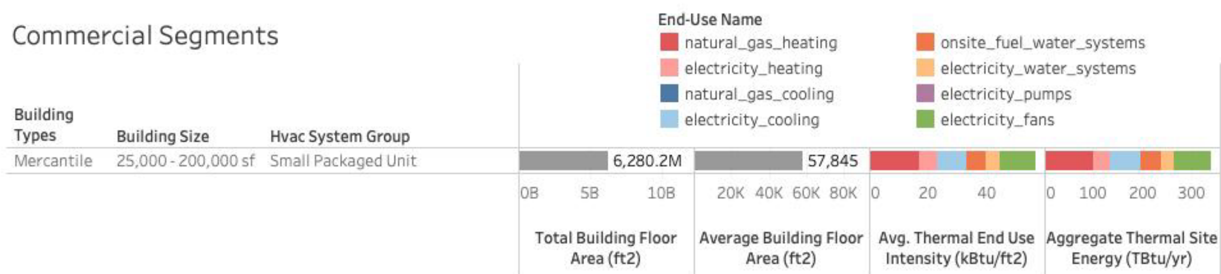


Figure 23. Commercial Segment 1

SEGMENT 2. ***Education, 25,000–200,000 ft², Small Packaged Unit***

This segment, which includes midsized primary and secondary education spaces, uses the second most thermal end-use energy in the commercial sector. Furthermore, most education buildings fall within the midsize bin (80% of floor area). HVAC solutions developed for small package unit systems in other segments can also likely be applied to this segment. This segment uses a substantial amount of thermal end-use energy for space heating (47%). Fan energy is 25% and water systems are another 13%, with cooling comprising the remaining 15% (Figure 24). Ventilation is the dominant cooling component load and the third contributing heating component load after envelope losses through the roof and other gains. Occupants and window solar are also a non-negligible proportion of the component loads for cooling. Forty percent of thermal end-use energy is on-site fuel, with most (80%) going to space heating.

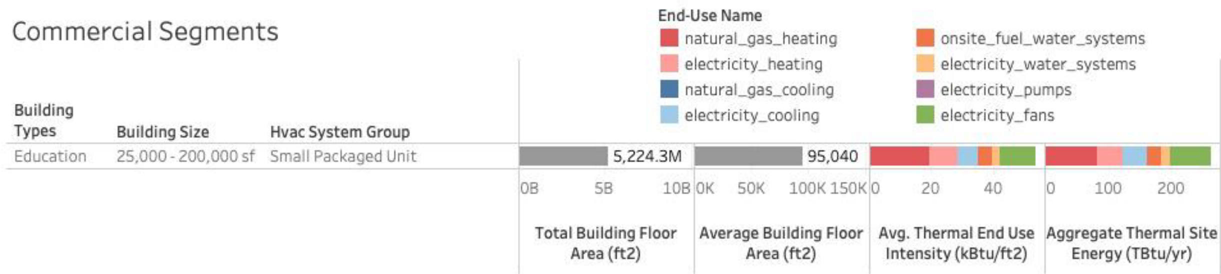


Figure 24. Commercial Segment 2

SEGMENT 3. ***Healthcare, >200,000 ft^2, Central Multizone System***

Large healthcare facilities, which are primarily hospitals, are energy-intensive in their thermal end-use energy consumption and have a substantial portion of the thermal end-use energy going to water systems (25%). Space heating is still the most prevalent end use at 52% of the thermal end-use energy, but fan electricity use for heating, cooling, and ventilation is at 7%, and cooling is at 13%. In this segment, 71% of the thermal energy use is met with on-site fossil fuel use, so removal of these on-site fossil fuels is a non-negligible task to decarbonize this sector. Healthcare, like most other building types, has the heating and cooling loads driven mostly by conditioning of ventilation air. Heat recovery for ventilation is a likely solution for this segment. For cooling, however, loads are also significantly driven by internal equipment gains. These types of equipment heat gains are largely unavoidable given the importance of medical equipment to the facility function and that these devices are primarily designed for their medical purposes, not for minimizing energy use or heat emanated. Instead, focusing on HVAC equipment efficiency to meet the necessary cooling loads is likely a more beneficial strategy when combined with electrification of loads via heat pump technologies.

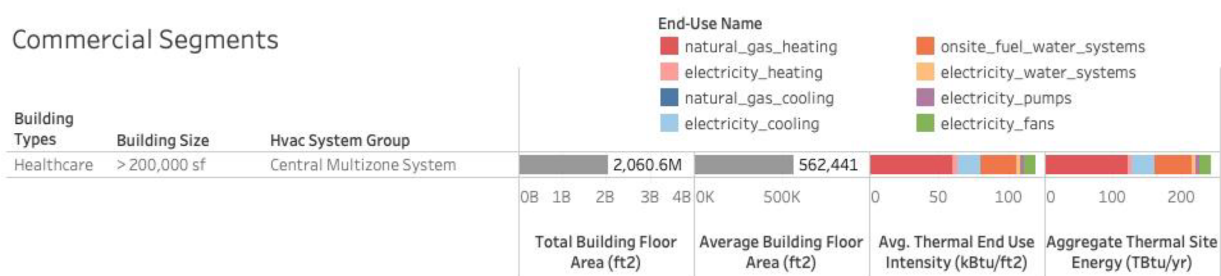


Figure 25. Commercial Segment 3

SEGMENT 4. ***Food Service, <25,000 ft^2, Small Packaged Unit***

The food service segments have the largest thermal energy end-use intensity, largely because of the greater water heating and ventilation needs of restaurants. In this segment, 30% of thermal energy use goes to space heating, 33% to water systems, and 22% to fan energy for heating, cooling, and ventilation. This sector might be especially challenging to decarbonize for a few reasons. Service water temperature needs in dishwashing systems are often much higher than can be produced through heat pump water heating systems, so finding electric technologies that can minimize demand is an important challenge. Furthermore, cooking creates high ventilation needs, so this contributes strongly to both the heating and cooling component loads of the segment, but energy recovery for this ventilation is challenging, as exhaust air from cooking is often contaminated with smoke and grease, which can damage heat recovery equipment. Demand-control ventilation, however, is a potentially effective strategy for reducing food service ventilation-related energy use. This segment is composed of many small energy-intense restaurants, so retrofitting this sector will involve dealing with a much larger number of buildings than some of the previously mentioned segments.

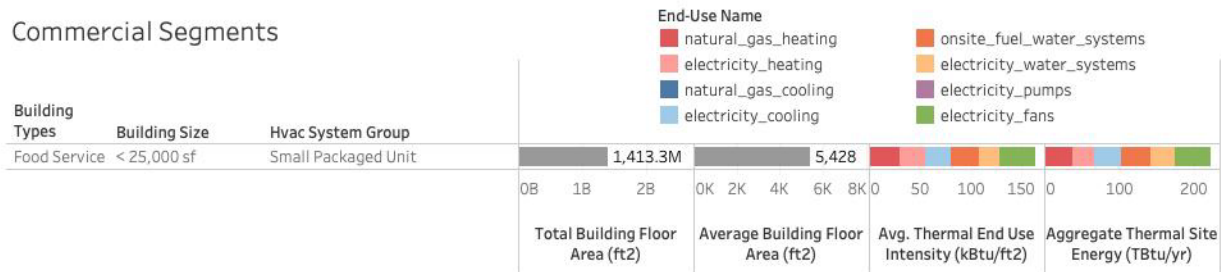


Figure 26. Commercial Segment 4

SEGMENT 5. ***Education, 25,000–200,000 ft^2, Central Multizone System***

This segment has similar characteristics to Segment 2, except that it uses a different HVAC configuration. Correspondingly, the thermal end-use breakdown is similar, with 57% of thermal end-use energy going to heating, much of which is driven by conditioning of ventilation air. This building segment is less common by floor area than the comparable midsized education building with a small packaged unit, but it is more energy-intense, especially in the heating needed per square foot. Like with Segment 2, when breaking down the component loads of heating in this segment, conditioning of outdoor air brought in for ventilation is the dominant driver of heating loads. Ventilation is also the top driver for cooling loads in this segment. Solutions for this segment may include augmentation or replacement of boilers with heat pump systems, or replacement of the multizone system with zone-by-zone split systems or variable refrigerant-flow systems plus a dedicated ventilation system.

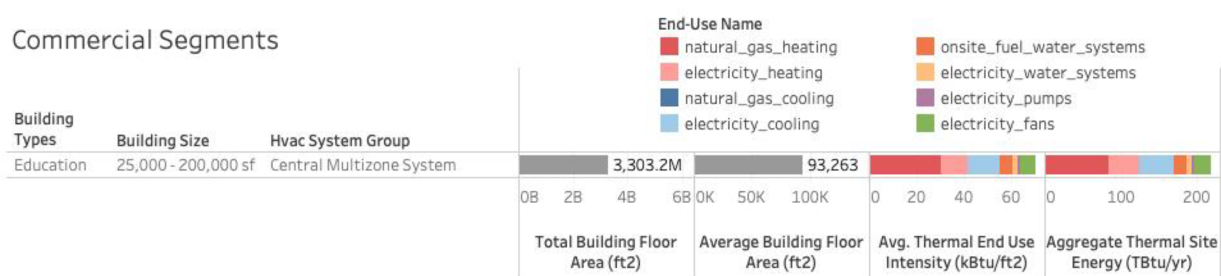


Figure 27. Commercial Segment 5

Figures 28 and 29 present the component loads breakdown for heating and cooling—i.e., specific contributors to heat gains and losses that comprise the heating and cooling loads. Summing across the row for a segment will sum to the total heating or cooling load of the segment. In the heating figure, Figure 28, positive numbers are heat losses (i.e., increase heating load) and represented by the color blue. In the cooling figure, Figure 29, positive numbers are heat gains (i.e., increase cooling loads) and are represented by the color orange. The largest number within a row will be the largest contributor of the component loads for that segment. These results are a preliminary development in ComStock, and the EnergyPlus reporting measure will be improved throughout the remaining duration of the project. Future updated results will be reported in the online dashboard.

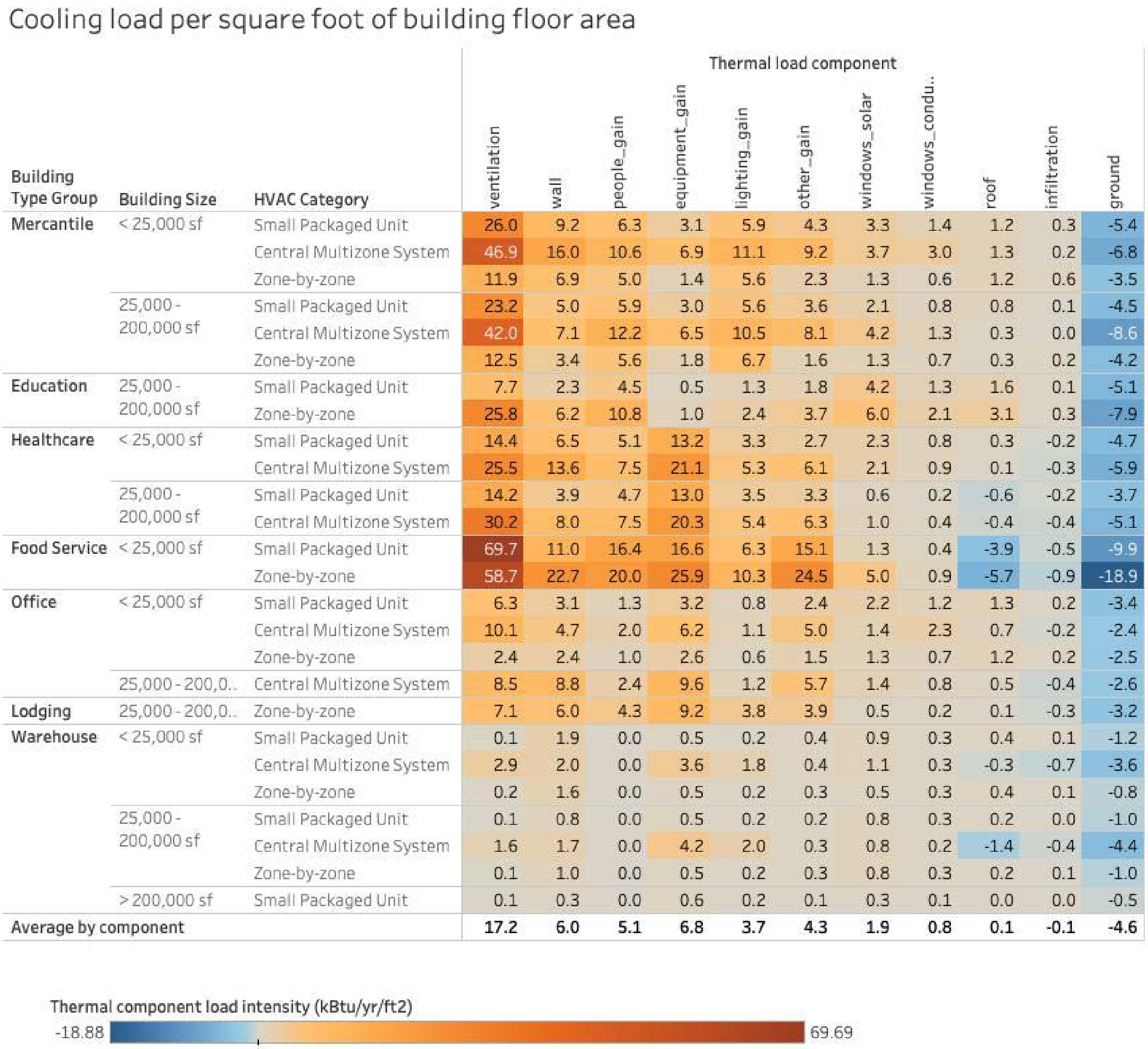
Heating load per square foot of building floor area

Building Type Group	Building Size	HVAC Category	Thermal load component: ventilation	wall	roof	other_gain	ground	infiltration	windows_condu..	windows_solar	people_gain	equipment_gain	lighting_gain
Mercantile	< 25,000 sf	Small Packaged Unit	4.2	2.8	1.4	1.1	1.2	1.3	0.8	-0.4	-0.7	-0.4	-1.1
		Central Multizone System	6.1	1.9	0.9	0.7	0.5	0.9	0.7	-0.2	-0.4	-0.3	-0.7
		Zone-by-zone	2.6	3.6	1.4	1.1	0.7	1.7	0.4	-0.2	-0.7	-0.3	-0.8
	25,000 - 200,000 sf	Small Packaged Unit	2.9	1.5	1.2	1.0	1.0	0.8	0.5	-0.3	-0.6	-0.3	-0.8
		Central Multizone System	5.9	1.1	1.2	0.8	0.6	0.5	0.5	-0.2	-0.4	-0.2	-0.6
		Zone-by-zone	2.1	1.6	1.1	0.8	0.6	0.9	0.6	-0.2	-0.4	-0.3	-0.6
Education	25,000 - 200,000 sf	Small Packaged Unit	2.1	1.6	2.4	2.3	2.1	0.7	0.9	-0.6	-1.6	-0.4	-0.9
		Zone-by-zone	7.6	1.6	2.0	1.8	1.5	0.8	0.6	-0.5	-1.4	-0.3	-0.7
Healthcare	< 25,000 sf	Small Packaged Unit	3.5	3.3	2.1	1.7	2.3	1.0	1.2	-0.6	-0.7	-1.9	-1.0
		Central Multizone System	3.9	3.1	1.4	1.1	0.6	1.1	0.6	-0.1	-0.4	-1.1	-0.6
	25,000 - 200,000 sf	Small Packaged Unit	4.2	1.5	2.0	1.9	1.8	0.7	0.7	-0.2	-0.5	-1.6	-0.9
		Central Multizone System	2.9	1.1	0.9	0.7	0.3	0.6	0.4	0.0	-0.2	-0.6	-0.4
Food Service	< 25,000 sf	Small Packaged Unit	13.0	-0.4	1.6	-1.6	1.6	0.5	0.3	-0.2	-1.5	-2.4	-1.1
		Zone-by-zone	11.5	-1.9	1.1	-3.0	1.7	0.6	0.3	-0.4	-4.1	-4.3	-1.5
Office	< 25,000 sf	Small Packaged Unit	2.9	2.3	1.6	2.0	2.1	1.1	0.9	-0.6	-0.6	-1.9	-0.4
		Central Multizone System	4.3	3.1	0.7	1.6	0.5	2.9	2.5	-0.3	-0.6	-1.3	-0.3
		Zone-by-zone	0.9	1.4	1.1	1.0	0.6	0.6	0.4	-0.2	-0.3	-0.8	-0.2
	25,000 - 200,000 sf	Small Packaged Unit	1.2	1.9	0.5	0.8	0.7	1.6	0.9	-0.3	-0.5	-1.3	-0.2
		Central Multizone System	5.6	1.8	0.9	1.2	0.5	1.5	1.3	-0.1	-0.4	-1.0	-0.2
Lodging	25,000 - 200,0..	Zone-by-zone	2.1	1.1	0.8	0.8	0.2	0.9	0.7	0.0	-0.4	-0.6	-0.5
Warehouse	< 25,000 sf	Small Packaged Unit	0.1	1.6	0.6	0.3	0.2	0.9	0.3	-0.1	0.0	-0.2	-0.1
		Central Multizone System	1.3	1.0	0.6	0.2	-0.3	1.2	0.2	-0.1	0.0	-0.3	-0.2
		Zone-by-zone	0.2	1.1	0.5	0.2	0.0	0.7	0.2	0.0	0.0	-0.2	-0.1
	25,000 - 200,000 sf	Small Packaged Unit	0.1	0.6	0.4	0.2	0.3	0.4	0.3	-0.2	0.0	-0.2	-0.1
		Central Multizone System	1.4	0.4	0.3	0.1	0.0	0.4	0.1	0.0	0.0	-0.2	-0.1
		Zone-by-zone	0.1	0.6	0.4	0.2	0.1	0.4	0.3	-0.1	0.0	-0.1	-0.1
	> 200,000 sf	Small Packaged Unit	0.0	0.2	0.3	0.2	0.2	0.2	0.1	-0.1	0.0	-0.2	-0.1
Average by component			**3.4**	**1.5**	**1.1**	**0.7**	**0.8**	**0.9**	**0.6**	**-0.2**	**-0.6**	**-0.8**	**-0.5**

Thermal component load intensity (kBtu/yr/ft2)

-4.32 … 13.04

Figure 28. Commercial building stock heating component loads



Cooling load per square foot of building floor area

Building Type Group	Building Size	HVAC Category	ventilation	wall	people_gain	equipment_gain	lighting_gain	other_gain	windows_solar	windows_condu..	roof	infiltration	ground
Mercantile	< 25,000 sf	Small Packaged Unit	26.0	9.2	6.3	3.1	5.9	4.3	3.3	1.4	1.2	0.3	-5.4
		Central Multizone System	46.9	16.0	10.6	6.9	11.1	9.2	3.7	3.0	1.3	0.2	-6.8
		Zone-by-zone	11.9	6.9	5.0	1.4	5.6	2.3	1.3	0.6	1.2	0.6	-3.5
	25,000 - 200,000 sf	Small Packaged Unit	23.2	5.0	5.9	3.0	5.6	3.6	2.1	0.8	0.8	0.1	-4.5
		Central Multizone System	42.0	7.1	12.2	6.5	10.5	8.1	4.2	1.3	0.3	0.0	-8.6
		Zone-by-zone	12.5	3.4	5.6	1.8	6.7	1.6	1.3	0.7	0.3	0.2	-4.2
Education	25,000 - 200,000 sf	Small Packaged Unit	7.7	2.3	4.5	0.5	1.3	1.8	4.2	1.3	1.6	0.1	-5.1
		Zone-by-zone	25.8	6.2	10.8	1.0	2.4	3.7	6.0	2.1	3.1	0.3	-7.9
Healthcare	< 25,000 sf	Small Packaged Unit	14.4	6.5	5.1	13.2	3.3	2.7	2.3	0.8	0.3	-0.2	-4.7
		Central Multizone System	25.5	13.6	7.5	21.1	5.3	6.1	2.1	0.9	0.1	-0.3	-5.9
	25,000 - 200,000 sf	Small Packaged Unit	14.2	3.9	4.7	13.0	3.5	3.3	0.6	0.2	-0.6	-0.2	-3.7
		Central Multizone System	30.2	8.0	7.5	20.3	5.4	6.3	1.0	0.4	-0.4	-0.4	-5.1
Food Service	< 25,000 sf	Small Packaged Unit	69.7	11.0	16.4	16.6	6.3	15.1	1.3	0.4	-3.9	-0.5	-9.9
		Zone-by-zone	58.7	22.7	20.0	25.9	10.3	24.5	5.0	0.9	-5.7	-0.9	-18.9
Office	< 25,000 sf	Small Packaged Unit	6.3	3.1	1.3	3.2	0.8	2.4	2.2	1.2	1.3	0.2	-3.4
		Central Multizone System	10.1	4.7	2.0	6.2	1.1	5.0	1.4	2.3	0.7	-0.2	-2.4
		Zone-by-zone	2.4	2.4	1.0	2.6	0.6	1.5	1.3	0.7	1.2	0.2	-2.5
	25,000 - 200,0..	Central Multizone System	8.5	8.8	2.4	9.6	1.2	5.7	1.4	0.8	0.5	-0.4	-2.6
Lodging	25,000 - 200,0..	Zone-by-zone	7.1	6.0	4.3	9.2	3.8	3.9	0.5	0.2	0.1	-0.3	-3.2
Warehouse	< 25,000 sf	Small Packaged Unit	0.1	1.9	0.0	0.5	0.2	0.4	0.9	0.3	0.4	0.1	-1.2
		Central Multizone System	2.9	2.0	0.0	3.6	1.8	0.4	1.1	0.3	-0.3	-0.7	-3.6
		Zone-by-zone	0.2	1.6	0.0	0.5	0.2	0.3	0.5	0.3	0.4	0.1	-0.8
	25,000 - 200,000 sf	Small Packaged Unit	0.1	0.8	0.0	0.5	0.2	0.2	0.8	0.3	0.2	0.0	-1.0
		Central Multizone System	1.6	1.7	0.0	4.2	2.0	0.3	0.8	0.2	-1.4	-0.4	-4.4
		Zone-by-zone	0.1	1.0	0.0	0.5	0.2	0.3	0.8	0.3	0.2	0.1	-1.0
	> 200,000 sf	Small Packaged Unit	0.1	0.3	0.0	0.6	0.2	0.1	0.3	0.1	0.0	0.0	-0.5
Average by component			**17.2**	**6.0**	**5.1**	**6.8**	**3.7**	**4.3**	**1.9**	**0.8**	**0.1**	**-0.1**	**-4.6**

Figure 29. Commercial building stock cooling component loads

3.2.2 Conclusions for Commercial Typology Segmentation

There are several major takeaways from the commercial typology segmentation:

- **Upgrading small packaged units presents a significant cross-segment opportunity.** Small packaged units are the most common HVAC classification, serving 55% of the commercial floor area and 73% of the commercial buildings by count[22] in the United States. Furthermore, although they are most common in small buildings, they are also found in much larger buildings as well. The majority of existing small packaged units use fossil fuel (63%), so there is an opportunity to swap these systems with heat pump packaged units, both electrifying the end use and increasing the efficiency. The impact of

[22] Based on the top 14 building types available in ComStock

these systems could be integrating energy recovery ventilation into the same unit. An alternate replacement for this system could involve decoupling ventilation and space conditioning, replacing the central unit with energy recovery ventilation and using zone-level split heat pumps.

- **Ventilation is a driver of energy use.** Across climate regions, ventilation accounts for a large share of thermal load intensity and total thermal loads in commercial buildings, both as ventilation fan electricity and outdoor air ventilation as a component load for heating and cooling. In all climate regions, ventilation is the component that drives heating and cooling loads due to energy used for conditioning outdoor air that is brought into the building for ventilation. Improvements in ventilation that can be achieved through energy recovery or demand control ventilation could yield benefits in terms of reduced heating and cooling loads in most commercial building segments, indicating the importance of such solutions.

- **Commercial buildings have a high percentage of on-site fossil fuel use.** Across building segments, there is a significant proportion (45%) of thermal end-use energy being met by fossil fuel sources. Depending on the building type and end use, electrification of these loads might be a significant challenge in the commercial sector. For example, some commercial buildings require higher service water heating temperatures than residential buildings, which might not be as easily met with electric heat pumps. Electrification could pose a significant challenge in some commercial building types or applications, and there might not yet be acceptable electric equipment options for all situations. Finding solutions to replace these fossil fuel technologies is essential to achieving full decarbonization

- **Climate is not a significant driver for commercial thermal energy end uses.** In contrast to the residential sector typologies, in the commercial sector there is less variation in segments' thermal energy use ranking across climate regions. In our results, climate region shifted the split of heating and cooling load within a segment, but generally didn't change the rankings of the segments between regions (Appendix B). Instead, general building function is the main driver given the diversity of functions and energy needs of commercial buildings. There is, however, considerable variation in thermal load intensity within identical segments in different climate regions and in the relative contributions of different end uses. This takeaway implies that solution development should focus more on building function and existing HVAC equipment, irrespective of climate region.

- **Solutions are likely transferable between segments.** Similar to the residential sector, solutions can likely be transferred from one segment to another within the commercial building stock. Most of the solutions for reducing thermal energy use and associated carbon emissions in the commercial sector will likely focus on equipment retrofits rather than envelope retrofits. As such, equipment can likely be widely deployed across segments with either similar existing equipment or similar existing system needs.

4 Typology Applications and Limitations

4.1 Use Cases and Applications

Given the richness of the typology segments developed in the previous section, there exist numerous potential use cases and applications of these data. Detailed segmentation and characterization of the U.S. building stock will enable several subsequent analysis applications that are specific to the ABC Initiative, but other uses cases also exist. In this section, we review these potential applications, explaining how the developed typologies will inform future work to model and deploy deep retrofit packages for residential and commercial building segments.

4.1.1 ABC Modeled Package Development

The primary ABC-related application of this national building characterization study is the development of retrofit packages that can be applied to reduce thermal energy use in buildings. Retrofit packages will be determined collaboratively by the DOE and the ABC Collaborative. We anticipate a range of upgrade measures covering all HVAC- and water-heating-related loads. Because the retrofit package modeling is designed to inform ABC solution cost targets, the package modeling is explicitly a parametric analysis and not an optimization that seeks to minimize building life cycle costs.

For existing buildings, we anticipate that upgrade modeling will proceed in iterative steps. For the initial upgrade modeling, we will simulate the individual upgrades directed by the Collaborative and apply them to the entire building stock, only changing the upgrade application logic as necessary (e.g., the upgrade is less efficient than the technology already installed, or a particular technology is an inappropriate upgrade given the current state of the building). With these individual upgrades applied, we can then begin to bundle them into deep energy packages targeting the top typology segments. At this stage, we could potentially identify subsegments based on technology applicability; conversely, we might find technology packages that are applicable to multiple segments (including ones that are not the primary target of the upgrade) and decide to aggregate them together. One of the advantages to applying the upgrades to the entire ResStock and ComStock synthetic stocks is the flexibility to reaggregate results across different segmentations; we are also able to quantify the number of housing units eligible for various retrofit technologies, even beyond those that apply to the top typology segments.

The outputs of the ABC package modeling will be included in the forthcoming Industry Guidance Report from RMI.

4.1.2 ABC Performance and Cost Target Development

A related effort that will draw on the results of this characterization study is the development of performance and capital cost targets for the ABC modeled upgrades. The aim of this work is to develop guidance materials for industry that will specify performance standards and cost targets for whole-building retrofit and new construction packages across prioritized building typology segments to ensure these packages can achieve broader market adoption.

As in the case of the ABC modeled package development, performance and cost target setting for whole-building retrofit and new construction packages is dependent on the identification of residential and commercial building segments and the subsequent prioritization of these segments. This study provides the basis for these analysis activities that are essential to the ABC Initiative and the industry-facing work of the ABC Collaborative.

4.1.3 Other Applications

ABC Goals Development. This characterization study will inform the development of high-level goals for the ABC Initiative, especially those related to energy performance, affordability, and carbon neutrality. The segments identified and further characterized in this study will enable more specific goal and target setting for energy performance and cost compression.

ABC R&D Roadmap Development. The ABC R&D Roadmap will identify specific R&D opportunities for the ABC Initiative based on findings from a gaps analysis (Metzger et al., forthcoming) and reviews of past BTO projects and other projects related to ABC. This characterization study can inform the development of the ABC R&D Roadmap by identifying priority segments of the residential and commercial building stock that require new technology R&D in order to achieve ABC goals related to energy performance, affordability, and carbon neutrality.

Building Electrification Impacts. The focus on thermal energy use throughout this study makes the results suitable for numerous applications relating to building electrification research. For instance, the typology results can help identify which specific building segments might be able to decarbonize through equipment swaps alone versus comprehensive whole-building deep retrofits. Determining the most cost-effective upgrade package to reach carbon neutrality for a given building segment is an objective that can be informed by the baseline characterizations presented in this study.

4.2 Study Limitations

4.2.1 Data Limitations

Our proposed approach has some limitations, particularly around the availability of national-scale data relevant for upgrades. As discussed in Section 2.3, inputs to ResStock are based on available national-scale surveys such as national-compiled parcel data, RECS, American Housing Survey, and American Community Survey, and then supplemented with expert knowledge or smaller data sets where national data do not exist. For ComStock, nearly all inputs are linked via vintage, building type, and climate zone to the appropriate ASHRAE 90.1 code characteristics. Building construction and urban form, however, vary widely throughout the United States, even city to city, and these existing data sources do not capture all of the variability, and are missing key fields that are important for deep energy retrofits (e.g., presence of balconies). No centrally collected databases exist for most of these location-specific characteristics. Much of the data on buildings in the United States is disparate, local (e.g., tax assessor databases), and varying in quality depending on what is collected. Furthermore, code adoption (especially for residential buildings) varies state to state, and code compliance for all buildings also varies.

Throughout the remainder of the characterization study, as we identify key inputs that are missing, we will work with the ABC Collaborative to create simple heuristics for mapping characteristics, where possible. For example, in ResStock, we currently obtain the wall type from a national parcel database that primarily compiles tax assessor data. From this data, we separate out exterior finishes from the main wall construction material (e.g., concrete, steel, wood frame, structural brick). However, given that the quality of information collected on structural materials varies county-to-county (or might not be collected at all), there is still some uncertainty on these wall material proportions. In the context of ABC, this matters quite a bit, as in most cases the structural brick will be able to support much more weight compared to wood frame construction with face brick, so the cost and complexity of a prefabricated panel upgrade might change dramatically depending on whether the existing wall is able to support the panel.

4.2.2 Scope Limitations

The breadth of this full characterization study—covering essentially all residential and most commercial building market segments across all U.S. climate zones—makes it impossible to achieve the depth of the retrofit deployment-oriented typology studies discussed in Section 1.1. Each city's building stock has unique architectural context and history with potential implications on ABC retrofit solutions. Consider, for example, how the 1871 Chicago fire or 1906 San Francisco earthquake impacted local building codes, or how local building materials (e.g., brownstones in New York City, greystones in Chicago) or construction practices (e.g., asbestos siding) might or might not affect retrofit applicability at a very localized level. Identifying city-specific architectural details and retrofit considerations are beyond the scope of this initial characterization study; however, we plan to reference existing city-specific typology analyses and coordinate with ongoing research efforts in this area, particularly the RMI-led REALIZE-CA[23] as well as the American Institute of Architects (AIA)-funded "Envelope Retrofit Guide: Net Zero Energy Ready Strategies for Existing Buildings,"[24] which is initially focusing on architectural analysis of affordable multifamily building typology in the northeast United States.

[23] For more information, see: https://rmi.org/our-work/buildings/realize/realize-ca/.
[24] For more information, see: https://architecture.pratt.edu/articles/envelope-retrofitguide.

5 Conclusions and Next Steps

In this report, we discussed the first comprehensive, nationwide building characterization study for the United States. Leveraging the ResStock and ComStock models, we are able to characterize and segment the residential and commercial building stocks, respectively. Furthermore, we developed a flexible approach for adapting the segmentation based on use case and application. This characterization study will directly support development of technology targets and goals and will support other aspects of ABC-related analyses. Furthermore, the supporting data behind the typology study in the online dashboard can serve as a baseline for the development of local efficiency and decarbonization strategies.

The next step of this project involves working with the ABC Analysis Working Group to identify the main building segments of interest; this report has highlighted some of the highest thermal energy use segments for both the residential and commercial sectors, but there will likely be other aspects of interest to the working group and DOE, and we will work with the larger group to prioritize segments and integrate them with other goals of the ABC analysis work. With the segments selected, we will then model a series of individual and packaged upgrades to identify appropriate solutions for segments of interest.

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Appendix A

HVAC Category	ComStock HVAC System	Prevalence by Floor Area
Central Multizone System	Packaged variable air volume with district hot water reheat	0.9%
	Packaged variable air volume with gas boiler reheat	4.4%
	Packaged variable air volume with gas heat with electric reheat	4.2%
	Packaged variable air volume with parallel fan powered boxes	4.2%
	Variable air volume air-cooled chiller with district hot water reheat	0.3%
	Variable air volume air-cooled chiller with gas boiler reheat	3.4%
	Variable air volume air-cooled chiller with parallel fan powered boxes	1.0%
	Variable air volume chiller with district hot water reheat	0.6%
	Variable air volume chiller with gas boiler reheat	4.5%
	Variable air volume chiller with parallel fan powered boxes	2.4%
	Variable air volume district chilled water with district hot water reheat	2.7%
	Variable air volume district chilled water with gas boiler reheat	0.1%
	Variable air volume district chilled water with parallel fan powered boxes	0.3%
	Total	**28.9%**
Small Packaged Unit	Direct evaporative coolers with baseboard electric	0.1%
	Direct evaporative coolers with baseboard gas boiler	0.0%
	Direct evaporative coolers with forced air furnace	0.6%
	Packaged single zone – air conditioner district chilled water with district hot water	0.2%
	Packaged single zone – air conditioner district chilled water with electric coil	1.0%
	Packaged single zone – air conditioner district hot water	0.3%
	Packaged single zone – air conditioner with electric coil	18.9%
	Packaged single zone – air conditioner with gas boiler	3.7%
	Packaged single zone – air conditioner with gas coil	22.2%
	Packaged single zone – heat pump	0.3%
	Residential air conditioner with residential forced air furnace	6.4%
	Residential forced air furnace	1.3%
	Total	**55.1%**
Zone-by-Zone	Baseboard electric	0.2%
	Baseboard gas boiler	0.0%
	Dedicated outdoor air system with fan coil air-cooled chiller with baseboard electric	0.0%

HVAC Category	ComStock HVAC System	Prevalence by Floor Area
	Dedicated outdoor air system with fan coil air-cooled chiller with boiler	0.6%
	Dedicated outdoor air system with fan coil air-cooled chiller with district hot water	0.2%
	Dedicated outdoor air system with fan coil chiller with baseboard electric	0.1%
	Dedicated outdoor air system with fan coil chiller with boiler	0.8%
	Dedicated outdoor air system with fan coil chiller with district hot water	0.0%
	Dedicated outdoor air system with fan coil district chilled water with baseboard electric	0.1%
	Dedicated outdoor air system with fan coil district chilled water with boiler	0.1%
	Dedicated outdoor air system with fan coil district chilled water with district hot water	0.1%
	Dedicated outdoor air system with variable refrigerant flow	0.7%
	Dedicated outdoor air system with water source heat pumps cooling tower with boiler	1.6%
	Dedicated outdoor air system with water source heat pumps with ground source heat pump	1.3%
	Gas unit heaters	0.5%
	Packaged terminal air conditioner with baseboard district hot water	0.1%
	Packaged terminal air conditioner with electric coil	2.9%
	Packaged terminal air conditioner with gas boiler	0.0%
	Packaged terminal air conditioner with gas coil	0.2%
	Packaged terminal heat pump	6.6%
	Total	**16.0%**

Appendix B

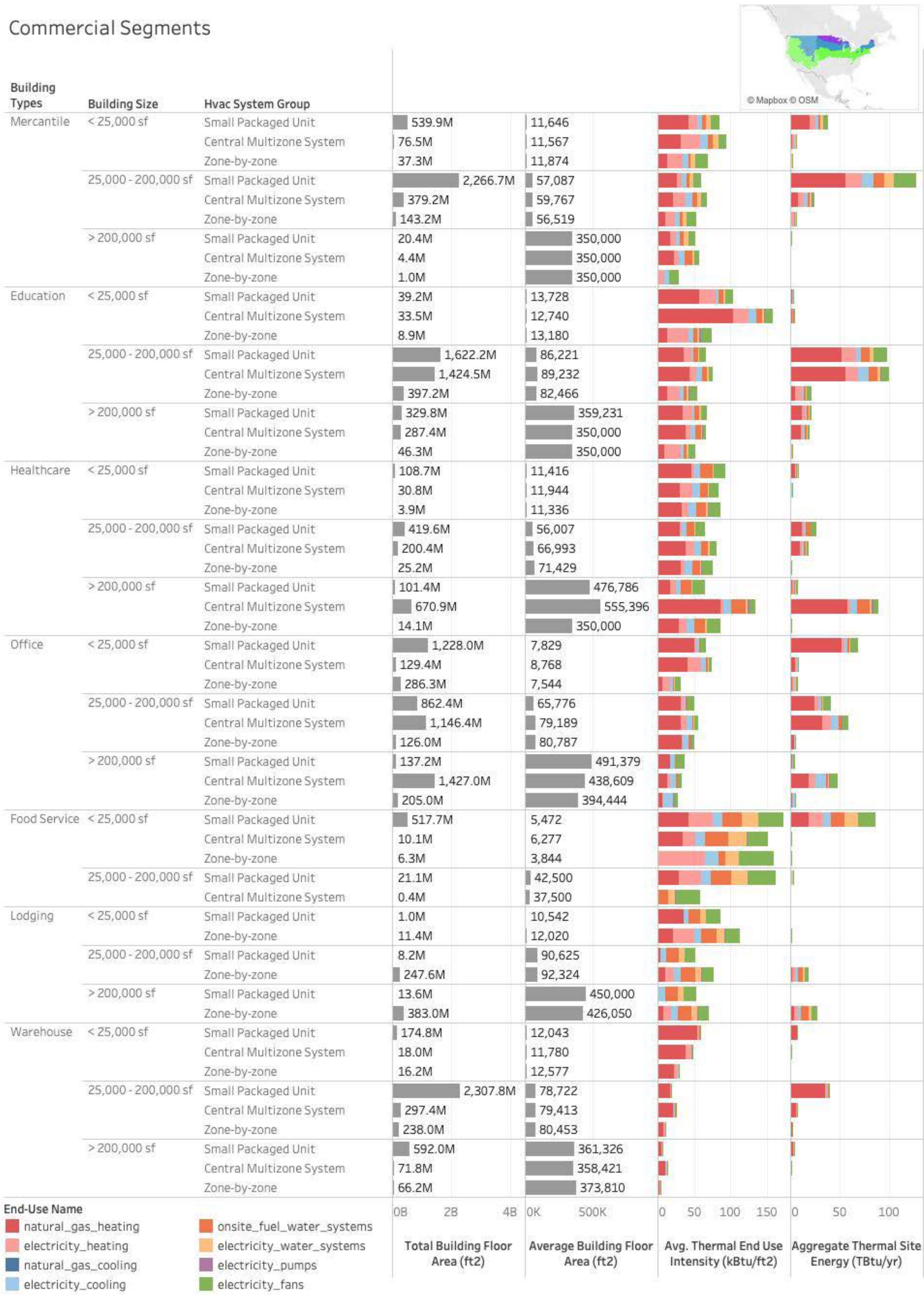

Figure B-1. Commercial segments, cold

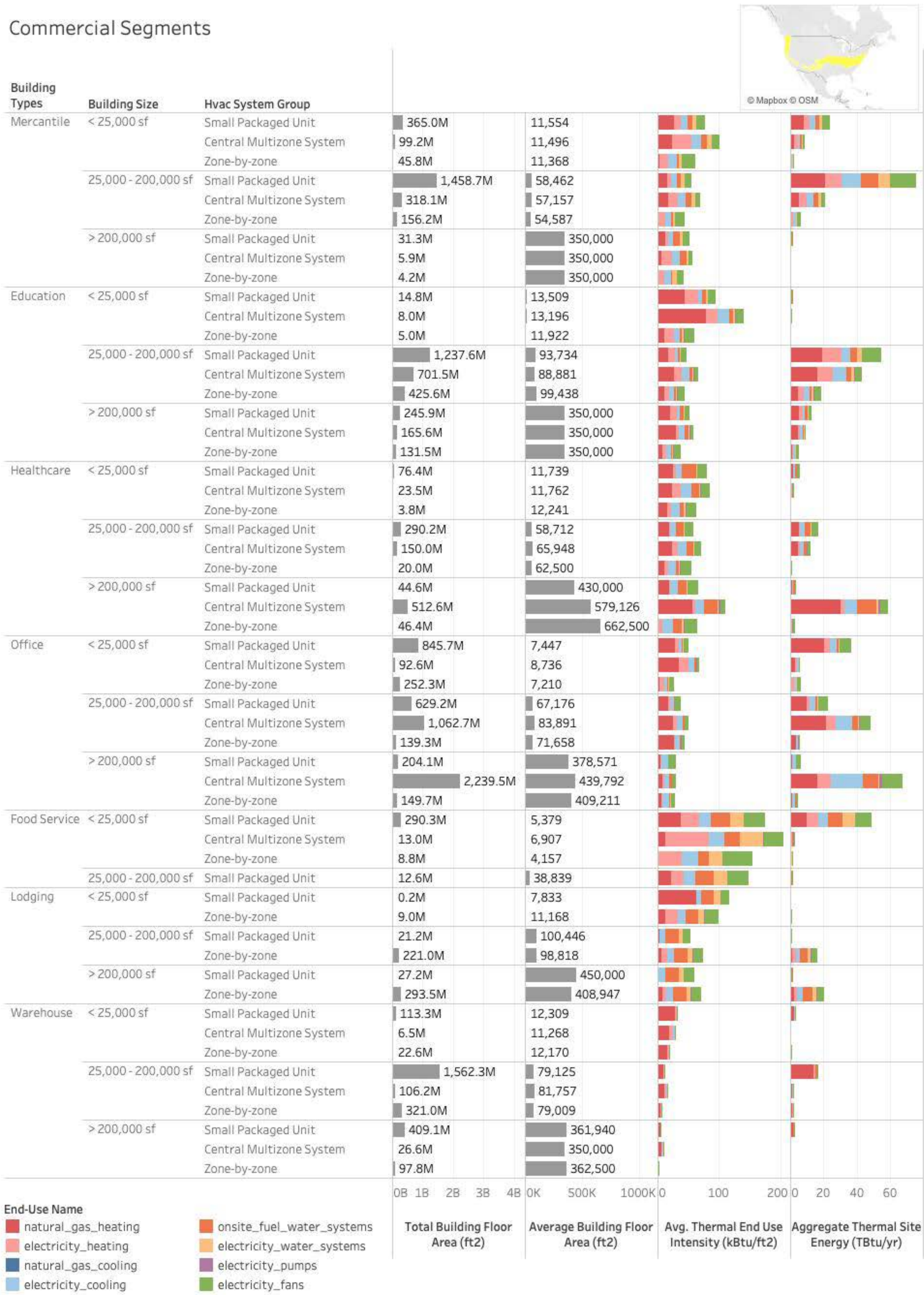

Figure B-2. Commercial segments, mixed

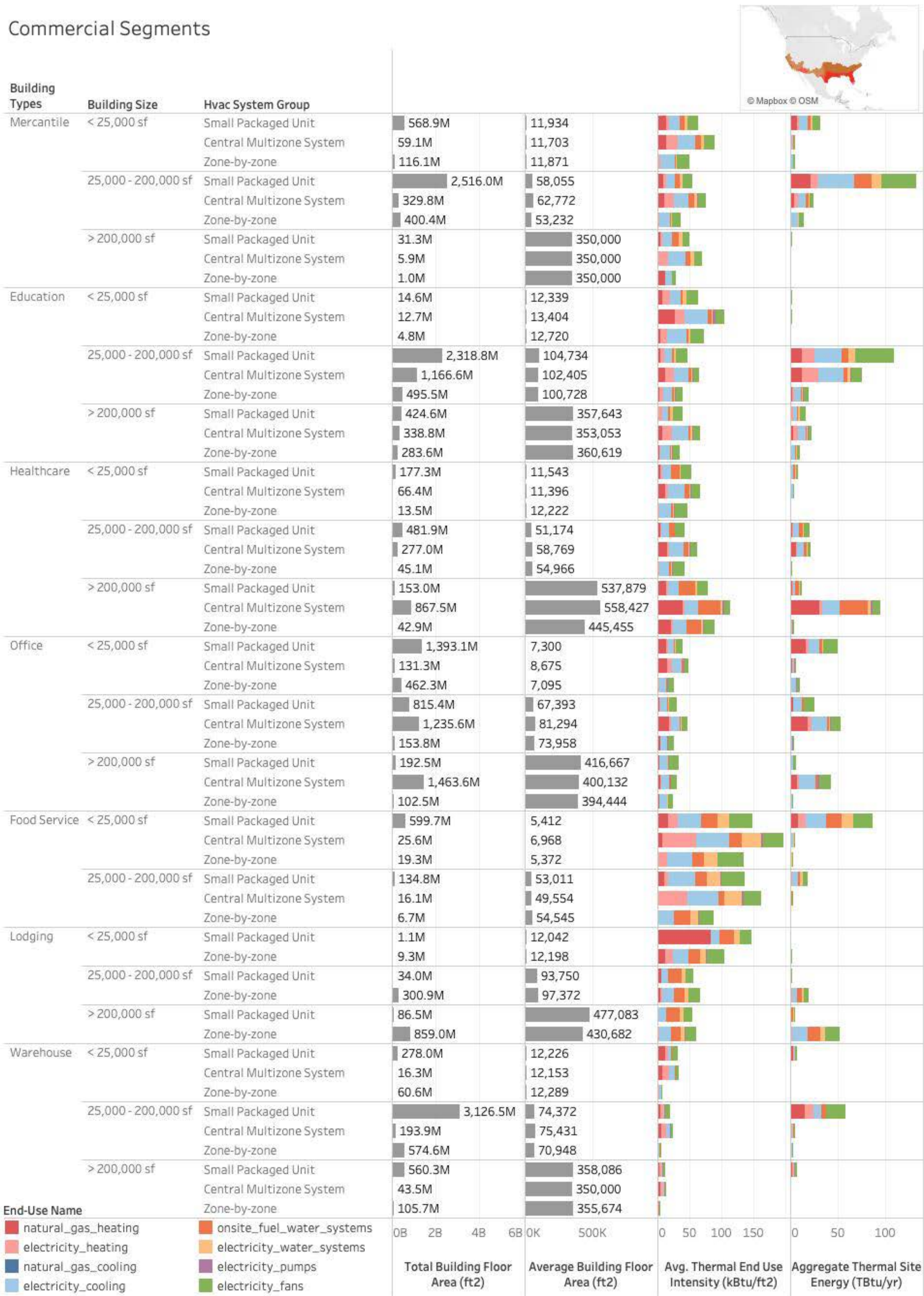

Figure B-3. Commercial segments, hot