

Carbon Free Boston

Buildings Technical Report 2019



Project Team

Arup Group Ltd.

Brian Swett
Rebecca Hatchadorian
Rob Best

Katie Wholey
Alexandra Calven
Erica Levine

Sara Tepfer

Institute for Sustainable Energy (ISE), Boston University

Cutler J. Cleveland
Principal Investigator
Professor, Department of Earth and
Environment, ISE

Peter Fox-Penner
Co-Principal Investigator
Director, ISE
Professor of Practice, Questrom School of
Business

Michael J. Walsh
Technical Lead, ISE
Research Assistant Professor, Department
of Earth and Environment

Margaret Cherne-Hendrick
Senior Policy Associate, ISE
Sucharita Gopal
Professor, Department of Earth and
Environment, ISE

Joshua R. Castigliero
Research Fellow, ISE

Taylor Perez
Graduate Research Assistant, ISE

Adam Pollack
PhD Student, Department of Earth and
Environment, ISE

Kevin Zheng
Research Fellow, ISE

Robert Perry
Administrative Coordinator, ISE

Laura Hurley
Communications Manager, ISE

Olivia Simpson
Web Site Developer, ISE

Carbon Free Boston Steering Committee

Janet Atkins
Ridgeway Philanthropy

Vineet Gupta
City of Boston

Richard McGuinness
Boston Planning & Development Agency

Bud Ris
Boston Green Ribbon Commission

Carl Spector
City of Boston

Kathleen Theoharides
Commonwealth of Massachusetts

Green Ribbon Commission Staff

John Cleveland
Amy Longsworth

Green Ribbon Commission Carbon Free Boston Working Group

Mindy Lubber
Ceres (Chair)

Robert A. Brown
Boston University

Christopher Cook
City of Boston

Bill Fahey
Veolia

Amos B. Hostetter, Jr.
Barr Foundation

Katherine Lapp
Harvard University

Alexandra Liftman
Bank of America

Penni McLean-Conner
Eversource

Marcy Reed
National Grid

Israel Ruiz
MIT

Al Scaramelli
Beacon Capital Partners

City of Boston Staff

Alison Brizius
Kat Eshel

Lexi Smith
Vineet Gupta

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Carbon Free Boston: Buildings Technical Report

Rebecca Hatchadorian,¹ Rob Best,¹ Katie Wholey,¹ Alexandra Calven,¹ Erica Levine,¹ Sara Tepfer,¹
Brian Swett,¹ Michael J. Walsh,^{2,3} Adam Pollack,^{2,3} Taylor Perez,^{2,3} Joshua R. Castigliero,^{2,3}
and Cutler J. Cleveland^{2,3}

¹Arup Group Ltd., Boston, MA, USA

²Institute for Sustainable Energy, Boston University, Boston, MA, USA

³Department of Earth and Environment, Boston University, Boston, MA, USA

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Carbon Free Boston: Technical Summary
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Carbon Free Boston: Waste Technical Report
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Carbon Free Boston: Offsets Technical Report

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1 OVERVIEW

Boston is known for its historic iconic buildings, from the Paul Revere House in the North End, to City Hall in Government Center, to the Old South Meeting House in Downtown Crossing, to the African Meeting House on Beacon Hill, to 200 Clarendon (the Hancock Tower) in Back Bay, to Abbotsford in Roxbury. In total, there are over 86,000 buildings that comprise more than 647 million square feet of area. Most of these buildings will still be in use in 2050.

Floorspace (square footage) is almost evenly split between residential and non-residential uses, but residential buildings account for nearly 80,000 (93 percent) of the 86,000 buildings. Boston's buildings are used for a diverse range of activities that include homes, offices, hospitals, factories, laboratories, schools, public service, retail, hotels, restaurants, and convention space. Building type strongly influences energy use; for example, restaurants, hospitals, and laboratories have high energy demands compared to other commercial uses.

Boston's building stock is characterized by thousands of turn-of-the-20th century homes and a post-World War II building boom that expanded both residential buildings and commercial space. Boston is in the midst of another boom in building construction that is transforming neighborhoods across the city.

The age of Boston's building stock is important because many of the city's residences were built before the 1950's and the establishment of the first building energy codes. These buildings typically have less insulation, are less air-tight, and use older, inefficient equipment, all of which result in higher energy use and GHG emissions compared to newer buildings. Recent buildings conform to a common energy code that aims to balance cost-effectiveness, building comfort, and environmental goals that leads to lower energy use and GHG emissions.

Carbon-neutral buildings are highly efficient and do not use fossil fuels for heating and other services. New buildings will be built to the highest possible performance standards while avoiding the lock-in of fossil fuels. Existing buildings will require deep retrofits that reduce energy consumption and electrify heating systems. Achieving these goals requires a synergistic mix of fast-acting policies such as net zero codes, performance mandates, and retrofit requirements. These changes generate significant benefits but require significant upfront capital, a trained labor force, and the willingness and capacity of Boston's residents, businesses and institutions to invest in their buildings. These actions must also give socially vulnerable populations access to information, technical assistance, and financial resources. This will ensure that they can reap the benefits of lower utility bills, and not be further displaced as a result of higher housing costs, or left out of benefits that accrue to residents of new, efficient buildings.

2 SUMMARY OF KEY FINDINGS

- Boston's building stock generates approximately three-quarters of the City's GHG emissions from the consumption of electricity, and the combustion of natural gas and fuel oil.
- Building energy modeling was applied to the entire city using calibrated models representing the city's building stock. These models were used to identify optimal energy efficiency and decarbonization strategies.

- Current policy and trajectory will not meet the goal of carbon neutrality by 2050. Additional action is needed to significantly reduction GHG emissions over the next 32 years.
- Both incentives and mandates play an important role in rewarding and driving behavior and both will have a role to play for Boston to achieve carbon neutrality. While important, incentive-based policies and programs alone do not provide the market penetration needed. Only mandates provide the level of penetration required to make a significant impact on emissions reductions.
- New construction is only a small part of the challenge. As this analysis demonstrates, predicted growth will only represent 15 percent of the building stock by 2050. While new building net zero emissions codes are necessary to offset growth, they alone will not make a deep reduction in GHG emissions from buildings.
- The thermal loads in buildings needs to be electrified to the greatest extent feasible. Deep levels of energy reduction need to be realized at the same time to lower the cost of electrification.
- Significant action needs to be taken in the next decade. The policy timelines included in the analysis predominantly begin implementation over the next decade in order to start to bend the trajectory aligned with the City's commitments.

3 BACKGROUND

The scope of this study focused on evaluating various energy conservation measures and strategies required to reduce sector-wide GHG emissions to zero by 2050. Achieving this goal will require changes to two existing policy regimes. First, the planning and development process needs to require new buildings to eliminate the on-site use of fossil fuels. Second, existing buildings will need to be retrofitted to eliminate the on-site use of fossil fuels. Supply, cost and delivery constraints associated with carbon-free electricity and fuels will likely necessitate efforts to reduce overall energy consumption. These constraints are explored in detail in the *Carbon Free Boston Energy Technical Report*, but are used here to frame the analysis.

From a technical standpoint, the decarbonization of the building sector will require most buildings to be electrified and powered by GHG-free electricity. This primarily involves conversion of combustion-based thermal systems (heating and hot water) to electric heat pumps and boilers, as well as electrifying cooking and backup services. Electrification will need to be paired with whole-building energy conservation measures to ensure feasibility, minimize energy costs and promote occupant comfort and wellbeing. Some buildings and services are challenging to fully electrify, here renewable fuels may help to aid decarbonization, but the supply of such fuels likely will be limited.

Our approach here uses building energy modeling (BEM) to evaluate the impact of various energy conservation measures, electrification measures, and performance targets across a representative group of building use classes and vintages. Using these detailed building-level analyses, we assess how different policy regimes impact city-wide building sector emissions. This study compares the relative impact of individual and packaged ECMs in the context of incentive-based and mandate-based policy regimes.

We find that found that achieving the goal of carbon neutrality will require retrofitting a large proportion of Boston's building stock over the next 30 years. Currently, the life-cycle cost of building

thermal electrification is generally higher than the use of thermal services based on fossil fuel combustion. Lowering building energy consumption to avoid the constraints noted above will require the application of whole-building energy conservation measures that may require large upfront capital costs. Innovative financing programs will be required to overcome the capital hurdle. Retrofitting tens of thousands of buildings over the next 30 years will require a large, local and well-trained workforce. Such aggressive action will require a regulatory regime that is simultaneously comprehensive and flexible, and is supported by a number of enabling policies.

The benefits of carbon-neutral buildings extend well beyond lower GHG emissions. Energy conservation measures can significantly reduce operational costs that lower the energy burden of Boston's low-income residents and saves money for its businesses. Energy retrofits can also make buildings more climate-resilient, reducing the future costs of heat stress and flooding. Such retrofits can improve indoor air quality and comfort for building occupants. Affordable, new zero net emissions buildings can attract more people to the urban core and thus reduce transportation-related GHG emissions. Overcoming cost barriers will require recognizing the additional benefits from the improvement of Boston's built environment.

4 BOSTON'S BUILDING STOCK

4.1 EXISTING BUILDING STOCK

The energy use, emissions, potential interventions, and applicable policy instruments will all be influenced by the building's use, vintage and ownership. To capture this diversity and inventory Boston's building stock, this analysis leveraged the Tax Parcel ID Database from the City's Assessor's Office. Updated in 2018, this database assigns a use type classification, defined by the Commonwealth of Massachusetts Division of Local Services, to each separate parcel in the city (*Property Type Classification Codes Non-arm's Length Codes and Sales Report Spreadsheet Specifications*, 2018). Over 86,000 buildings and 647 million square feet applicable to the building sector were identified in the database. Parcels with non-building usages were not included and tax-exempt parcels were further classified using an accessory database provided by the Boston Planning and Development Authority (BPDA). Unit size, number of condominium units, and aggregate square footage was used to segment single, small multifamily (triple deckers of 2-4 units) and large multifamily (five or more units) buildings. In some instances, additional cleaning or processing of the data was needed to address issues such as many buildings on one parcel, or multiple parcels of mixed uses. Parcel and building year-built values were then used to segment by building age ranges defined for this study. Total floorspace by use and age range and other select attributes was subsequently aggregated to be used for calculation of total energy use.

This building stock was segmented into fifteen (15) representative building typologies which define their primary use (Table 1). Within each of those building types, four (4) age ranges have been further defined, yielding a total of 60 building types to represent the City of Boston for the study. The age ranges defined for the buildings align with energy code development and changes as well as with the methodology used in the *Community Energy Study*. Figure 1 shows the distribution of floorspace by building type and age class.

Over 60 percent of Boston's floorspace and 84 percent of its buildings was built before 1950 when no energy codes existed. Over half (55 percent) of total square footage and 93 percent of buildings (80,000) are residential. Boston's commercial buildings are predominantly office buildings. Commercial office buildings comprise 18 percent of the square footage but only 2 percent of the total number of buildings (1,700). Boston's buildings stock is predominantly comprised of small residential buildings typically ranging from 1,000 to 5,000 square feet (Figure 2 left). Despite the large number of small buildings, half of Boston's floorspace is dominated by its largest 4,000 buildings (Figure 2 right).

Size is often used as a cutoff for building regulation. For example Boston's BERDO regulation covers buildings over 35,000 square feet or parcels with over 100,000 square feet, which covers over 2,000 buildings. Figure 3 shows the distribution of floorspace and building counts by different size classes. The predominant amount of commercial space is distributed across approximately 700 buildings greater than 100,000 square feet.

Buildings were also classified by ownership using owner occupancy codes in the residential sector, and exempt-property ownership data obtained from the BPDA. Ownership structures have different relationships to benefits, drivers and motivations. Breakdowns of ownership by building use class (Figure 4) and of building class by building use class by ownership (Figure 5) further demonstrate the diversity of the building stock and demonstrate the need for comprehensive but flexible policy regimes needed for reducing GHG emissions.

Figure 1. Building GHG Emissions by Age and Type of Building

The GHG emissions from Boston’s buildings are influenced by the age and floorspace in each type of building. This chart shows the amount of floorspace (top bar) and emissions (bottom bar) by building use class (columns) and age class (colored blocks). The area of a block relative to the total area is proportional to the floor space or emissions associated with a specific building use class and age class segment. New Construction is the amount of floorspace that is projected to be built between 2018 and 2050. Note that newer buildings are significantly less GHG intensive than the existing stock, while Medical, Laboratory, Industrial Buildings are much more energy intensive than the average stock. Retail etc. includes retail stores, hotels, and restaurants. Public services include K-12 schools, fire and police stations. Source: Boston Assessors Database & model calculations

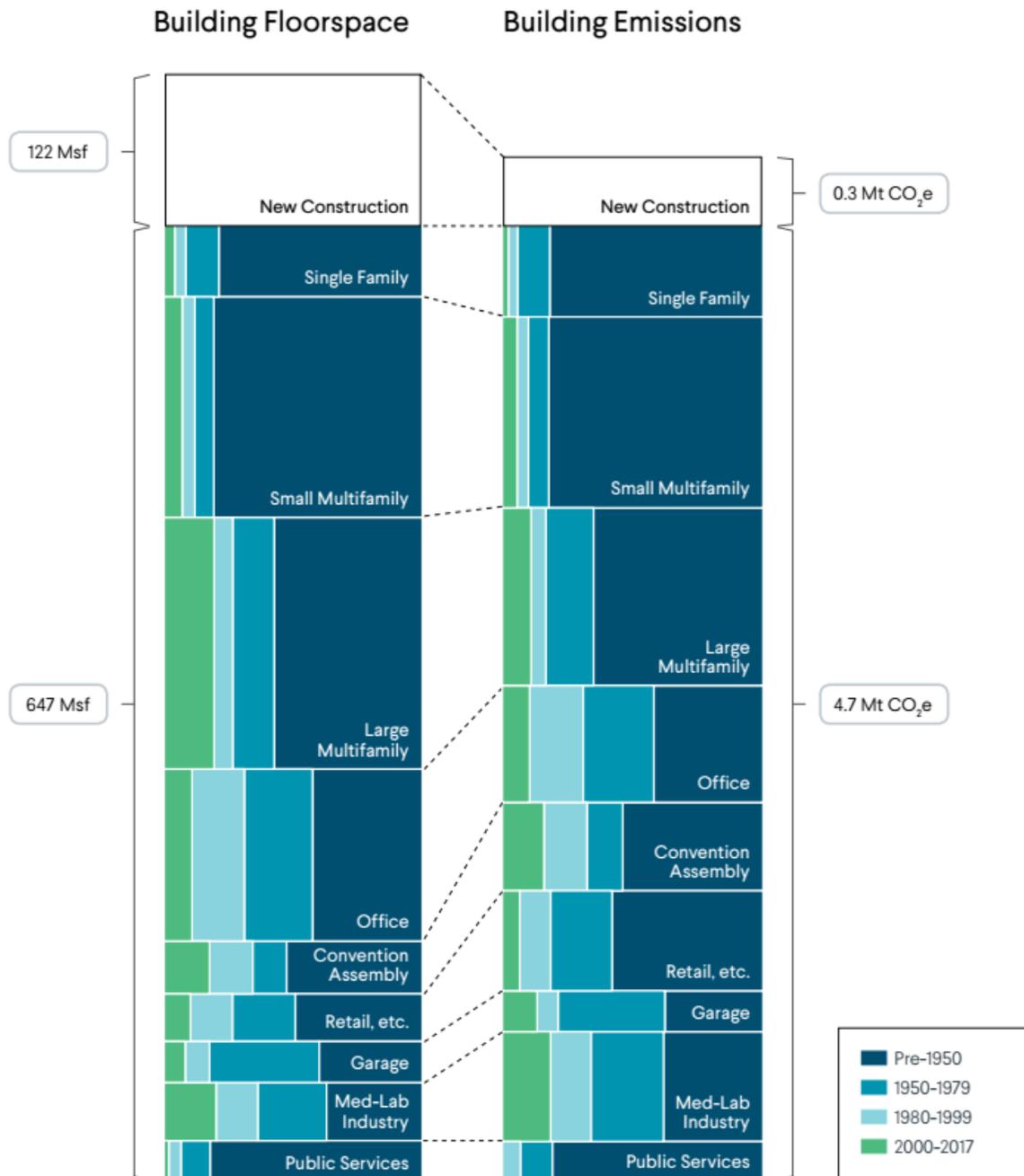
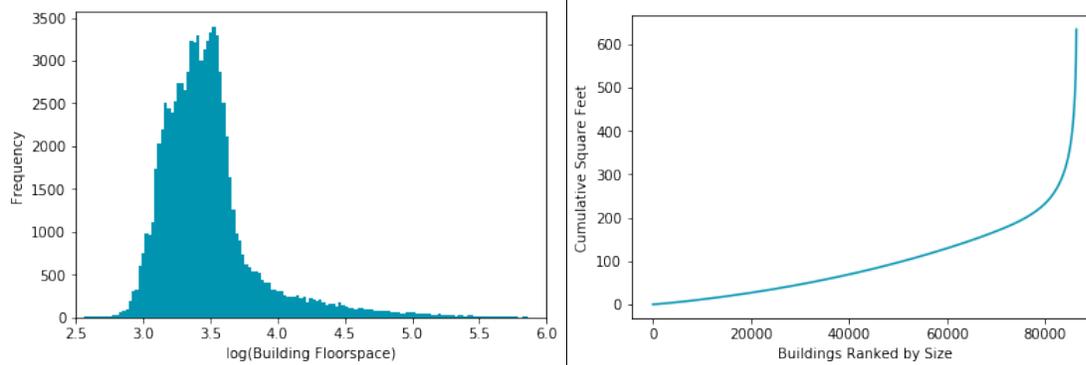


Table 1. Building use class typology definitions

USE CLASS	DESCRIPTION
SINGLE FAMILY RESIDENTIAL	Buildings that have one living unit per building footprint. Living area has been used for area calculations.
SMALL MULTI-FAMILY	2-4 family residences, intended to represent the triple decker that is prominent in Boston. Living area has been used for area calculations, except for condominiums where building area was used.
MULTI-FAMILY RESIDENTIAL	This typology is defined as 5+ family residences. Gross area has been used for area calculations, except for condominiums where building area was used.
OFFICE	This typology is largely composed of buildings on tax parcels classified as multiple story offices, but also consists of administrative buildings linked to owner classes like the city, the state, and the federal government. This is the largest commercial typology with most buildings directly classified based on direct property type matching, but a fair number of which are classified based on unknown property types and the judgement that offices represent particular descriptions better than our more specifically defined, other commercial typologies.
FIRE/POLICE	Boston Fire and Police Department buildings.
CONVENTION/ASSEMBLY	Arenas, auditoriums, large restaurants, movie theaters, libraries, and some college or university buildings. Convention/assembly is similar to office in that it's not as specifically defined as other commercial typologies so specific property keys without a clear mapping were mapped to it based on their lack of fit with specific typologies.
HOTEL	Inns, motels, and hotels.
MEDICAL/LAB/PRODUCTION	Hospitals, laboratories, and industrial uses. Many property type codes map to industrial uses best classified in this typology.
RESTAURANT	This typology is defined as standalone restaurants only. The largest of these, with square footage above 10,000 square feet were renamed convention/assembly.
RETAIL	Standalone retail, laundromats, stores in malls and even property types such as health clubs, marinas, and gas stations.
SCHOOL	Public and Private K-12 schools only. (Higher education buildings have been segmented per their predominant use type, not as a singular campus.)
SUPERMARKET	Standalone Supermarkets
WAREHOUSE	Storage facilities including cold and industrial storage.
WORSHIP	Churches, synagogues, and other places of worship. Also includes exempt properties coded as religious which could include some housing and other use space.
GARAGE	This typology is defined as standalone parking garages and parking lots with gross area used to represent the building area field.

Figure 2. Distribution of Boston's Buildings by Size

(left) Distribution of Boston's building stock by size. (right) Cumulative square feet by building size. Source: Boston Assessors Database & model calculations.



Within residential buildings, these include Owners, Condominium Associations (i.e. multiple owners needing to take collective action), Landlords and Tenants. Owners are able to take action at their own discretion and are the ones who reap the direct benefits of that action. The relationship is different in a Landlord/Tenant relationship where the Landlord is able to take action yet in most instances, it is the tenant who reaps the direct benefits of that action, for example in reduced utility bills. The policy mechanisms for both of these instances will likely require differentiation to recognize these relationships.

Within commercial buildings, there are an even wider array of actors including public entities (i.e. Federal, State, Quasi-public and City), Institutions (i.e. the Medical and Educational institutions), Developers, Property Owners, Owner occupiers and Tenants again all of which have different relationships to benefits, drivers and motivations.

Figure 3. Boston's building stock by size class

Left three columns represent the residential stock. Right five columns represent the commercial stock. Column labels represent the count of buildings in each size class. Source: Boston Assessors Database & model calculations.

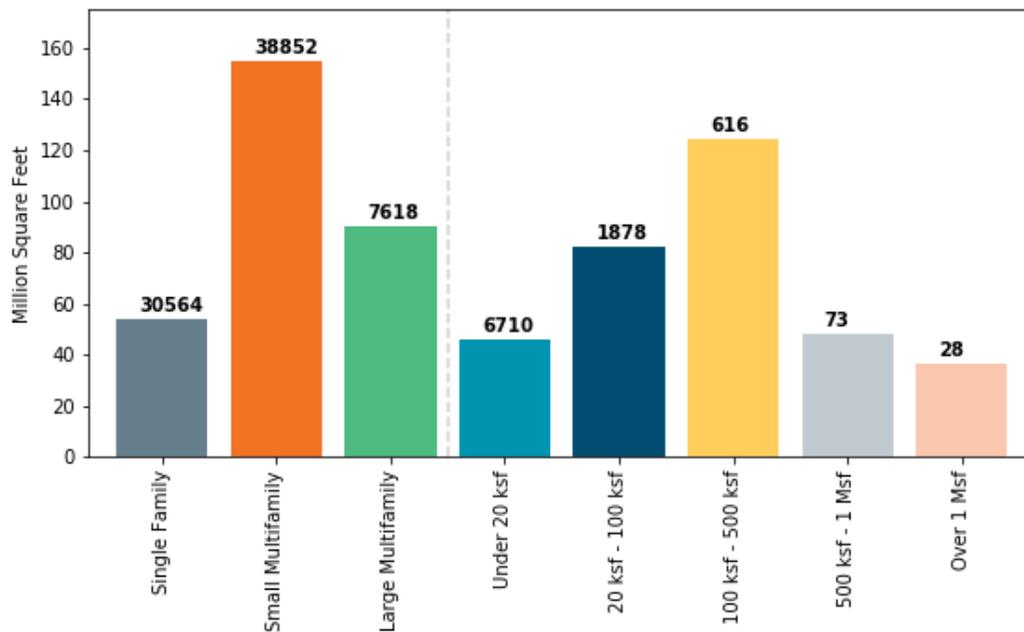


Figure 4. Building ownership (colors) building use class (bars)

Source: Boston Assessors Database & model calculations

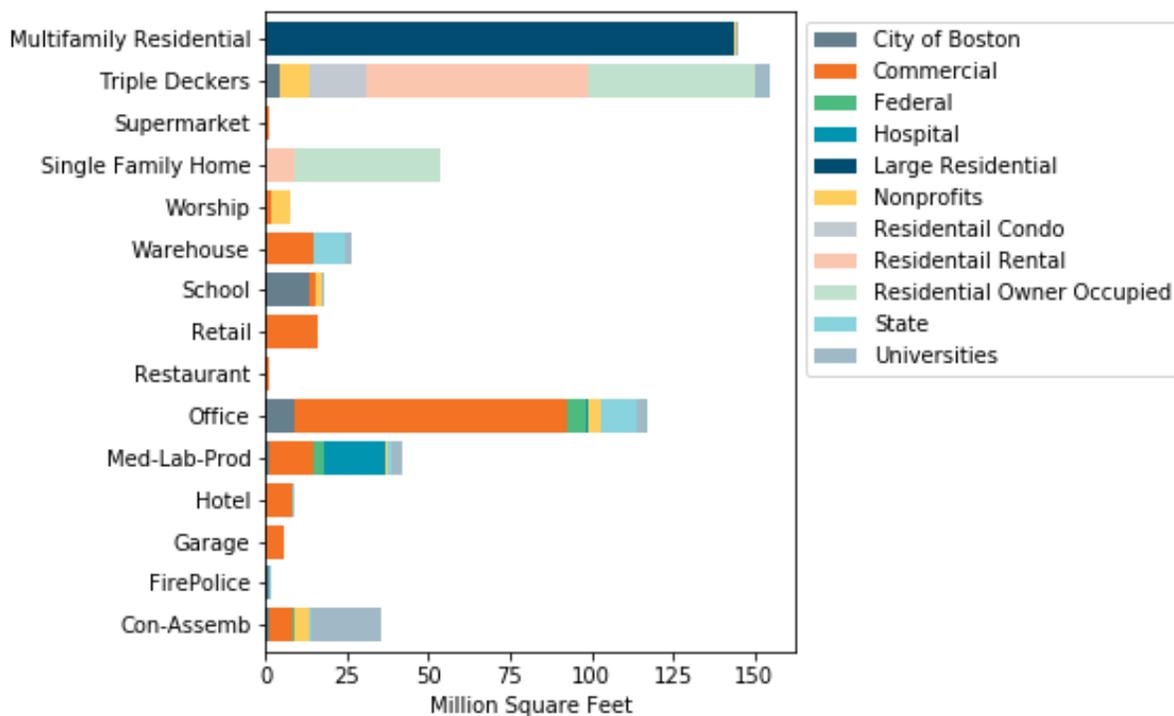
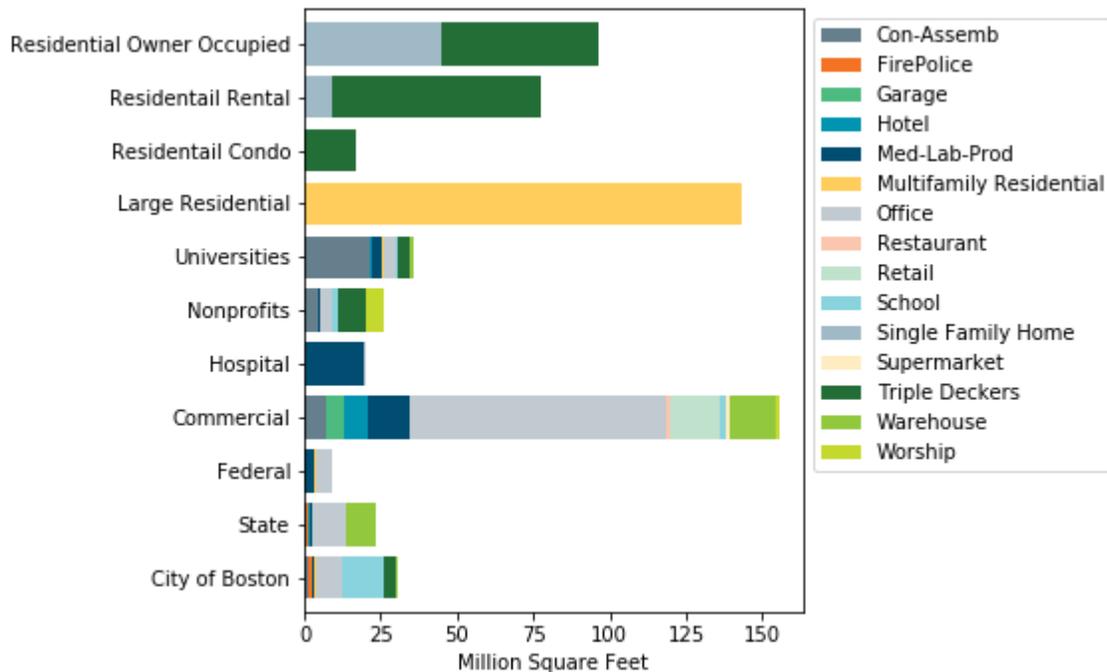


Figure 5. Building use class (colors) by building ownership

Source: Boston Assessors Database & model calculations



It is important to note that the tax parcel database is intended to be used for property valuations, and has several limitations for this study in its application as an inventory for a bottom-up citywide energy model. Some of these limitations include:

- Lack of mapping parcels to a specific building or set of buildings.
- Insufficient differentiation of building use under a given property use code. For example, a rehabilitation facility classified as a hospital would be categorized as an energy intensive Med-Lab-Production building rather than a less energy intensive office building.
- Insufficient accounting of mixed uses, meaning the predominant use is often provided. This results in a large portion of retail (e.g., first floor of an office or residential building) or underground garage space not able to be accounted for. Instead all area is segmented to the primary use which may have a significantly different energy intensity.
- Tax-exempt properties such as hospitals, universities, etc., which make up a significant portion of Boston's building stock often are assigned use-codes that are insufficient to accurately map to specific building use classes.
- A moderate amount of parcels are identified as 'unknown age' which could not be mapped.
- The database does not record when a major renovation occurs, only the date of original construction. As such, the City cannot understand the rate or frequency of major renovations, nor have an accurate picture of the condition of its building stock.

4.2 BOSTON'S FUTURE GROWTH

Boston has experienced a building boom over the past decade. Given current socioeconomic trends and focus on urban development, it is anticipated that Boston will continue to grow significantly though

2050. The *Imagine Boston 2030* report [2] projects that by 2050, Boston’s estimated population will be over 800,000 people, and that the city will add around 77,500 new housing units and 40 million square feet of non-residential space. In that time it is expected that some existing buildings are demolished. Boston’s future building stock is thus defined for this analysis as the existing stock minus demolition plus any new construction:

$$\text{Future building stock} = \text{2017 square footage (existing)} - \text{demolition} + \text{new construction} \quad \text{Eq (1)}$$

The demolition rate was assumed at 0.25% per year across all typologies, which are assumed to be replaced by new construction of the same use class. This replacement is in addition to the new growth projected below.

Residential growth projections were obtained from *Imagine Boston 2030* [2] which were derived from the *Metropolitan Area Planning Council’s 2014 Growth Projections* [3]. *Imagine Boston 2030* identifies the number of housing units needed by 2030 and 2050, 53,000 units and 42,000 units respectively for a total of 95,000 housing units by 2050. The 53,000 units by 2030 is measured from a baseline year of 2011, as such a number of those units have already been built.

To calculate the number of new housing units from 2011-2017, project counts from the *Housing a Changing City Boston 2030* [4] reports were used. This data showed that 17,507 housing units were completed from 2012-2017. This result is slightly ahead of a linear projection for 53,000 new units from 2011-2030 which would have resulted in 16,737 units. Accordingly, 35,493 units are anticipated from 2018-2030.

Our analysis used 2017 as the baseline year for projecting growth. The 35,493 housing units to 2030 and the 42,000 units to 2050 were translated to square footage based on an assumption of 1,000 gross square feet (gsf) per unit resulting in 35,493,000 square feet of residential growth between 2017-2030 and 42 million square feet of residential growth between 2031-2050.

Table 2. Projected New Growth Allocations to Building Use Classes

Source: [2]–[4] and model assumptions.

Building Use Class	2018-2050 Growth (Msf)
Single Family	3.88
Small Multifamily	20.41
Large Multifamily	52.76
Convention/Assembly	2.65
Hotel	2.27
Med/Lab/Production	4.05
Office	19.80
Restaurant	0.11
Retail	3.96
Supermarket	0.85
Warehouse/Storage	0.00
Worship	1.68
Fire and Police	0.38
Schools	4.04
Garage	0.00
Total	116.84

The total residential growth square footage was then allocated to each of the three (3) typologies. From the existing building stock data set, the post-2000 age range was used for its proportion of single family, small multi-family and large multi-family rather than the total housing stock (i.e. all age ranges) to reflect the most recent trend in new construction housing to large multi-family residential. As a result, the residential sector is projected to grow by over 77 million square feet by 2050, with 35 million square feet by 2030 and 42 million square feet by 2050.

Imagine Boston 2030 projects 20 million square feet of commercial growth by 2030, with an additional 20 million square feet built between 2030 and 2050, for a total net growth of 40 million new square feet. This growth was assumed to be applicable to the following typologies: Office, Convention/Assembly, Hotel, Medical/Lab/Production, Supermarket, Restaurant, Retail and Warehouse. Like residential projections, the 20 million square feet by 2030 is measured from a baseline year of 2011. The square footage to 2030 has been allocated consistently from 2011 to 2030 for an addition of 1,052,632 new square footage per year. It is therefore assumed that 6,315,789 square feet has already been completed by 2017 and that 13,684,211 square feet of growth is yet to be built by 2030. To allocate new development, the BPDA planning pipeline was used to allocate the 20 M sf of commercial floorspace for each typology (Table 2). This allocation assumes a predominant growth in the low-EUI typology of office. If actual growth is in more energy-intensive sectors such as Medical/Lab/Production projected emissions will likely be higher than assumed here and represented in our results such as (Figure 1).

Growth in three typologies typically representing solely institutional buildings (Fire/Police, Schools and Worship) was assumed to be correlated with population growth. Current floorspace per capita of these typologies was used as the basis for extrapolation. Accordingly, these buildings are projected to grow by over 6 million square feet by 2050, 2.8 million square feet by 2030 and 3.3 million square feet by 2050.

Parking garage floorspace is kept constant as it is anticipated singular structure parking garages will not be built in significant numbers in the future and therefore not have a meaningful impact on the outcome of this analysis. A small amount of future growth is accounted for in several other buildings such as basement garage in an office building.

In total, Boston's building stock is predicted to grow 116,875,000 square feet by 2050. While the predicted growth over the next three decades is substantial, it is still relatively small in comparison to Boston's 647,000,000 square feet of existing buildings. Growth will represent only 15 percent of Boston's building stock by 2050.

The largest growth is predicted to be in large multi-family residential (5+ family). This segment alone represents 45 percent of growth or 52 million square feet. This growth in the large multi-family is consistent with expected with the goal to meet an increasing demand for housing. The projection also shows there is a significant shift in growth which has not happened in the past 70 years with residential representing the largest proportion of total growth.

Even if all new construction was net zero emissions starting immediately, Boston would still have its existing GHG emissions footprint. Therefore, deep reductions in emissions from Boston's existing building stock will be the key to Boston achieving its goal for carbon neutrality.

To Grow or Not to Grow the City?

Over the course of the Carbon Free Boston study a common question arose in technical and community discussions: does the City of Boston's growth objectives conflict with its goal to be carbon neutral? Simply put, these goals do not inherently conflict. In fact, sustainable density-focused growth should be a part of city's carbon mitigation strategy even if it makes achieving near and long-term carbon reductions harder within its own boundaries. The reason for this is that all urban economic and social activity is less carbon intensive than if that activity took place in less densified environment. In urban settings, space is more efficiently used in both the residential and commercial sector, leading to less energy used per building occupant or for economic output. Density also enables people and jobs to be more easily connected with public transportation. If Boston were to place a cap on growth, people and jobs would locate outside the city where they would have a higher carbon intensity. While this would help to curtail Boston's GHG emissions, it would drive an increase in regional emissions. Regional analysis is necessary to fully evaluate growth scenarios associated with densification. In the absence of such a comprehensive analysis, densification, even within Boston's city limits, should remain a core strategy for GHG mitigation.

4.3 CURRENT ENERGY DEMANDS

Building sector GHG stem from the onsite combustion of fossil fuels (natural gas and fuel oil), the consumption of electricity generated from fossil fuels, and the consumption of steam generated by the combustion of fossil fuels. Total electricity, natural gas and steam¹ consumption in buildings are reported by the operating utilities in the city and are used to directly determine emissions from the consumption of these energy sources. Since fuel oil is supplied by a number of independent delivery services it is difficult get an accurate accounting of fuel oil consumption in the city. Currently the City of Boston estimates fuel oil use by downscaling state consumption data based on the city's share of commercial floorspace and estimates of households using fuel oil [5].

Figure 6 shows the distribution in household heating fuel type by neighborhood for the city of Boston. Note that rates of gas, electricity and oil usage vary widely by neighborhood. Such a distribution is influenced by historical trends in the installation of utility infrastructure such as gas pipelines, housing ownership, and existing building energy infrastructure. Figure 7 shows the historical trend in primary household heating fuel, demonstrating a significant decline in oil over the past decade, while natural gas and electricity has increased as primary heating fuels.

While electricity use is ubiquitous across the building sector, the use of other energy sources can vary due to a variety of factors. District steam is used in a handful of legacy systems across the city. In downtown Boston, the Veolia network provides steam to a number of buildings with a high energy demand ranging from large office space to hospital buildings. A district system servicing the medical buildings in Longwood (MATEP), as well as several other systems mostly based at the city's large universities, also use steam to heat a number of buildings. Modern district systems such as MATEP also provide efficient cooling through adsorption chillers.

¹ Here, we use "steam" to describe any district scale steam heating that occurs in the city. This differs from the City of Boston's GHG inventory in which steam refers to only that which is imported from outside the City's boundary such as those generated at the Harvard Blackstone facility and the Kendall generating station, both in Cambridge.

Figure 6. Breakdown of Primary Household Heating Fuel by Neighborhood

Source: American Community Survey [5]

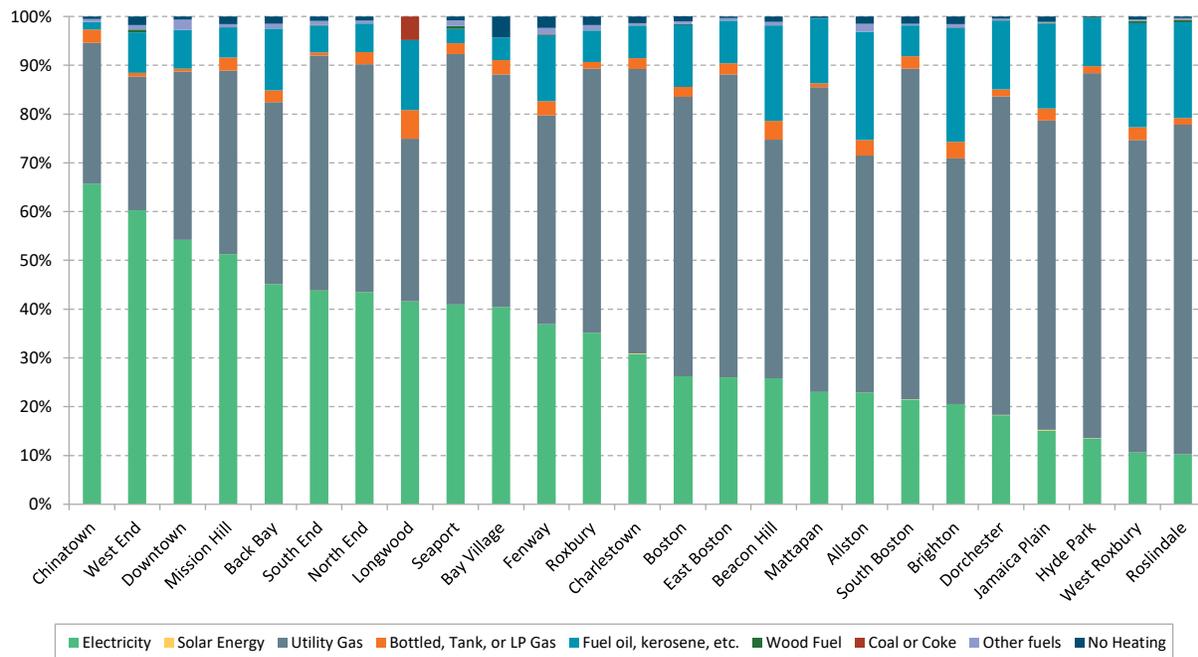
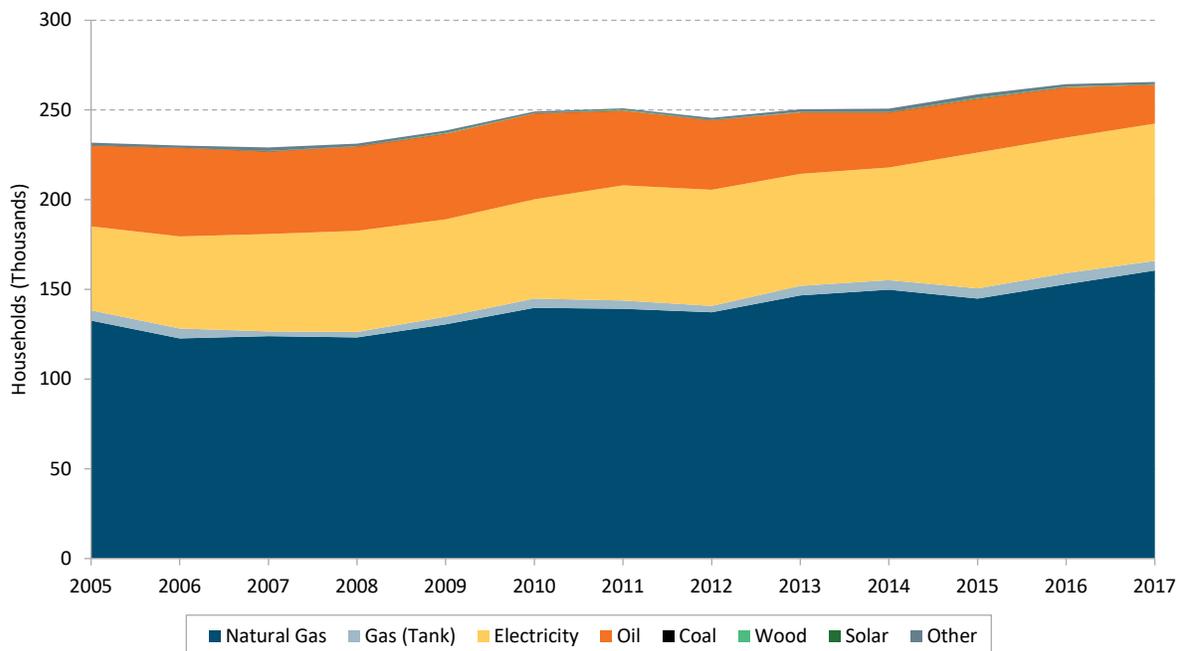


Figure 7. Boston Households by Primary Fuel Type

Source: American Community Survey [5]



Oil is typically regarded as a legacy fuel that is being phased out due to its higher cost, emissions intensity and impacts on air quality. Most commercial buildings have moved away from oil as a primary fuel. However, due to its ease of long-term storage, oil is still widely used as a backup and peaking fuel

in many large buildings, especially those such as hospitals and industrial facilities. It is also used as a peaking fuel in district energy plants. Households have been slower to transition away from oil, typically due to informational barriers and capital costs. Still, across the commercial and residential sectors, oil use has been halved between 2005 and 2017 [5].

On average, the cost of natural gas is lower than oil and electricity. Natural gas currently has a lower emissions intensity than oil and electricity, although as more carbon-free electricity comes online electricity will ultimately become less carbon intensive than natural gas on a per unit of energy basis.² The cost, and cleaner burning nature of natural gas has been the primary driver of the shift away from oil and has also sifted some households away from electric-resistance heating. Utility-sponsored rebate programs through MassSave have promoted this shift by offering incentives towards the purchase of high-efficiency gas-based heating systems. These transitions and growth in Boston's building sector has led to an observable increase in gas use over the past 12 years.

Electricity is used in numerous ways across the building stock. Over a quarter of Boston's households rely on it for primary heating services despite its higher cost, mostly via resistance heating. Many of these situations result from ad hoc building conversions such as the creation of a third-floor apartment in three decker that was previously 2 units served by gas or oil. Electricity is the primary energy source for cooling which leads to the city's highest demand days in the heat of the summer. Electricity is also used in the powering of many building services and activities such as lighting, ventilation, refrigeration and electronics. Despite growth in demand for building floorspace and these activities, electricity demand has mostly been stable over the last decade, being kept low by efficiency gains.

Energy use in Boston's building sector has remained generally flat in recent years (Figure 8) despite significant growth in Boston's built environment and economic activity. This stability is mostly a testament to measurable efficiency gains realized in both new and existing buildings that offset the increased energy demand. A modest decline in emissions in the buildings sector is mostly attributable to the increasing share of carbon-free electricity being supplied to the city's buildings as a result of a greening grid (Figure 9). The last decade has shown that Boston has been able to stabilize its emissions, however more substantial actions will be needed to reduce emissions.

² Under the Massachusetts Clean Energy Standard this transition will likely occur in 2035 when 50% of delivered electricity in Massachusetts is required to come from carbon-free sources. The City could accelerate this transition by making a dedicated city-scale procurement.

Figure 8. City-wide energy use by fuel

Source: City of Boston GHG Inventory [6]

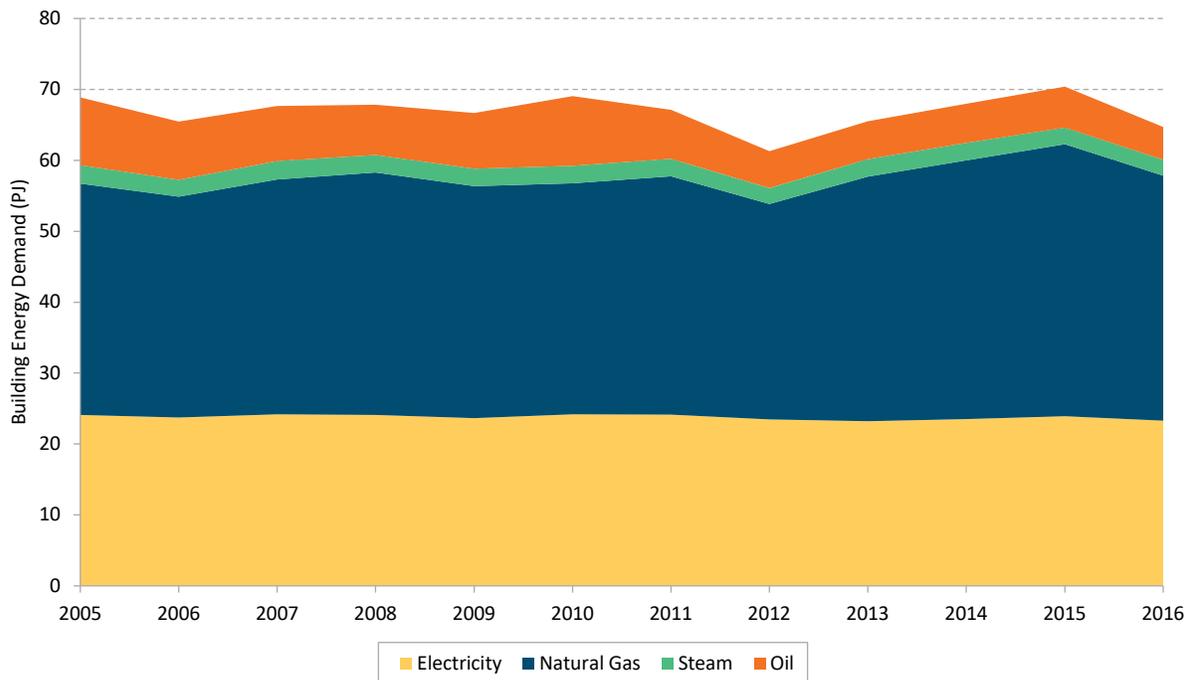
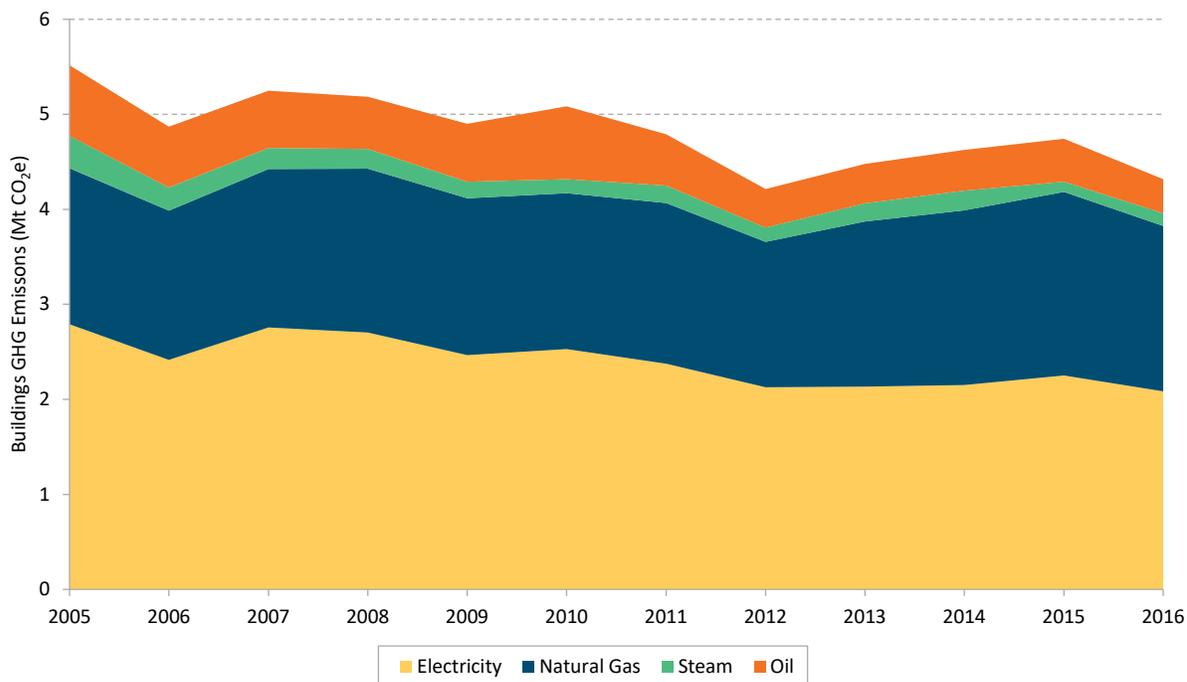


Figure 9. City-wide emissions by fuel

Source: City of Boston GHG Inventory [6]



5 BUILDINGS SECTOR MODEL

This study developed a bottom-up, city-scale building energy model resolved across 15 building types and 5 vintages representing the city's existing and future building stock. Individual building energy models representing these typologies were calibrated using data obtained from local utilities and energy providers to construct a relatively accurate representation of the city's electricity and natural gas consumption. Individual prototypes were calibrated to a reasonable level of accuracy in accordance to ASHRAE and leading academic standards for calibration.

The workflow described herein was implemented through a series of custom scripts integrating existing software developed by the team for this project. Scripts were coded in Python, and energy simulation was performed in EnergyPlus, a free, open-source energy simulation software created and maintained by the U.S. Department of Energy and considered to be among the leading building simulation engines (Torcellini, et al. 2004).

5.1 MODEL ASSUMPTIONS

Creating realistic energy models for each archetype required providing assumptions for key energy use drivers for each building use and vintage in the set of 60 building typologies. As a starting point, the US Department of Energy commercial and residential reference building models were used. Built by three national laboratories, these models were developed for 17 building types using attributes and construction types that represent 70% of the US commercial building stock[7]. The models for each building type are replicated three times to represent buildings constructed in the present ("new construction"), post-1980, and pre-1980. The DOE commercial reference building models used for this project were developed for ASHRAE climate zone 5A, in which the city of Boston is located.

Of these models, 10 were found to have use types that directly match those selected for Carbon Free Boston. For these, the geometry provided in the DOE models was used as the starting point for simulation. For the remaining four types (worship, convention/assembly, fire/police, triple decker, and parking garage), custom models of geometry and zones were used as the starting point. Additionally, within the DOE reference models, the 3 provided vintages align closely with the post-1980, 1980-2000, and post-2000 categories used in this study. However additional models were created for the pre-1950 vintage. Within the existing reference models, the geometry of the building is held constant to allow for a more accurate inter-vintage comparison of energy performance. Following this practice, the geometry of the pre-1950 vintage was held constant with the other vintages as well.

In all cases, the existing and constructed models were modified to better reflect the building characteristics of the city of Boston. Inputs for all vintages and building types were derived from the Commercial Buildings Energy Consumption Survey (CBECS) and the Residential Energy Consumption Survey (RECS). CBECS and RECS are national surveys by the US Energy Information Administration that collect building characteristic and energy use data from the US building stock[8]. Relevant CBECS and RECS data was pulled for the New England region and sorted by building type and by vintage. For quantitative variables (e.g. number of occupants), data was averaged across the sample size. For qualitative variables (e.g. window type), the percentage of buildings following into each category was calculated. The most common responses for qualitative variables were transferred into quantitative inputs using COMNET Appendix B for facades, ASHRAE 90.1-2004 for HVAC, and engineering judgment

for lighting. In addition to deriving input data for missing building types and vintages, the CBECS and RECS data was also used to verify that the DOE reference model inputs accurately reflect the Boston building stock. Data sources by model are summarized in Table 3 and Table 4.

Table 3. Corresponding vintages for project and DOE reference building models

Project Vintage	DOE Reference Building Vintage
Pre-1950s	N/A
1950-1980	Pre-1980
1980-2000	Post-1980
Post-2000	New construction

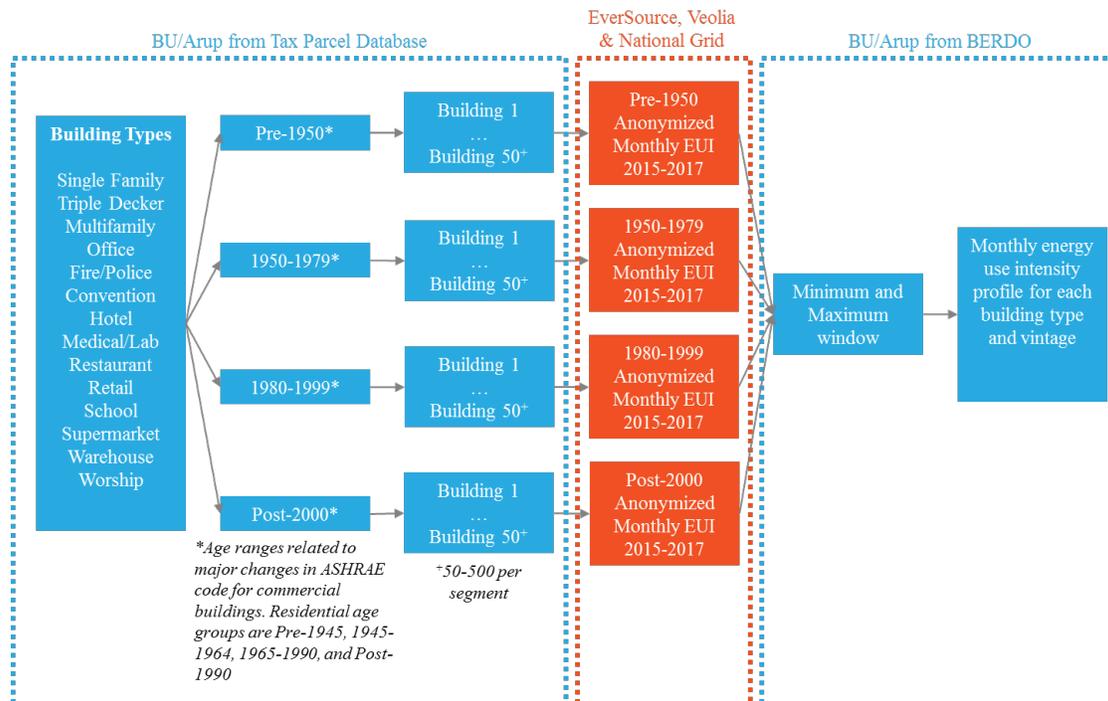
Table 4. Corresponding building types for project and DOE reference building models

Project Building Type	DOE Reference Building Type
Convention/assembly	Constructions: warehouse Internal gains: small office Process loads: CBECS for restaurants
Fire/police	Small office + modifications per CBECS
Hotel	Large hotel
Office	Large office
Medical/laboratory/production	Hospital
Multi-family residential	Midrise apartment
Parking garage	
Restaurant	Full service restaurant
Retail	Stand-alone retail
School	Primary school
Single-family residential	RECS
Supermarket	Supermarket
Triple decker residential	RECS
Warehouse	Warehouse
Worship	Small office + modifications per CBECS

5.2 UTILITY DATA CALIBRATION

While inputs from the national surveys and prototype models offers a reasonable starting point for energy simulation, these may not lead to the most accurate energy estimations for Boston. This conclusion was posited in the *Boston Community Energy Study*, which suggested that future work identifying savings opportunities for the city should leverage metered data to calibrate energy models. Through the City of Boston, a partnership with three utility providers in the city (Eversource, National Grid and Veolia) was established for which energy data for 2015, 2016, and 2017 for buildings in was sourced according to the process shown in Figure 10. For city owned buildings, metered data was received directly from the City of Boston.

Figure 10. Workflow for building model calibration



All three utility providers were able to share significant datasets with the team representing nearly 8,000 buildings. This allowed the archetypes to be further tailored to the City of Boston. Prior to using the received data to calibrate the archetypes, additional data processing was performed to ensure the quality of the values received. First, each dataset was reviewed to remove outlier series with extremely high or low average energy consumption. In some datasets, visual observation revealed that such outliers were present, and may be caused by inaccurate reporting of building area or a single meter feeding multiple buildings. There is likely to be some error introduced due to the fact that reported usage could have occurred during any 30-day window ending in a calendar month, and not representing usage of calendar month. Outlier elimination was performed by calculating the average monthly EUI and removing those over three standard deviations above the mean. Second, monthly datapoints which appeared to be anomalies in data reporting were removed from individual datasets using a similar approach of excluding values above and below three standard deviations of the mean of the individual account. Third, accounts missing more than one month of data were removed to ensure that occupied buildings were used for calibration. Finally, the remaining profiles were averaged to create an energy use profile representative of each age and vintage. It should be noted that uncertainty still exists in this data given that readings could be taken at any point in the month, so the months to which readings are assigned may not represent an accurate demarcation of the calendar month.

To further refine the data, the team derived a window of anticipated minimum and maximum monthly energy consumption for each building type from BERDO data. The outlier analysis was rerun using these windows, generating results that more closely matched BERDO benchmarks and had a more consistent seasonal profile.

After initial inputs were developed, all 60 energy models were calibrated to match the average energy use intensity of actual buildings in Boston. To calibrate the models, a combined automated and manual process was developed in Python.

This approach first performed an automatic calibration by altering variables defined by the project team within windows of acceptable values based on ranges of expected values from industry experience, CBECS, and RECS. The automated calibration utilized a heuristic optimization which tested combinations of these variables and identified the one which provided the greatest reduction error between the utility data and the simulated result. To ensure that the result represented realistic building inputs, these outputs were reviewed manually and the final variables determined by a combination of evaluating the error and the visual fit of the modeled data to the utility data.

ASHRAE Guideline 14 sets standards for the statistical tests and performance boundaries for calibrating models for retrofit using Normalized Mean Bias Error (NMBE) and Coefficient of Variation of the Root Mean Squared Error (CV[RMSE]). Calculation of NMBE and CV[RMSE] involves comparing the modeled data in each time period (M_i) with the observed data in the same time period (O_i) and a total number of data points (N). These two tests serve different purposes:

NMBE tests if there is a continuous over- or under-estimation of energy performance within the model. NMBE, denoted B_{NMB} , is calculate as follows:

$$B_{NMB} = \frac{\sum_{i=1}^N (M_i - O_i)}{\sum_{i=1}^N O_i} \times 100\% \quad Eq (2)$$

CV[RMSE] test if the magnitude of difference between the modeled and observed data is significant. CV[RMSE], denoted CV_{RMSE} , is calculated as follows:

$$CV_{RMSE} = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^N (M_i - O_i)^2}}{\frac{1}{N} \sum_{i=1}^N O_i} \quad Eq (3)$$

ASHRAE Guideline 14 specifies that “the computer model shall have an NMBE [Normalized Mean Bias Error] of 5% and a CV(RMSE) [Coefficient of Variation of the Root Mean Squared Error] of 15% relative to monthly calibration data. If hourly calibration data are used, these requirements shall be 10% and 30%, respectively.” However these standards are intended for use in cases where a building model has been created for a specific building and is calibrated against metered data for that building. In such cases geometry, occupancy, and other key factors are expected to be aligned between the model and the building. Guidelines for expected metrics are less clear when calibrating archetypes to representative or average data. Academic studies using utility data to fit representative models in similar cases have determined that NMBE values of approximately 20% and CV[RMSE] of approximately 55% for monthly data can be good fits, and significantly better than uncalibrated models [9], [10].

Based on these studies, for the Carbon Free Boston study, the aim was to improve upon these metrics, with targets to achieve

- Normalized Mean Bias Error (NMBE) of $\pm 10\%$ using hourly data across one full year
- Coefficient of Variation of the Root Mean Squared error (CV[RMSE]) of less than 30% using monthly data across three years

Each of the 60 prototypes was calibrated with the aim of reaching the NMBE and CV[RMSE] targets described. Due to the variation in reliable utility data available, some use and vintage segments had smaller samples sizes of actual data for calibration; in these cases if the sample size could not be considered significant, meeting the targets was not necessarily attempted as strictly. Instead, final input parameters for each model were determined as a combination of segment calibration and by comparison to inputs of other vintages within the same use with more robust datasets for calibration. In general, this led to good agreement between the modeled and measured data for most building segments, and consistency within use types for final modeled inputs.

The calibrated results were scaled up to create a modeled city emissions profile and compared to 2015 reported emissions. For electricity and gas, the scaled results showed under a 5% difference between the modeled approach and the reported energy consumption of the city, as shown in Table 5.

Table 5. Comparison of reported and simulated city energy use

	2015 Citywide Reported Use (kWh)	2015 Citywide Simulated Use (kWh)	Percent Difference
Gas	11,047,008,059	11,132,296,461	0.8%
Electricity	6,682,689,530	6,950,938,598	4.0%

5.3 CARBON INTENSITY OF ENERGY SUPPLIED TO BOSTON'S BUILDINGS.

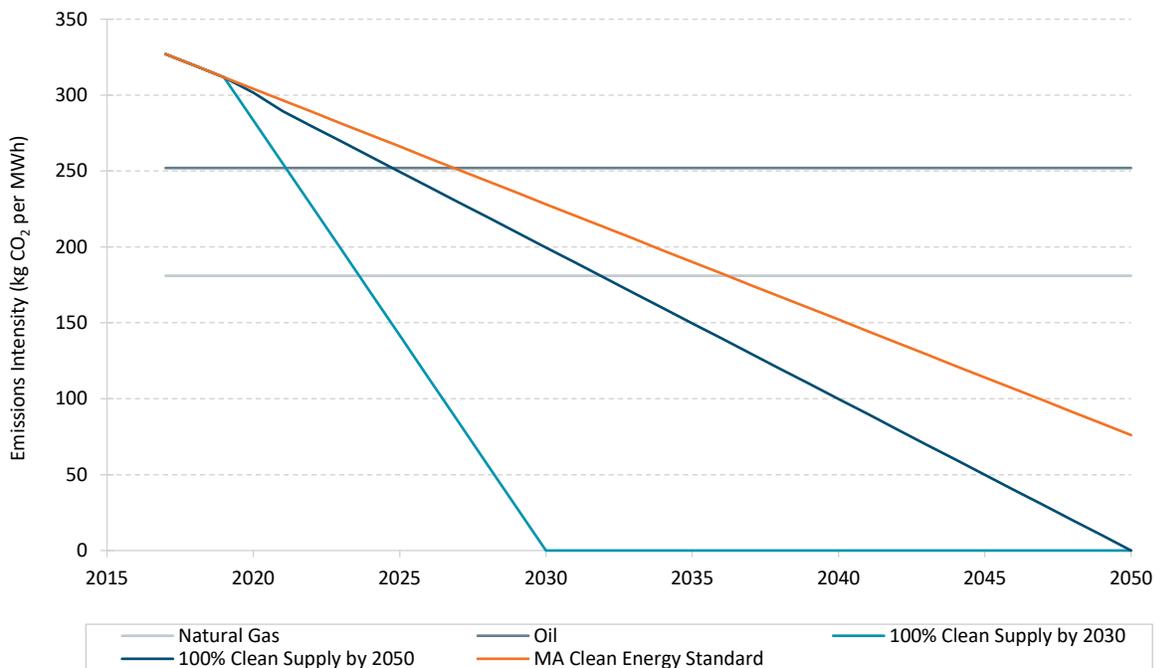
The carbon intensity of grid-sourced electricity and fuels used in Boston's buildings is a major driver of the total emissions from Boston's buildings. The rate of decline in the carbon intensity of electricity will also affect the relative impacts of energy conservation and electrification strategies. A rapidly decarbonizing electricity supply would prioritize electrification strategies over energy conservation measures.

Historically, the carbon intensity of the grid, and thus electricity supplied to Boston has been outside of the city's control. The most significant driver of the emissions intensity of the grid is the MA Clean Energy Standard. This state policy stipulates that electricity sold in Massachusetts becomes steadily less carbon intensive in the coming years reaching 80% carbon-free by 2050. Given policy trends in other states, it is likely that this goal may be revised to a more ambitious target that achieves 100% carbon-free electricity by 2050.

Achieving carbon-neutrality would effectively require 100% carbon-free electricity or the procurement of offsets. Pursuing rapid decarbonization targets such as the city's 50% by 2030 goal will also require an early procurement of 100% carbon-free electricity. In recent years Boston's institutions have sought to procure renewable electricity as part of their sustainability commitments. Currently the City is exploring the feasibility of a carbon-free power purchase agreement for municipal electricity supply. Additionally, the City is in the process of implementing a Community Choice Aggregation that aims to provide additional renewable electricity on top of the Clean Energy Standard requirements and give its residents the option of procuring 100% renewable electricity.

To illustrate the impact of these potential scenarios three trajectories describing the carbon intensity of the city's electricity supply were developed (Figure 11) to reflect the Clean Energy Standard, a 100% by 2050 grid, and an early 100% by 2030 city-wide procurement strategy. These scenarios are used for framing the impact of given evaluated below. Given trends in renewable electricity technologies, state level policies and need to rapidly decarbonize, it is likely that a 100% clean energy procurement strategy would be pursued early. Although options exist for lowering the carbon intensity of fuels such as natural gas and diesel oil, such options are currently limited. The greening grid, related policy frameworks, and the potential for renewable fuels are discussed in the Carbon Free Boston Energy Sector Report.

Figure 11. Emissions intensity trajectories used in this analysis



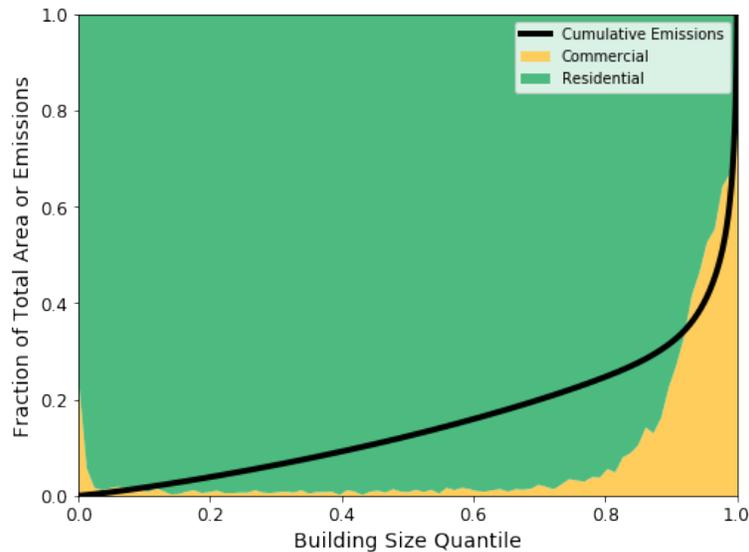
5.4 BASELINE RESULTS

Figure 1 shows emissions by building use class and vintage alongside the equivalent floorspace. While emissions scale with floorspace, some building types are more energy and emissions intensive than others. In general, older buildings tend to be more energy and emissions intensive than younger buildings. This is observed by the fact that the Pre-1950 vintages comprise a larger share of each typology's emissions than its respective share of floorspace. Further, new construction is relatively efficient compared to the existing stock: while future growth will comprise 15% of floorspace in 2050, it will only comprise 6% of emissions in 2050. This is predominantly due to newer buildings being more efficient and driven by our assumption that over the next 30 years the building code will steadily improve, reaching net-zero equivalency in 2045.

Some building typologies are more efficient than others. In the residential sector, larger multifamily buildings tend to be more efficient than smaller single-family homes. Office space generally has lower intensities compared to rest of the commercial stock. Retail, supermarkets, convention spaces, and especially medical/laboratory/industrial buildings tend to be very energy intensive and subsequently

have higher emissions relative to their floorspace. For example, Convention/Assembly buildings are 6% of total square footage but represent 13% of total GHG emissions, while Med/Lab/Production buildings are 6.5% of total square footage but represent 12% of total GHG emissions.

Figure 12. Cumulative emissions by building size quantile (black line) and proportion of building area in either commercial (yellow) or residential (green) subsectors



As noted earlier, individual building size varies drastically in Boston with small residential buildings comprising the bulk of individual buildings in Boston (Figure 2), while floorspace is dominated by larger commercial and multifamily buildings. Emissions from the building stock follow this trend with the top 10% of emitters being responsible for nearly two-thirds of sector emissions (Figure 13). These buildings are predominantly commercial, but would also include a number of large multifamily that would likely be regulated in a similar fashion to commercial buildings.

5.5 BASELINE SCENARIO TO 2050

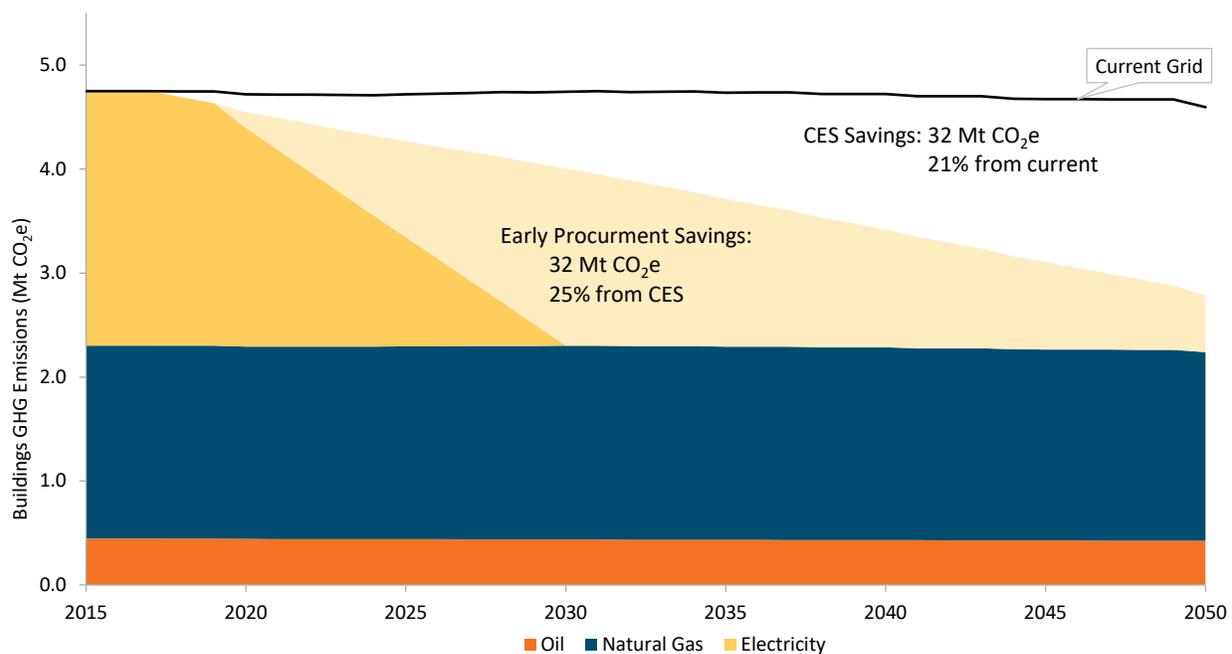
A baseline scenario (Figure 13) was used to estimate future emissions assuming the continued application of existing policy and no additional effort to reduce emissions. The baseline used three key assumptions for the projection addressing new construction, efficiency in existing buildings and the carbon intensity of the electricity grid over time. For new construction, the energy code was utilized as the basis to continue to drive future efficiency in new construction. The important distinction is that the energy code regulates energy performance, not emissions. As such, the baseline assumption continues to assume energy efficiency only in new construction, not an increase in decarbonization through greater adoption of electrification of HVAC systems. Referencing past code improvements in ASHRAE 90.1 over the past 40 years, a projection on an increasingly stringent energy code was made and implemented on the current 3-year basis as required by the Green Communities Act. This established net zero energy level performance for new construction by 2045 in a linear trajectory. It is important to note that even this baseline assumption requires ongoing action by the Massachusetts Board of Building Regulation and Standards (BBRS) to continue to adopt ever more stringent energy codes.

For existing building efficiency, BERDO was utilized as the basis to continue to drive future efficiency in existing buildings. No changes were assumed to the current ordinance in terms of its reporting threshold or energy action requirement. The important distinction is that BERDO requires an energy action, not action on GHG emissions. Existing regulations use energy as the proxy to realize emissions reductions. No data exists as to how building owners are meeting the energy action requirement. 2018 (reported in 2019) is the first year of the requirement to demonstrate an energy action for compliance. In its current form, there is a wide range of pathways for compliance organized on three categories, highly efficient buildings, energy action and energy assessment. As data becomes available, it is imperative that tracking what energy actions are being undertaken and levels of efficiency achieved for compliance is monitored by the City. This information will be critical to informing if and more likely how the policy may need to be augmented in the future.

For the purposes of this analysis, it was assumed that half of the current applicable buildings under BERDO would achieve energy reductions at a rate of 5% for the initial reporting period starting in 2020 when all buildings under the ordinance will have reported. A 2.5% reduction in energy consumption for the subsequent 5-year periods was assumed recognizing that energy efficiency gets harder and harder to achieve over time.

Figure 13. Baseline Buildings Emissions Projections under Alternative Grid Scenarios

Emissions savings are shown for electricity as the grid transitions from its current emissions intensity (maintained by the black line) to a Clean Energy Standard (CES) trajectory (white area below black line) to an early city-wide procurement trajectory that fully decarbonizes electricity by 2030. Source: model calculations.



5.6 PROJECTED CHANGES IN ENERGY DEMAND DUE TO CLIMATE CHANGE

The calibrated results indicate the energy consumption of the City of Boston using recent weather data. However, climate change will impact the amount of electricity and gas used in the future across the city, and may advantage or disadvantage building energy and emissions conservation strategies and impact their cost-effectiveness. To test the impact of future climate on reported city energy use, the team

simulated the calibrated buildings models using a future typical meteorological year (TMY) file created using WeatherShift. WeatherShift uses global circulation models in combination with historic TMY weather files to generate a projection of typical future weather at a point in the future using a selected global emissions pathway [11]. For this study, a future weather scenario for 2050 under the IPCC Representative Concentration Pathway 8.5 was used which corresponds to a 1.4 to 2.6 °C (2.5 – 4.7 °F) increase globally. This estimates weather for Boston at mid-century on the current emissions trajectory. Under this scenario the number of days per year with the daily minimum temperature reaching 5°F or below declines from 14 to 2, and the number of days where the daily maximum temperature exceeds 90 increase from 8 to nearly 50.

For Boston's current building stock, assuming now growth or application of ECMs, this change will cause gas consumption to drop by approximately 9%, while electricity use in buildings will rise by 0.5%. The shift away from gas is driven by an increasingly warm winter reducing the need for heating. Similarly, the increase in electricity is representative of warmer summers driving greater electricity demand. Electricity gains are not as pronounced in the projection due to higher efficiencies of cooling equipment and a reduction in electricity use for heating in some spaces today balancing the gain in summer demand. This provides an advantage for decarbonization by reducing citywide reliance on natural gas, and advantages the cost-effectiveness of measures which aim to reduce cooling energy use.

5.7 FUTURE IMPROVEMENT WITH URBAN ENERGY MODEL FOR BOSTON

In evaluating the energy performance of the buildings, two key ways in which this analysis could be improved were identified. First, while the prototype models developed rely on accepted building characteristics from national survey data, these may not capture the complete reality of building system and operating characteristics in Boston. The CBECS and RECS datasets are both national inventories, so by necessity have only a few hundred buildings sampled in the northeast, of which it is unknown how many are representative of Boston's building stock specifically. These served as the starting point for assumptions and adjustments were made according to local knowledge from the team and technical advisory group. In a typology-based approach like this, it is a challenge to make assumptions that need to represent all buildings of a particular type and/or age when it is recognized there is wide variation in actual building characteristics, systems and operation. While the assumptions of building performance in this study were tailored to Boston based on local expertise and findings from prior studies, future work could benefit from a better understanding of the building end uses and system types present in Boston. Findings from energy audits of existing buildings in Boston would help build a robust database of building characteristics that could improve the accuracy of building prototype models tailored for Boston. This additional data on existing Boston buildings would enable the further segmentation of the 60 building uses and vintages documented in this study to capture the diversity of buildings in the city at a higher level of granularity. Whether additional segmentation encompasses additional uses or the diversity of building types within the proposed uses (e.g., large vs. small office, or hospital vs. nursing home), additional segmentation could better improve the accuracy of the city energy estimate and better tailor recommendations of energy saving strategies.

An additional suggested next step is for the city and utilities to continue to collaborate on understanding energy use and patterns of buildings in the city including refinement of monthly average profiles for electricity and natural gas for buildings by segment in Boston. As was noted in this work, the quality of utility data received required led to significant post-processing and the exclusion of a large number of

data points. As a result, the calibrated models may not be as accurate as desired, particularly for building segments where only a very small sample size could be used. Working with the utilities, the City of Boston should develop average monthly energy use patterns for each building segment to better calibrate the archetype models and improve the accuracy of the models. The process of creating better profiles will also help streamline the utility data collection and management infrastructure, which is key for ordinances such as utility data reporting which rely on matching accounts to addresses and mapping to city data.

Additionally, standard profiles could be useful for testing the potential of new technological solutions that may help unlock Boston's energy and carbon conservation measures. Making average profiles available for study and use will help accelerate the incorporation of low energy technologies in the city by providing confidence that proposed solutions can work on a range of typical users.

Another recommendation to improve the accuracy of urban energy model creation is to extend the amount of data collected, aggregated, and disseminated through the Tax Parcel database to include additional fields helpful in understanding building use and energy performance. As previously identified, the city features a large number of mixed-use buildings for which the database currently lists only the primary use. When scaling energy consumption based on segmentation, this results in misclassification of some floor area based on the primary use type. Assessing for each property the area of each individual use would allow for a more accurate understanding of the true energy consumption. Additionally, for any given building, a more accurate picture of likely end uses could be developed, allowing energy saving solutions to be appropriately targeted to each building. For instance, in a mixed-use office tower with restaurant space on the first floor, commercial kitchen equipment upgrades should be leveraged, but the database today would not allow this type of use type differentiation.

Other cities such as New York and San Francisco maintain more comprehensive property and building inventories that are used for several additional municipal services including planning, health and zoning. New York City's PLUTO database has detailed breakouts of floor space by space classes (office, garage, factory) for a single parcel and more detailed use classes (e.g., hospital, nursing home) that would enable more representative building energy modeling.

6 BUILDING-LEVEL STRATEGIES: RESULTS & ANALYSIS

There are two primary means of reducing carbon emissions in buildings. The first is through reducing the demand for energy in buildings and the second is through changing the source of energy consumed to one that has less or no carbon emissions. While significant efficiency gains can be achieved through strategies that reduce demand, even the most efficient buildings still require energy to deliver necessary services like ventilation, heating, cooling, lighting, hot water and power for a range of devices. Thus, carbon neutrality, will ultimately require the decarbonization of the energy required to provide services in buildings. This can be accomplished primarily through the electrification of services that typically rely on combustion of fossil fuel-based energy (i.e. natural gas or fuel oil) for heating, hot water and other process services. Complete decarbonization via electrification requires the use of carbon-free electricity.

Approximately building interventions were modeled across the 60 building energy models representing existing stock, and 15 models representing future growth. The results determined the potential impact of a single or combination of strategies if they were implemented across the building stock, thereby

establishing the most effective strategies to reduce carbon emissions. Both energy efficiency (i.e., HVAC replacement, deep energy retrofits) and decarbonization (i.e., fuel switching, electrification, demand response) strategies were analyzed. Strategies were identified from several sources, including the City of Boston, previous and current MassSave programs, and the Carbon Free Boston Buildings Technical Advisory Group which comprised industry experts.

Each strategy was modeled in a combination of EnergyPlus and Python using the calibrated models as the baseline. For strategies which required meeting performance targets, a combination of assumed improvements in technical characteristics modeled within EnergyPlus and a reduction in resulting EUI was used to simulate the impact and achieve the defined level of performance. In some instances, strategies were defined as only applicable to specific building types and therefore only simulated for those buildings. Appendix A provides details for each strategy in the analysis including identification of which strategy was applicable to which building type.

6.1 SINGLE-ACTION MEASURE ENERGY CONSERVATION MEASURES

Energy efficiency is the cornerstone of any plan to realize carbon-neutral buildings. ECMs are actions that reduce the quantity of energy needed to deliver ventilation, thermal comfort, illumination, and all the other services that a building provides for its occupants. ECMs include actions like switching to more efficient lighting and appliances, reducing air leaks, adding insulation, optimizing HVAC system performance and recovering energy where possible. These single-action ECMs include taking action on one specific aspect of a building, such as replacing light bulbs or lamps, replacing equipment with more energy efficient versions, installing programmable thermostats and other controls-based changes, or adding/increasing insulation. These actions are typically easy to implement, result in energy savings and are very cost effective. However, they have a limited impact in reducing emissions across the city since they only address one isolated aspect of where and how energy is consumed in a building. Even collectively, all these single-action ECMs will not achieve the level of emissions reductions required.

6.2 PERFORMANCE-BASED (“PACKAGED”) STRATEGIES

In addition to single-action ECMs, several performance-based strategies were analyzed (). These strategies establish a level of performance that a building is required to achieve. A benefit is that these strategies provide flexibility in how that level of performance is achieved. The current Energy Code and Stretch Energy Code are examples of performance-based requirements.

For several of the performance-based strategies, the Advanced Energy Retrofit Guides for Existing Buildings published by The US Department of Energy (DOE) [12]–[16] have been used as a key reference to define the level of performance achieved. These guides were commissioned by the DOE and produced by the Pacific Northwest National Laboratory to address key segments of the US commercial building stock, namely Commercial Office, Retail, K-12 Schools, Hospitals/Healthcare and Grocery Store buildings. They provide information (both energy analysis and cost savings estimates) that is climate specific across individual ECMs as well as three recommended packages of energy conservation measures. For this analysis, the AERGs were used to define the level of savings associated with each of the three (3) performance-based strategies according to building type. Technical specifications for these are listed with the ECMs in Appendix A.

Existing Building Commissioning (EBCx) also known as retrocommissioning assumed energy savings ranging from 8.5-10% and assumed changes to controls such as set points, turndown and other sequence of operations would be implemented. EBCx is typically easily implemented across all building types with little to no disruption to service or occupancy and are highly cost effective. Such measures can often be achieved through building operator training on best practices. This measure is not applicable to small residential units.

Table 6. Simulated building intervention targets.

Existing Building Commissioning (EBCx)	Standard Retrofit	Deep Energy Retrofit / Passive House Retrofits
Operations and maintenance improvements, including strategies such as changes to controls and regular maintenance to prevent decline to optimize performance of equipment, systems and assemblies.	Implementing incremental capital upgrades to systems, equipment and assemblies in a building. These include strategies such as replacement of equipment (e.g a boiler, Air Handling Unit or Chiller), or building envelope components (e.g. roof or window replacement or adding insulation to walls).	Implementing a whole-building design approach to a building for both the building envelope and its systems and equipment. Deep retrofits include upgrades or replacement to the building envelope, i.e. walls, roof and windows, and air leakage, and HVAC systems, controls and lighting in a holistic renovation.
Target EUI Reduction: 8.5-10%	Target EUI Reduction: 25-30%	Target EUI Reduction: 50%

Standard Retrofits assumed replacement of all HVAC equipment with more efficient versions. These incremental upgrades require planning and sequencing of improvements to optimize savings, but can be implemented with minimal to moderate disruption to service and occupancy and are also typically cost effective. Replacements of equipment already occur in buildings as equipment reaches its end of life. The work can be scheduled to occur during appropriate times of the year with regard to weather and during off-hours when a building is unoccupied. This can be challenging in buildings that require 24/7/365 operation such as hospitals, laboratories or manufacturing facilities but can be accomplished with built-in redundancy or temporary services. Improvements or replacements to building envelope components are typically more disruptive and have longer payback periods.

Deep Energy Retrofits energy savings assumed building envelope improvements, addition of ventilation, in addition to the standard retrofit measures were implemented. While deep retrofits present the largest opportunity for savings, they require significant capital, have longer payback periods and are disruptive to service and occupancy in a building. Depending on the use of the building, this can be even more challenging to implement, especially compared to a standard retrofit. For example, in a residential building, occupants can continue to occupy and live through a major renovation or temporarily relocate while construction is completed. In a school or office building, a phased approach is more typical and can be implemented to only renovate portions of a building at a given time. While this adds time to the overall length of construction and cost, it minimizes vacancy and the relocation of occupants and maintains service and operation for the majority of the building. Buildings can also be fully vacated for a deep energy retrofit if relocation can be arranged and provides the opportunity for alignment with

repositioning in the market to further optimize the business case. Like standard retrofits, realizing a deep energy retrofit can be extremely challenging in buildings that require 24/7/365 operation such as hospitals, laboratories or manufacturing facilities.

Despite their high upfront cost and potential for disruption targeting comprehensive deep Energy Retrofits can provide some substantial benefits in addition to energy savings. Despite Boston's best efforts to curb emissions, the city must be prepared for a modest-to-significant rise in temperatures, flooding events, and other extreme events. Boston's built environment was not designed for these future climate realities. Flooding has the potential to impact building energy infrastructure that has historically been housed in basements. Extreme heat events will make Boston's buildings dangerously hot for its most vulnerable residents. Comprehensive retrofits can make these buildings more resilient to climate change. Deep retrofits can also make Boston's buildings healthier by improving indoor air quality. Poor air circulation, water infiltration, mold are common problems across the city's aged residential stock, and Class B and Class C commercial space. The risks of these conditions are exacerbated in the low-income housing stock which house vulnerable populations. This has the potential to improve occupant health and reduce costly treatments, hospital admissions, and lost work days can arise from poor indoor air quality.

CASE STUDY: DEEP RETROFIT IN THE JAMAICA PLAIN GREEN HOUSE

The JP Green House in an urban homestead in Jamaica Plain, owned by Andrée Zaleska. Purchased after a foreclosure in 2008, the residence was transformed from a former corner-store, in derelict condition, into an energy-positive (zero-carbon) home. JP Green House was rebuilt to meet rigorous Passive House efficiency standards and generates all its electricity needs through its 5.625kW rooftop solar array. Additionally, the residence is retrofitted to minimize heat loss, utilizing measures such as thick insulation, southern-facing triple-glaze windows and a heat recovery ventilation system. In the winter months, the house can maintain an indoor temperature of 63°F without any heat. There is no gas or oil system and the home deploys an extremely efficient air-to-water heat pump. The combination of these energy conservation measures and on-site generate makes JP Green House energy positive, meaning that it produces excess electricity generation.

Additionally, Zaleska and her business partner, Kannan Thiruvengadam, utilized the land to build a large urban organic garden, which provides all the produce for Zaleska's family as well as many neighbors. They use the space both for food production and as an urban classroom, offering educational programs to youth and teens based around sustainability concepts. The main project of the nonprofit, JP Green School, a self-directed learning center for the study of sustainability that was based in the house for three years, and has now moved to Hope Central Church in Jamaica Plain.

JP Green House demonstrates the ability for high-performance efficiency standards to be applied to existing homes – going energy positive does not have to be limited to new construction.

New Building Packaged Measures ranged from an *Enhanced Stretch Code*, to *Passive House Standard* to *Net Zero Energy-ready*. The Advanced Energy Design Guidelines (AEDGs) [17]–[21] were used as a reference to identify the package of strategies to achieve low-energy performance in new construction. They were developed in collaboration with The American Institute of Architects, Illuminating Engineering Society, US Green Building Council and US Department of Energy. The AEDGs similar to the AERGs address building types that represent major energy users in the US commercial building stock, i.e.

K-12 Schools, Hospitals, Retail, Commercial Office, and Grocery Stores. They are a series of publications designed to provide strategies and recommendations for achieving 50% energy savings over the minimum code requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004, Energy Standard for Buildings Except Low-Rise Residential Buildings.

The *Stretch Code* strategy maintained a 10% energy reduction from the baseline or code compliant energy performance while the *Passive House Standard* utilized the performance criteria required for certification by the Passive House Institute US (PHIUS). The criteria include, an ultra-low air infiltration rate, maximum annual heating and cooling load and source energy performance (kBtu/sf/year). Net Zero Energy-ready performance was defined by a low site energy use intensity (kBtu/sf/year) per building typology from The US DOE's Energy Star Portfolio Manager Target Finder tool. It is identified as "ready" since on-site energy production was not included in this strategy, which can vary based on building type. The AEDGs in addition to research by the New Buildings Institute were used as a reference the suite of strategies and EUIs to achieve Net Zero Energy-ready performance.

6.3 FUEL SWITCHING OIL-GAS

Fuel switching was included for existing buildings only. It has been an effective strategy over the past 10-15 years to help reduce GHG emissions. However, it is only an incremental step as it switches heating energy from fuel oil to natural gas. While natural gas has lower GHG emissions compared to fuel oil, natural gas is still fossil fuel-based energy.

6.4 BUILDING ELECTRIFICATION

Electrification shifts energy consumed for heating and hot water from fossil-fuel based energy, i.e. natural gas or fuel oil, to electricity which has the potential to be fossil-fuel free. The electrification of a building has two primary options given current technology. This strategy was applied to both new construction and existing buildings. For new construction, electrification was defined as an electric boiler for most commercial buildings which electricity to directly generate heat in a boiler or a radiant heater. For residential buildings, the electrification strategy was defined as an air-source heat pump system. Heat pumps use electricity to move heat from one location (e.g. outdoor air or ground) to another (the indoor building space). Heat pumps are very efficient and can reduce GHG reductions by more than 50 percent compared to a natural gas system under a low-carbon grid.

The results show that electrification is very effective at reducing carbon emissions by 2050. The challenge is that current electricity prices make electric boilers not cost-effective compared to natural gas since their overall efficiency is comparable (92-95% efficient). Air-source heat pump systems on the other hand, are cost-effective even today since they are very energy efficient. For this analysis, a coefficient of performance (COP) of 3.2 was defined for air-source heat pump systems, meaning that for every 1 unit of energy input, the system generates 3.2 units of energy output, heating in this instance. Incentives are currently available through the MassCEC for these systems. However, there are limitations for the application of these systems across building types and concerns of their reliability in extremely cold weather which Boston experiences. As temperatures drop, they become less efficient however manufacturers continue to improve system operation and now provide cold climate options where these systems can operate in temperatures as low as -13°F. As a result, some non-residential buildings may choose to use a mix of heat pumps *and* electric boilers, as supplemental for peak heating

days. Additionally, these systems require space outdoors for heat exchangers, which can pose challenges where outdoor space (e.g., rooftops) is constrained.

The potential of electrification as a GHG reduction measure is highly dependent on the carbon intensity of the grid to realize the savings. The impressive efficiency gain of electrification is muted in the near term because fossil fuels (mostly natural gas) currently generate 43 percent of electricity in the regional grid. The carbon intensity of the grid increases during peak weather conditions as well. For example, during very cold periods the current grid is forced to rely on oil-based peak generation plants, which increases the carbon intensity of electricity used for heating. Short-term and seasonal energy storage might be necessary to reduce peak electricity demand, accommodate the intermittent nature of wind and solar energy, and avoid straining the current capacity of the distribution network. Energy storage also provides important resiliency benefits during emergency events.

By itself electrification will greatly increase electricity demand, so it must be coupled with aggressive energy efficiency and storage to avoid straining generation, transmission and distribution resources. Expanding these resources to meet large demand would lead to increases in the cost of electricity. The largest potential reductions in emissions result when deep energy retrofits are combined with the electrification of heating (space and water) and cooking. Refer to the Energy chapter for further details.

CASE STUDY: BOSTON UNIVERSITY'S GEOTHERMAL WELL DRILLING INITIATIVE

Nearly ten years ago, Boston University installed its first geothermal system of six wells at the building spanning 882 to 888 Commonwealth Avenue. In 2018 the University announced that it aims to heat and cool the newly proposed Data Sciences Center at 645 Commonwealth Avenue with more enhanced geothermal technology. One of the major differences between these two projects is that the Data Sciences Center will be a 17-floor building which will require upwards of 30 geothermal wells to accommodate the heating and cooling needs of the building. As Dennis Carlberg told BU Today, "...this will be the biggest geothermal project in Boston yet."

Although the Data Sciences Center is not planned to begin construction until late 2019 early testing evaluated three alternative drilling approaches to inform the full installation of the planned geothermal system. The test wells will offer insight into the most effective drilling methods as well as the geology underneath the building site. Alternative drilling methods will be used for each test well to determine which technique can produce the straightest boreholes in the least amount of time. The design team requires this information before they can determine the well spacing and depth for the planned system.

The geology underneath the building site can vary greatly and will affect the heating and cooling capacity of the planned wellfield. This geological variability will be tested by drilling each test well in different locations across the building site. The heating and cooling capacity of the planned wellfield will be estimated based on measurements of thermal conductivity and borehole thermal resistance for each test well.

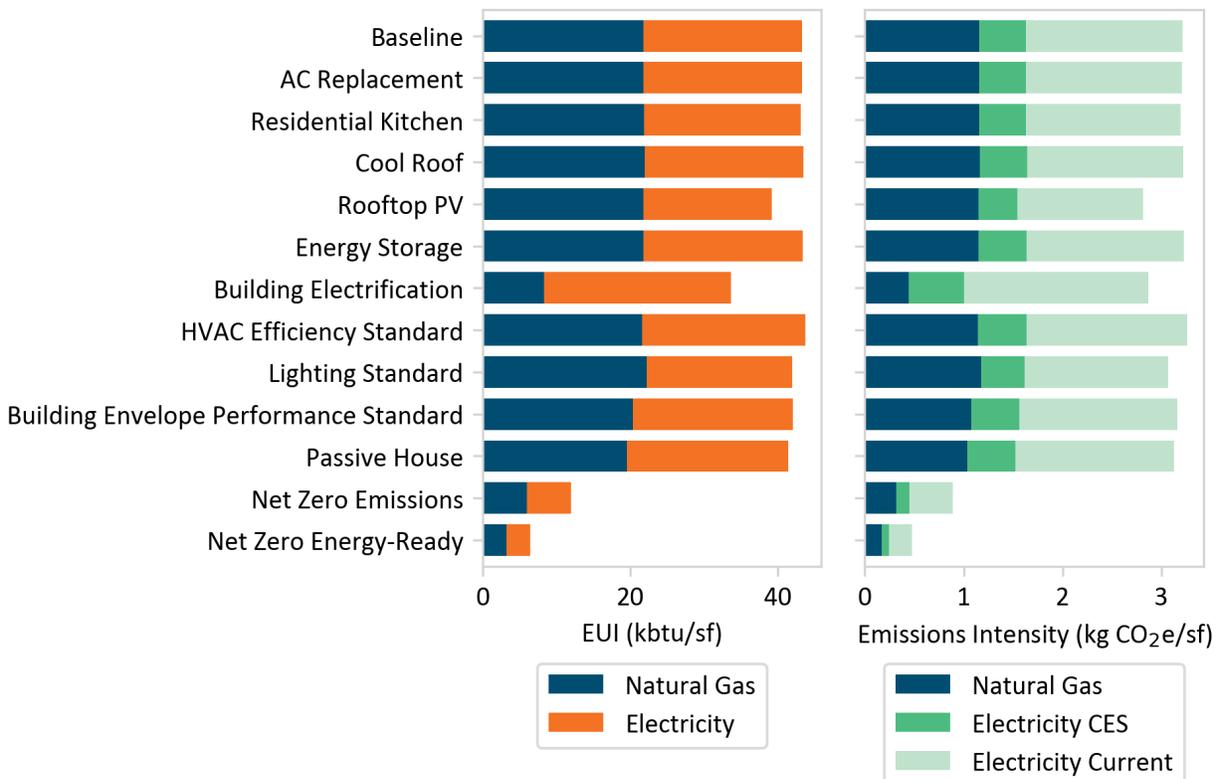
6.5 ON-SITE STORAGE

Energy storage systems provide dispatchable energy on-site, independent of the electricity grid. It allows buildings to offset a portion of electricity consumption, typically at times of peak demand when the grid is most stressed and generation is the most carbon intensive. This strategy does not save energy, but rather shifts when energy is consumed from the grid to reduce carbon emissions and peak demand charges which for many commercial buildings is a significant portion of electricity bills. As such, these systems typically are very cost effective and are relatively easy to implement. Finding space for the system is usually the most challenging aspect. While these systems are in their infancy, significant incentives are available through the MassCEC and it is expected that they will become increasingly common in the near future. These systems can be charged through the electricity grid at off-peak times, e.g. overnight, and/or through an on-site solar photovoltaic system. While the sizing of these systems will vary depending on a building's specific load profile and Client drivers for such a system, for this analysis, the strategy was defined to reduce peak demand 15% between 2-6pm for commercial buildings and 5-9pm for residential buildings.

6.6 BUILDING-LEVEL RESULTS

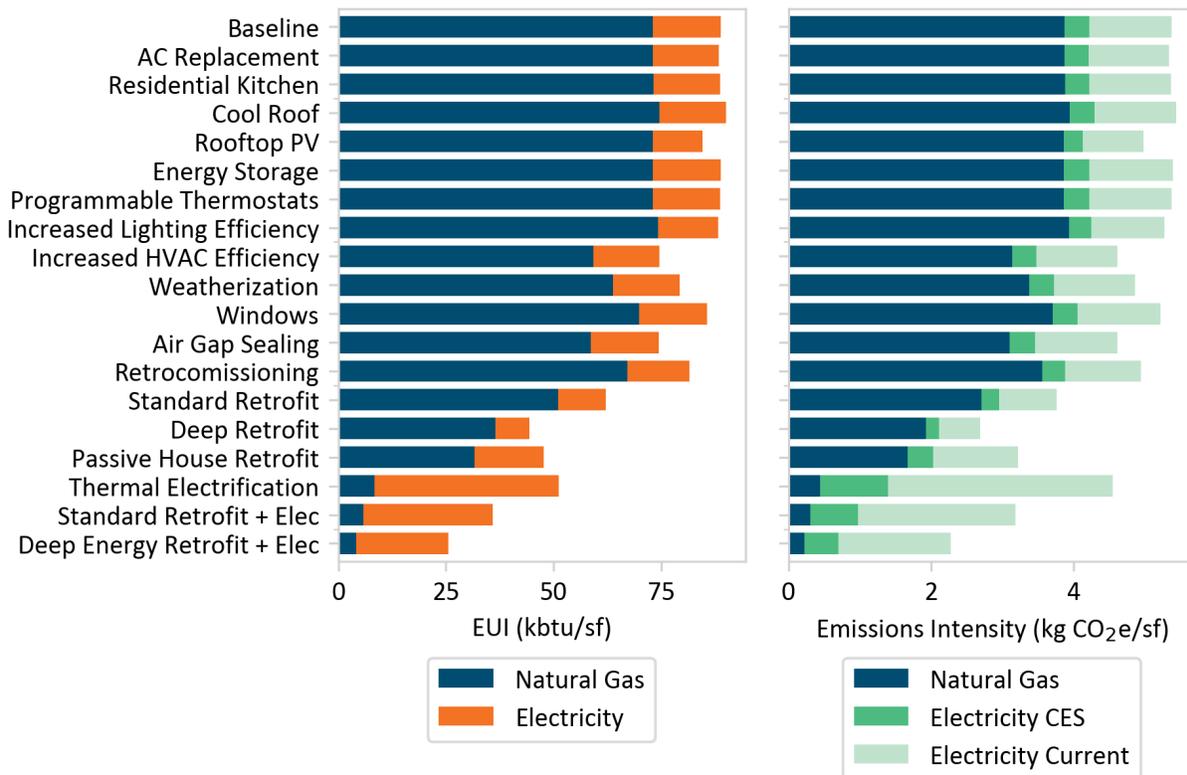
Energy use and emissions intensity by building typology and vintage are presented in the Policy and Strategy Appendix Excel File. Selected typologies and ECMs are presented below to illustrate and discuss the impact key highlights.

Figure 14. Large Multifamily Residential Strategies – New Construction



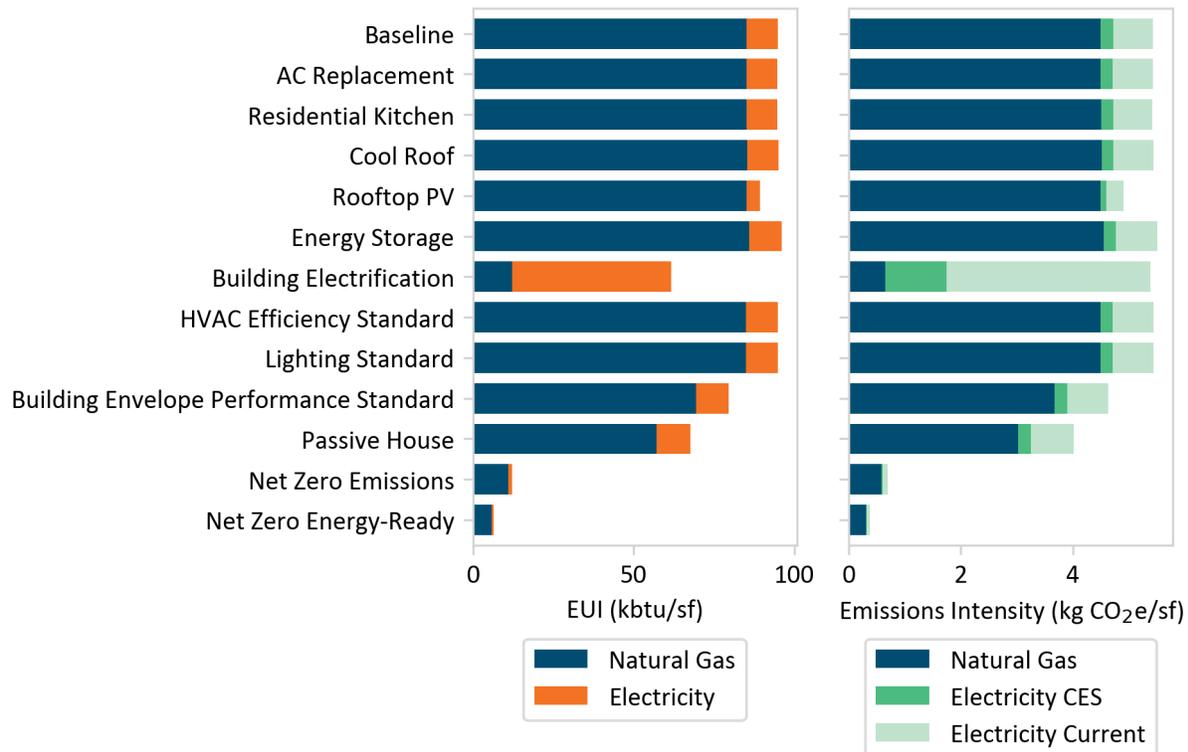
The most effective strategies for large multifamily residential new construction were those which incorporated dramatic reductions in the demand for energy, especially for heating energy. Passive House Standard, HVAC efficiency improvement and electrification, and net-zero ready buildings provided the greatest savings. Heating and hot water energy demands are the predominant energy demand which is typically met by high efficiency natural gas boilers in new construction. Given this profile, the strategies that address the efficiency and source of energy for heating and hot water are the most effective. HVAC electrification has a particularly profound emissions impact using 2050 emissions by converting a large portion of natural gas load to electricity. The emissions for electrification can be further reduced with carbon-free electricity beyond the 80 x 50 grid. Passive House emissions could be further reduced if it was coupled with electrification HVAC systems. Another key finding is the difference indicated by the Net Zero Energy and Net Zero Emissions strategies. Net Zero Energy performance realizes a highly energy efficient building, however, still allows the use of fossil-fuel based energy. Comparatively, Net Zero Emissions performance realizes the same energy efficient building and couples this with decarbonization in energy consumed, in this case assumed to be electrification.

Figure 15. Large Multifamily Residential Strategies – Existing



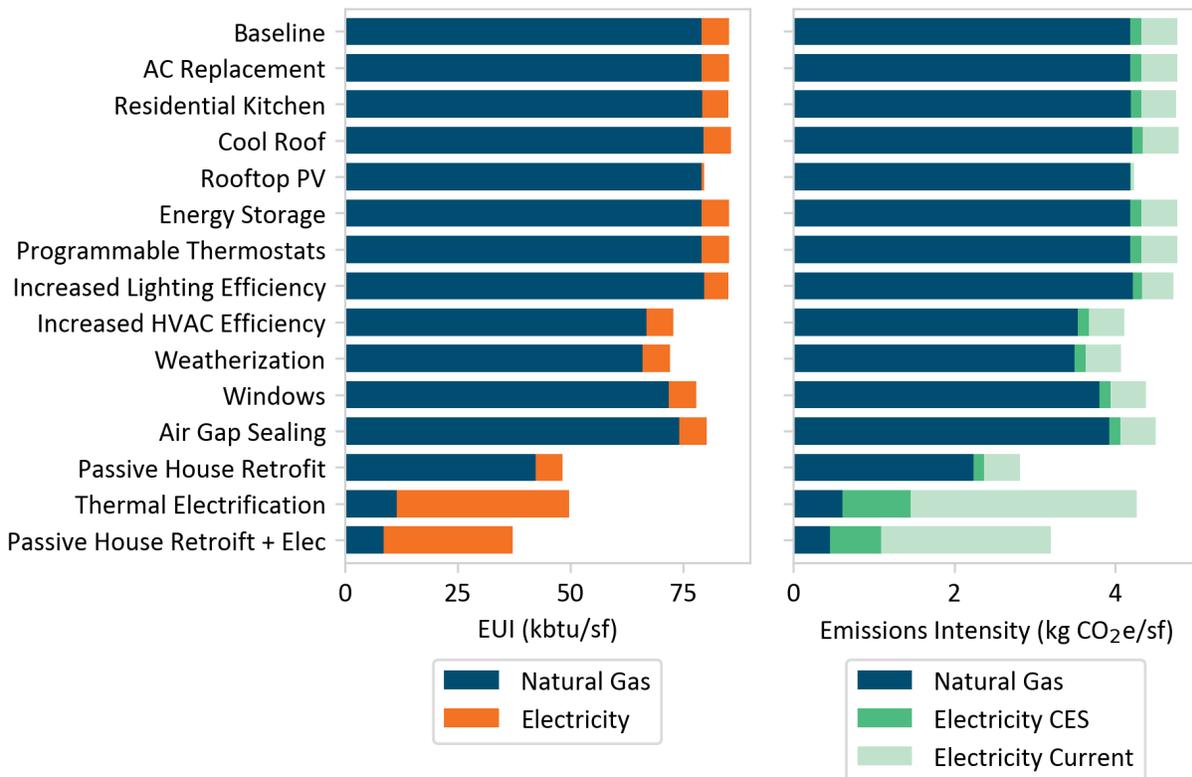
Similar to new construction, the largest energy and emissions savings in existing multifamily residential buildings are seen in HVAC improvements and electrification of end-uses. Both Passive House Standard retrofits and Deep energy retrofits realize significant emissions reductions, however even though they include holistic building envelope improvements, they are comparable to HVAC electrification if realized with fossil-fuel based energy for heating and hot water services. It is only if these performance standards are realized with electrification of heating and hot water services that the emissions savings dramatically improves compared to electrification alone. The emissions reductions can be increased further with a fully carbon-free electricity grid. All other strategies have minimal to moderate impact at reducing both energy demand and emissions.

Figure 16. Small Multifamily Residential Strategies – New Construction



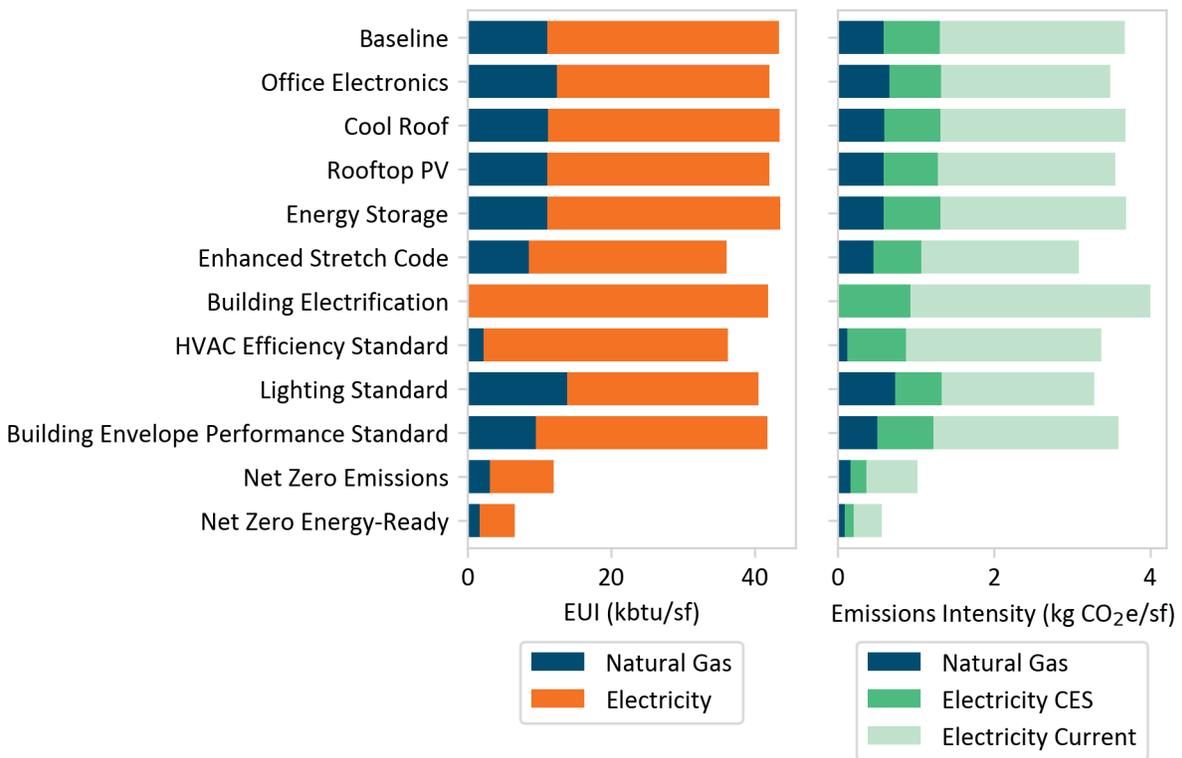
New small multifamily construction benefits most from improvements in the building envelope and HVAC system, whether through a requirement such as meeting Passive House standard or through increases in code requirements (HERS rating) for efficiency and HVAC electrification. Per unit of area, heating demand is significant for small multifamily buildings, suggesting that improvements which reduce heating energy use are likely to have the largest impact on energy and emissions reduction. Similarly, electrifying HVAC systems, and over time switching to heat pumps, will drastically reduce the emissions footprint of these buildings as the electricity grid becomes cleaner. The scale and size of these buildings make them excellent candidates for heat pump systems even today.

Figure 17. Small Multifamily Residential Strategies – Existing Buildings



The results for existing small multifamily buildings were generally consistent across age categories with small variations in the impact of envelope and HVAC measures. Older buildings tend to benefit more from improvements in insulation, and sealing gaps in the envelope in addition to HVAC efficiency. Similar to new construction, measures that reduced heating demand were found to have the greatest impact on reducing energy and emissions for small multifamily buildings. Electrification was found to have the most significant impact on emissions across all age categories, assuming the HVAC conversion was to a heat pump system. This could be fully carbon neutral depending on the carbon intensity of the electricity supply.

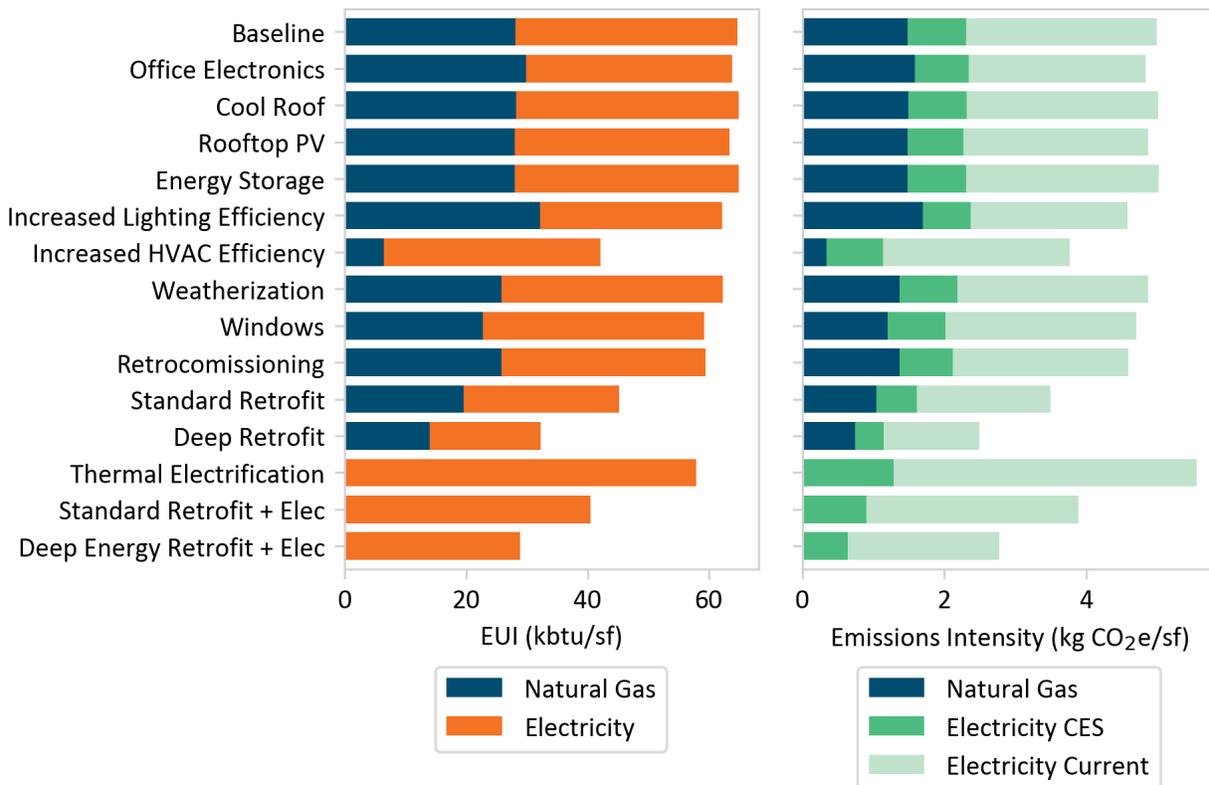
Figure 18. Commercial Office Strategies – New Construction



The most effective strategies for office new construction are performance-based strategies that accelerate energy and/or GHG emissions reductions from the baseline assumption. All prescriptive strategies consistently have small impacts (Less than 5%) on energy and GHG emissions. While electrification of HVAC systems has a minimal energy reduction (3.5%), this translates to 29% savings in GHG emissions with the baseline electricity grid in 2050.

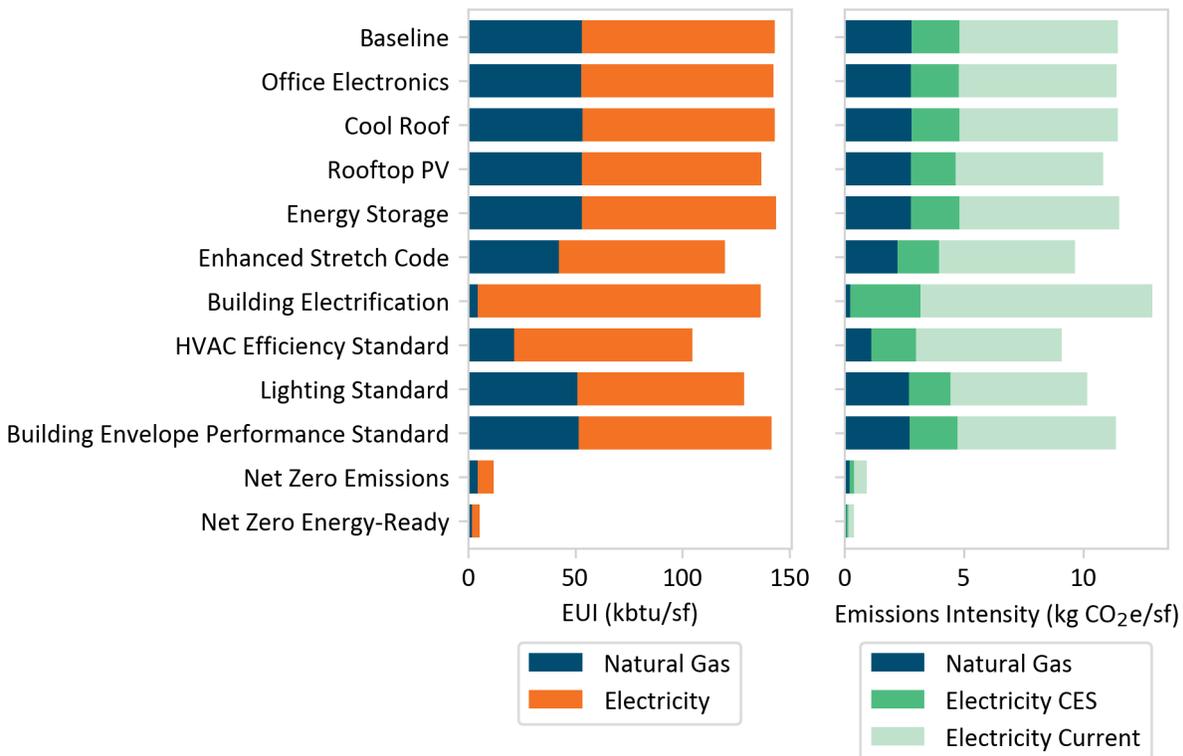
It is also remarkable that there is a material difference between Net Zero Energy and Net Zero Emissions strategies. This difference can be further increased if the electricity supply is carbon-free. The most aggressive performance is a cap-based approach, essentially working backwards from the 2050 carbon neutrality goal to allocate a emission budget per building.

Figure 19. Commercial Office Strategies – Existing Buildings 1950-1980



The strategy results for existing office buildings were generally consistent across all age ranges. Again, the most effective strategies are performance based that accelerate energy and/or GHG emissions reductions from the baseline assumption. The most effective prescriptive strategies are window replacements, retro commissioning and electrification of HVAC systems. Standard retrofits combine HVAC equipment replacements with increased efficiency which results in a considerable 30% energy savings. Electrification of HVAC systems continues to have a small energy reduction (10%), but translates to 55% savings in GHG emissions baseline electricity grid in 2050. It is also remarkable that there is a material difference between Deep energy (50% reduction) and Deep energy & electrification strategies, an additional 20% reduction in GHG emissions. This difference can be further increased if the electricity supply is carbon-free.

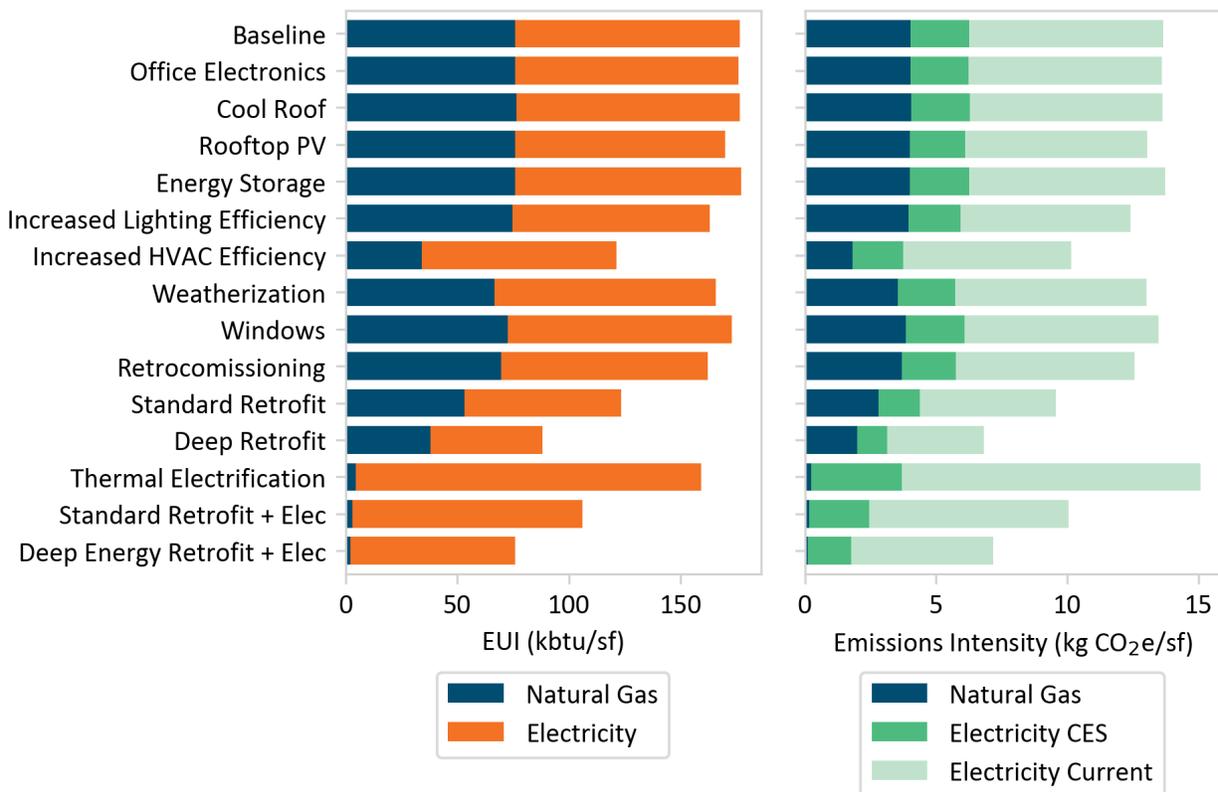
Figure 20. Med/Lab/Production Strategies – New Construction



The buildings that comprise the Med/Lab/Production typology are the most energy and emissions intensive buildings in this study. They include buildings such as hospitals, research laboratories and manufacturing facilities most of which have 24/7/365 operation and critical services. Driving energy and GHG emissions reductions in these buildings, while challenging, will have significant impacts to the city's GHG emissions profile. Like other typologies, the most effective strategies are performance-based strategies that accelerate energy and/or GHG emissions reductions from the baseline assumption.

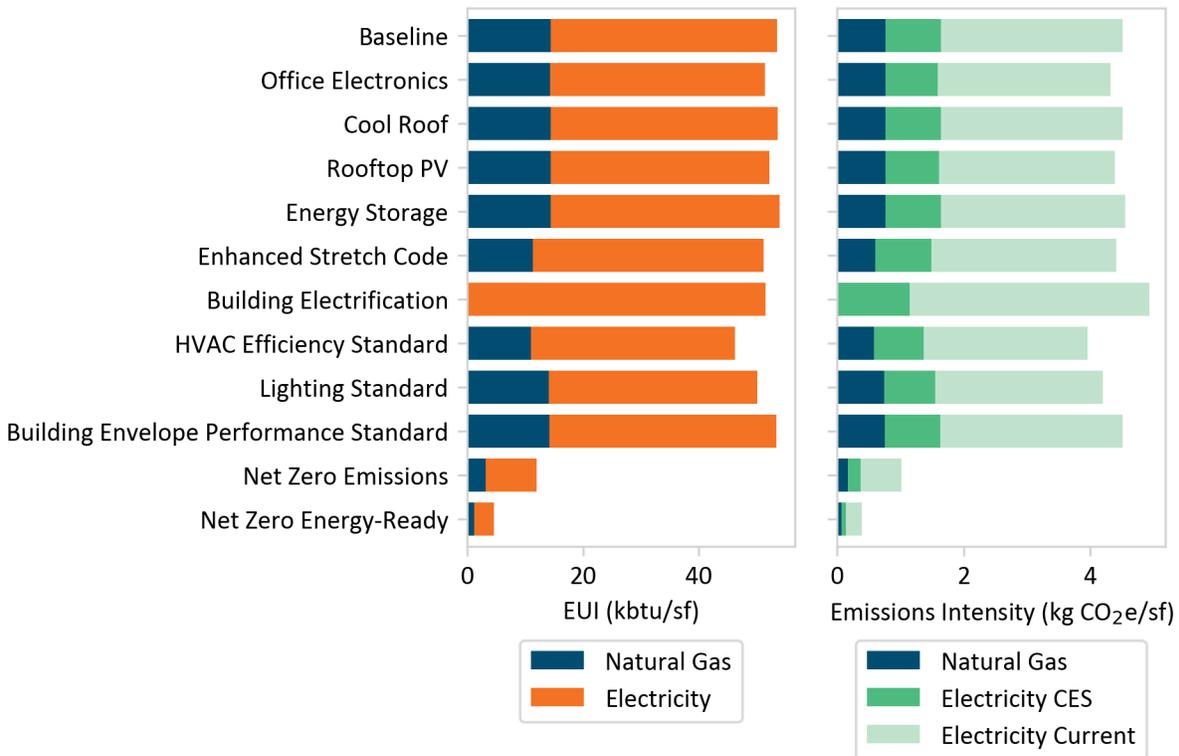
These buildings typically have very high process and plug loads, ventilation requirements and simultaneous need for both heating and cooling. They are not as sensitive to building envelope strategies as their energy consumption is internally driven. Most prescriptive strategies have small impacts (less than 1%) on energy and GHG emissions. Rooftop solar PV and lighting reductions are the most effective prescriptive strategies to reduce GHG emissions mainly due to their high hours of operation and space requirements for light levels. While electrification of HVAC systems has a moderate energy reduction (9%), this translates to 37% savings in GHG emissions with the baseline electricity grid in 2050. The same difference between Net Zero Energy and Net Zero Emissions strategies can also be seen. Their impact is dramatic due to the definition of these strategies on an ultra-low EUI basis (12-20 kbtu/sf/yr) compared to their current baseline (140 kbtu/sf/year).

Figure 21. Med/Lab/Production Strategies – Existing Buildings 1950-1980



Driving energy and GHG emissions reductions in existing Med/Lab/Production buildings, while very challenging, will have significant impacts to the city’s GHG emissions profile. These buildings typically have very high process and plug loads, ventilation requirements and simultaneous need for both heating and cooling and as a result, present significant opportunities for energy reduction. The most effective prescriptive strategies studied in this analysis are fuel switching, lighting retrofits, retro commissioning and electrification of HVAC systems. While the most effective strategies for Med/Lab/Production existing buildings continue to be the performance-based strategies, deep energy or emissions retrofits, they show a less dramatic reduction in energy consumption and emissions compared to new construction, approximately 50%.

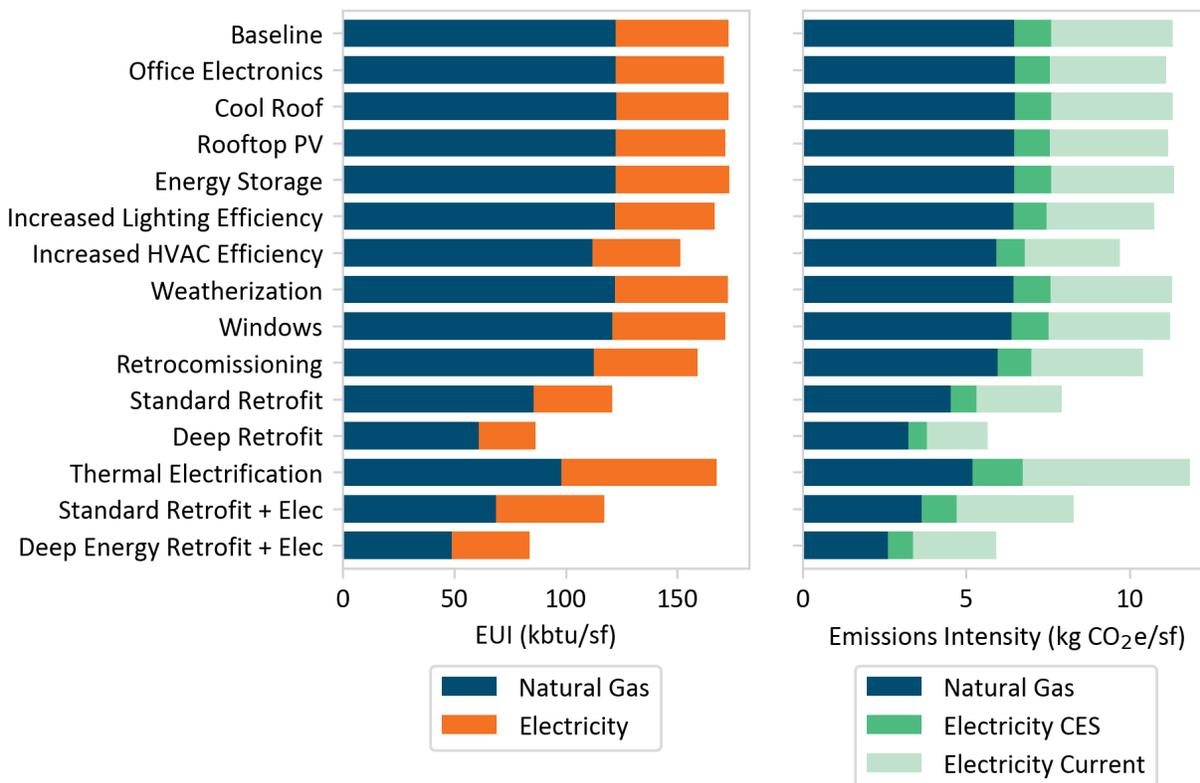
Figure 22. Convention/Assembly Strategies – New Construction



Convention/Assembly new construction buildings are moderate energy and emissions intensive buildings, like office buildings. As previously identified, this typology represents the widest range of buildings from arenas, auditoriums, and convention centers to large restaurants, movie theaters, libraries, and some college or university buildings.

These buildings typically have a large peak in their energy profile driven by when the building is fully occupied compared to minimally occupied and typically have high ventilation requirements. Having appropriate HVAC systems that can turn-down, and/or moderate according to occupancy and recover energy see the highest reductions. Again, the most effective strategies for Convention/Assembly new construction are performance-based strategies that accelerate energy and/or GHG emissions reductions from the baseline assumption. Most prescriptive strategies have small impacts (less than 10%) on energy and GHG emissions.

While electrification of HVAC systems has a moderate energy reduction (3.7%), this translates to 30% savings in GHG emissions with the baseline 2050 electricity grid. There also continues to be a material difference between Net Zero Energy and Net Zero Emissions strategies.

Figure 23. Convention/Assembly Existing Buildings 1980-2000

The results for existing Convention/Assembly buildings were generally consistent across all age ranges. The most effective strategies are performance-based strategies that accelerate deep energy and/or GHG emissions reductions from the baseline assumption, particularly ones that address natural gas consumption. The most effective prescriptive strategies are fuel switching, lighting retrofits, retro commissioning and retrofitting HVAC systems. Standard retrofits combine HVAC equipment replacements with increased efficiency which results in a considerable 30% energy and GHG emissions savings. Given the high natural gas use of this typology for non-heating uses including cooking in presumed café and restaurant spaces, electrification of HVAC systems has a much smaller impact on GHG emissions than other typologies. There continues to be a material difference between Deep energy (50% reduction) and Deep energy & electrification strategies, an additional 25% reduction in GHG emissions.

With a sound understanding of effective strategies, the next step was development of policies that would seek to achieve the desired outcomes (i.e. GHG emissions reductions in the building sector) established by the strategy analysis.

6.7 CITY-WIDE IMPACT OF STRATEGIES

Simulating individual strategies across 75 buildings revealed several key insights that were used to inform the selection of policies for further study. Single ECM's actions have a modest impact, even when applied city-wide (Figure 23) while the technical potential of packaged ECM's (Figure 24) is much greater. A number of ECMs have negative impacts either under all grid scenarios, or under clean grid scenarios. This behavior highlights some of the dynamic properties of a building. A cool roof may reduce cooling demands in the summer, but would increase heating demands in the winter. Older lighting and office electronics are inefficient and generate heat as waste energy, which reduces heating demand in a building. In the simulation reduced internal gains from more efficient lighting and equipment is made up by increasing natural gas use. The direction in this trade off in emissions is further influenced by the carbon intensity of the grid. Likewise, the generation of solar electricity has no impact on emissions if the grid-supplied electricity is carbon-neutral.

Packaged measures reflect a potential combination of many of the analyzed ECMs (Figure 24). For new buildings their potential reduction is limited to emissions that are created by future growth, which is a small contributor to future emissions. Still, passive house and net zero strategies are likely to be necessary for limiting growth and taking advantage of low-cost measures during building development. In existing buildings, the Standard, Deep and Passive House Retrofits strategies the only approaches that significantly move the needle on emissions via energy conservation. Thermal electrification of the building stock's primary heating loads can unlock deep emissions reductions only when the grid becomes less carbon intensive.

These packaged measures reduce emissions through a reduction or transformation of the building's energy demand (Figure 25). Such transformation could result in a significant reduction in natural gas and oil consumption. Thermal electrification does significantly increase electricity consumption in the city. A more detailed discussion of the impacts of this is contained in the Carbon Free Boston Energy Technical Report. Briefly, electricity consuming increase in aggregate and at times of peak thermal demand that will likely require new capacity development or peak management strategies. Coupling thermal electrification with aggressive energy conservation actions can result in a decrease in electricity use alongside fuel consumption.

Figure 24. City-wide impact of single energy conservation measures

* Indicates measure applicable to only new buildings

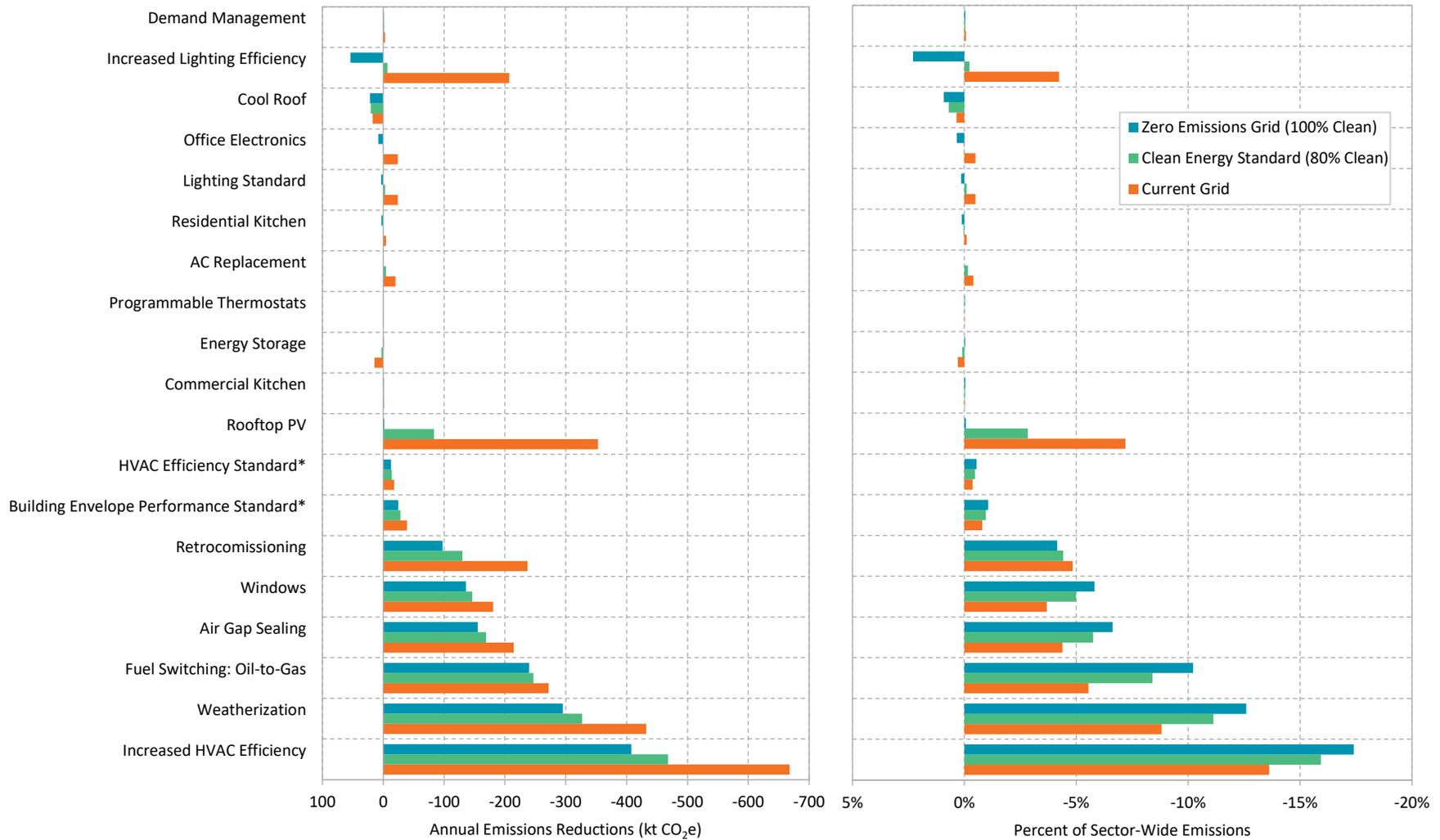


Figure 25. City-wide impact of packaged energy conservation measures and electrification actions

* Indicates measure applicable to only new buildings. Standard and deep retrofits are applicable to the commercial stock only, while passive house retrofits are applicable to the residential stock. Thermal electrification applies to all buildings.

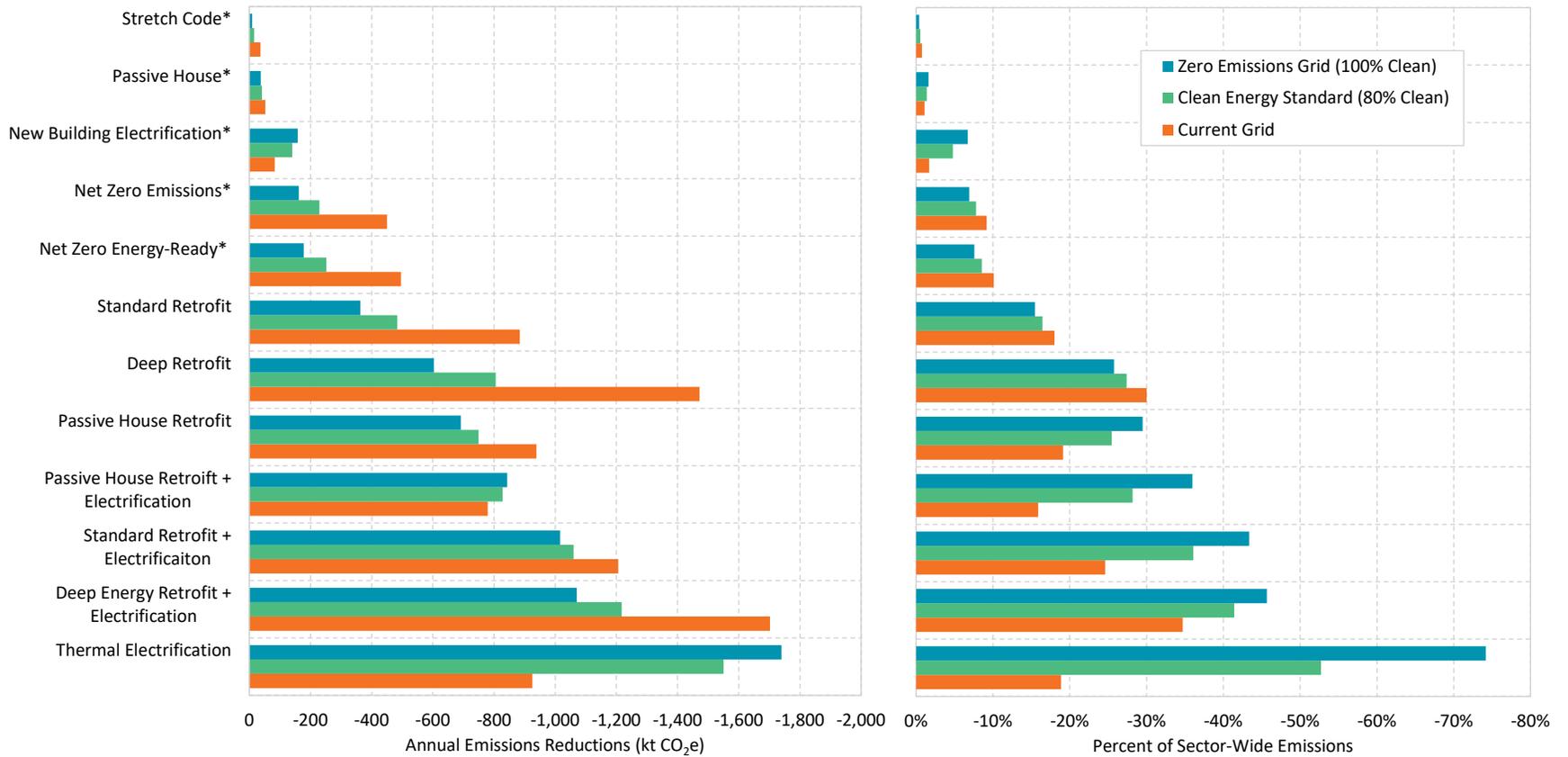
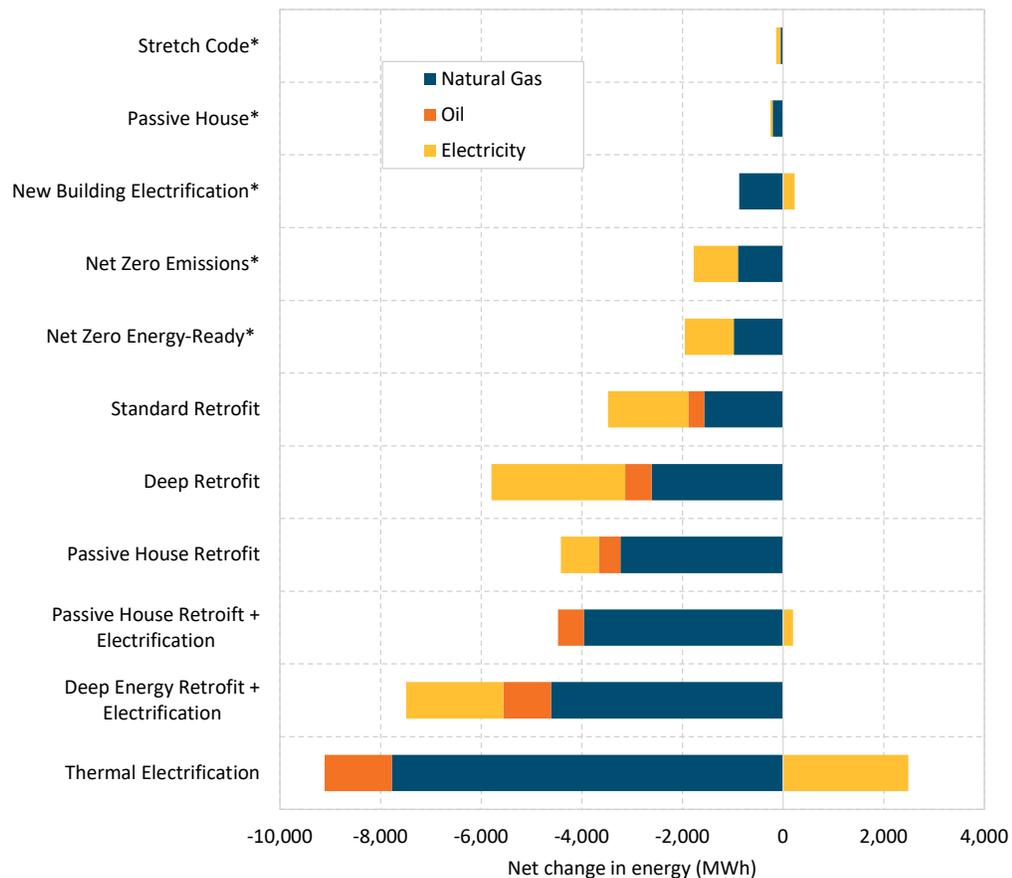


Figure 26. Technical potential net change in energy use for packaged energy conservation strategies

6.8 COST ANALYSIS

Cost estimate of various policies were evaluated to understand the relative tradeoffs between different strategies. Our cost estimation mostly utilizes incremental costs of energy conservation measures. This approach accounts for the marginal cost of a specific energy conservation measure over a conventional intervention. For new buildings, an incremental cost would thus reflect the additional cost incurred to employ a high-level of insulation versus a standard level of insulation as stipulated by the building code. For existing buildings such incremental costs would be recognized at the end-of-lifetime replacement point for existing building components. Identifying such a time point is hard to define especially for existing systems in buildings with a patchwork renovation history but would include the replacement of a boiler with an electric heat pump or the upgrading of insulation and windows during a renovation.

Such an assumption could be applied to the policy scenario that assumes that such interventions are applied at building construction (new buildings) or at a major renovation point (existing buildings). Based on historical trends, we assume that major renovations occur on a 30-year cycle or at a rate of 3.3% of the buildings stock per year. Such cost assumptions would not be applicable if such interventions were applied outside a renovation schedule.

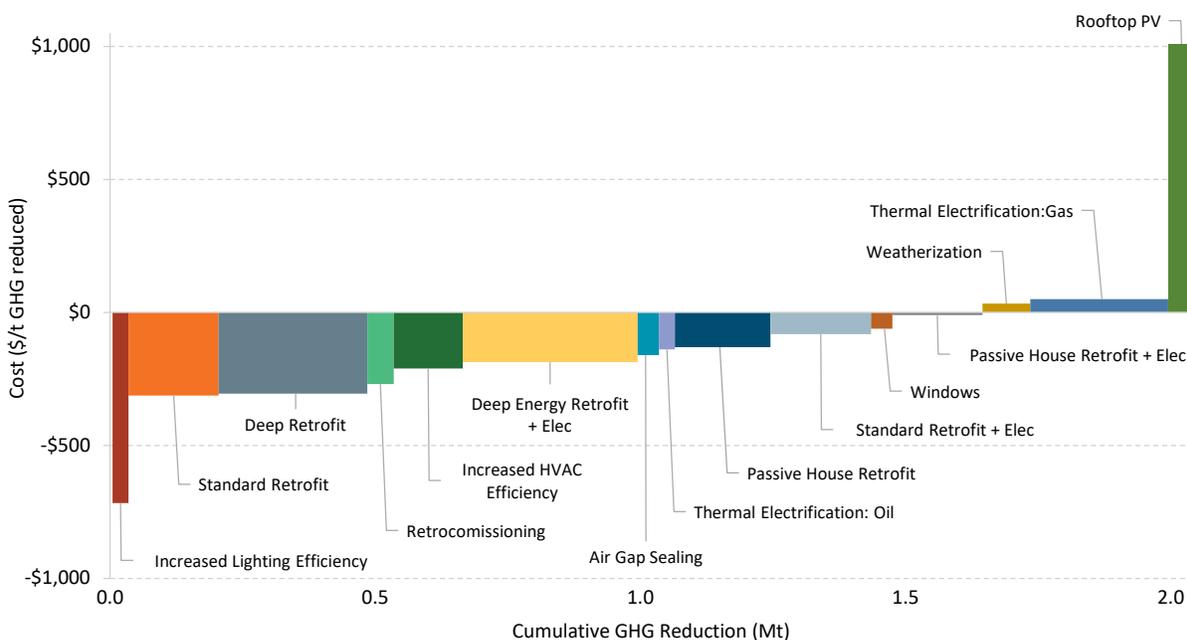
Due to large scale uncertainty in cost estimation our analysis here is intended to be a high-level estimation of the costs and savings associated with different degrees of energy conservation measures.

Incremental cost values were taken from One City Built to Last [22]. Cost values were assumed to be consistent across building class and vintages. Estimates for deep energy retrofits combined several of these values and were validated against the Advanced Energy Retrofit Guides (AERG) developed by the National Renewable Energy Laboratory (NREL) and Pacific Northwest National Laboratory [12]–[16]. Using the framework provided by the AERG’s Office Building study, we use a 6.5% discount rate in NPV calculations. Energy costs were calculated using the 2018 Annual Energy Outlook [23].

Future costs for individual and packaged measures are highly uncertain. While recent, local, residential deep energy interventions had high costs, there was a large degree of variability among the cases. A larger study found that a small number can be cost-effective. It is likely that costs will come down if this work is performed at a large scale. There is a lot of potential technological learning to be achieved in this nascent industry that could bring down costs.

Figure 27. Marginal Abatement Cost (MAC) Curve for Retrofitted Buildings

Many energy efficiency measures reduce energy use and GHG emissions while also saving money. The vertical axis is the cost associated with reducing GHG emissions by one metric ton for a particular strategy (\$/t CO₂e). The horizontal axis is the total reduction in GHG emissions caused by that strategy; the wider the bar, the greater reduction. Costs are averaged across 2020-2040 (20-year time horizon) and assume current best practices in the industry. Actual costs are likely to vary significantly by building type and age. *Source:* model calculations, ASHRE & DOE Advanced Energy Design Guides, One City: Built to Last (NYC).



The cost-effectiveness of measures to reduce GHG emissions is represented by a marginal abatement cost (MAC) curve (Figure 20). A MAC is a convenient tool that measures the impact of a measure in emissions abatement potential and economic terms (\$/ CO₂e), and thus provides a useful initial framing for a deeper policy discussion. A MAC curve should not be viewed as a recommendation for a rank ordering of policy implementation because important dimensions of decision-making are excluded, and because it measures costs under a narrow set of fixed conditions. The costs shown in Figure 7 assume current best practice in the industry that is used at the end of the normal life span of a window, heating system, etc., or in conjunction with a major renovation project.

Most strategies to decarbonize the building sector have negative costs—this means that the dollar value of energy saved is greater than the cost of implementation. In effect, most energy conservation measures pay for themselves. Individual measures that are readily available to households and businesses such as the installation of energy efficient lighting and weatherization unequivocally save energy and they reduce utility bills and emissions, but they yield small GHG reductions. Rooftop solar has a large cost and a modest GHG reduction potential, but it does enhance resiliency for the city by providing energy that does not rely on a connection to the grid. The replacement of an oil furnace with an electric heat pump results in a net savings over the lifetime of the heat pump. On the other hand, the replacement of a gas furnace with a heat pump is costly due the higher relative costs of electricity compared to natural gas.

Retrofits yield large reductions in GHG emissions over the lifetime of the equipment installed. The abatement cost of a deep energy retrofit is similar to a standard retrofit even though it has a higher initial cost. Over the lifetime of the equipment (~20 years), the approximately 50 percent energy savings from a deep retrofit make it cost-comparable to a standard retrofit, while delivering greater GHG reduction. The combination of a whole-building retrofit with the electrification of heating and cooking increases the GHG reduction compared to a retrofit alone. These results demonstrate that energy efficiency and electrification are complementary strategies when they implemented in tandem.

7 POLICY REVIEW

Reducing emissions across Boston's current and future building stock will require aggressive but flexible policies. This section evaluates current policies and their potential penetration into Boston's building stock.

Generally, policies directly regulating the building stock can be categorized as either incentives or mandates, and as either prescriptive or performance (Table 7). These policy approaches can work in concert to address a broad range of goals across the building sector. For example, the MassSave program has led the country in promoting energy efficiency incentivization by driving residential and commercial buildings owners and occupants to implement a number of prescribed ECMs. *Renew Boston* has augmented this work, aiming to educate the city's residents on the potential of energy conservation. At the same time, public recognition is significant incentive for high profile companies and institutions to perform better. Across Boston, universities, businesses, hospitals and institutions have committed to drastically reducing emissions in their buildings. Sometimes these efforts are promoted by a competition or a rating program, sometimes they simply reflect good citizenship and leadership.

Achieving carbon neutrality will require that more mandates be built on top of these programs. Boston's BERDO requirement makes owners of large buildings understand the energy use of their buildings and how it contributes climate change relative to other buildings in the city. To achieve carbon neutrality, especially in the absence of state and federal policy, the city's building stock will need to be more tightly regulated. Mandates regulating building performance allow building owners the flexibility to pursue emissions reductions in a manner suited to a building's unique attributes and use. This flexibility drives up the potential compliance rate. Limited prescriptive mandates are likely to be required to eliminate the use of fossil fuels where clean fuels or electricity are available. In particular, banning the use of heating oil (Figure 23) in the near future would reduce building sector emission by eight percent and

deliver air quality benefits. While such a mandate may be an effective strategy for decarbonizing the residential sector. Many larger buildings, including hospitals, use heating oil for backup. Thus different degrees of regulation may be needed in different sectors.

Table 7. Policy frameworks used for this analysis

Framework	Definition	Examples	Adoption Rate
<i>prescriptive incentive</i>	an incentive (typically financial) for a specified action be taken	Programs like MassSave and Renew Boston that offer financial incentives (e.g., rebates) for taking certain energy efficiency actions (light bulbs, heat pumps) are considered prescriptive incentives.	< 18%
<i>performance incentive</i>	an incentive that encourages building owners to meet a specified EUI or emissions performance target	The federal tax incentives [24]; accelerated approval; reduced fees; educational support; technical assistance; recognition programs; competitions. (Often includes programs outside of government)	15% - 28%
<i>prescriptive mandate</i>	a requirement issued by a governing body that a specified action be taken	The City of Boston's Building Energy Reporting and Disclosure Ordinance (BERDO) requires all buildings larger than 35,000 square feet or 35 units to annually report energy and water use as well as to complete an energy action every five years.	73% - 85%
<i>performance mandate</i>	a requirement issued by a governing body that buildings meet a specified performance target	Energy code & stretch code. The City of Boulder, CO implemented the SmartRegs program, which requires all licensed rental properties to meet a specified minimum level of energy performance (e.g., [25])	85%

The policy analysis below is used develop assumptions for how impactful certain policy regimes will be in the future. Regulating the built environment for emissions mitigation will be a necessary, but challenging endeavor. While the policy framework bounds policies that directly act on buildings, any policy regime will need to be supported by a number of enabling policies that span finance, workforce development, and building owner education.

7.1 CITY OF BOSTON POLICIES

7.1.1 BERDO (Existing Buildings)

Boston's Building Energy Reporting and Disclosure Ordinance (BERDO) [26] was passed by the City Council in May 2013 which was enacted as an amendment to the Air Pollution Control Commission (APCC) Ordinance. The stated purpose of BERDO is:

"to reduce the emissions of air pollutants, including greenhouse gases, from energy production, encourage efficiency use of energy and water, and develop further investment in building a green economy by requiring the reporting and disclosure of annual energy and water use in all large buildings in accordance with this article. {7-2.2 (a)}"

The ordinance has phased in buildings over the past five years and now currently includes nonresidential buildings that are 35,000 square feet or larger, residential buildings that are 35,000 square feet or larger or have 35 or more units and any parcel with multiple buildings that sum to 100,000 square feet or 100 units. Aside from the annual reporting requirement, section 7-2.2 (f) Energy Assessments or Actions

requires buildings under the ordinance complete an energy assessment or action such as the Commission shall specify with five (5) years of its first energy reporting deadline and within every five (5) year period thereafter. Additionally, section 7-2.2 (j) Enforcement and Penalties contains the ability for imposition of penalties by the APCC for non-compliance, including fines. It is important to note that to date, no fines have been issued for non-compliance, despite not achieving full compliance.

BERDO therefore is not solely a disclosure ordinance, but also includes requirements for ongoing action as well as a means of enforcement of the ordinance. The ordinance has the potential to play a role in driving changes in the buildings sector with further amendments, rather than needing to institute new policy. Several other cities around have similar disclosure and reporting ordinances. While each city has differing thresholds for compliance, most are similar to BERDO (Table 8).

Table 8. Disclosure Ordinance Compliance rates from various cities

Reported in % of applicable buildings for each year after implementation.

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Boston (BERDO)	73	76	79	82		
Cambridge (BEUDO) [27]	95	91				
New York (Local Law 84) [28]	56	74	80	82	83	90
San Francisco – Large [29]	83	83	81	82	82	
San Francisco – Midsize [29]	53	53	46	48		
San Francisco – Small [29]	41	36	39			
Seattle: Non-residential [30]	89	90	99			
Seattle: Residential [30]	97	95	99.5			
Chicago [31]	92	84	80	85		
Philadelphia [32]	86	90	91			

The compliance rate of Boston by number of buildings is comparable to other large cities. It is important to note that these data sets for mandates are relative to disclosure only and do not represent action being taken. It is a reasonable assumption that if action is required, compliance rates may decrease. In the coming years many of these ordinances, with require an energy reduction action. Compliance rates with these efforts can help to guide an understanding of the efficacy of building policies and their enforcement mechanisms.

7.1.2 Article 37 (New Buildings)

Article 37 is the green building zoning provision in Boston’s Zoning Code. The stated purposes of Article 37 are, “to ensure that major building projects are planned, designed, constructed, and managed to minimize adverse environmental impacts; to conserve natural resources; to promote sustainable development; and to enhance the quality of life in Boston.”

It requires that all projects subject to Large Project Review under Article 80 meet the minimum ‘certifiable’ level under the appropriate Leadership in Energy & Environmental Design (LEED) rating system. Article 37 also established the Interagency Green Building Committee (IGBC) to advise the BPDA and Inspectional Services Department (ISD) on project compliance with the City’s green building and climate resiliency policies and requirements [33]. Enforcement of Article 37 is provided by section 37.7 Commissioner of Inspectional Services shall not issue any building permit or use permit for a Proposed

Project that is subject to the provisions of this article unless the Director of the Boston Redevelopment Authority has issued a Certification of Compliance pursuant to Section 80B-6.

Article 37 drives the design of buildings to an intended level of performance that is tied to permitting (aka entitlements) as well as issuance of a final building permit. The Article also has the potential to play a role in driving changes in the buildings sector with further amendments, rather than needing to institute new policy.

7.1.3 Stretch Energy Code (New Buildings)

The City of Boston adopted the stretch energy code which is a performance-based mandate. While there is a prescriptive path, the performance based pathway is the predominant pathway to demonstrate compliance with energy performance. Again, the Mass EEAC has completed a study in March 2018, *Massachusetts Commercial Energy Code Compliance and Baseline for IECC 2012* [34], that estimated the compliance rate with the stretch energy code using two methodologies.

An additional study from July 2018, *Massachusetts TXC47 Non-Residential Code Compliance Support Initiative and Net Savings Assessment* [35] also provides insight to compliance with and without the Code Compliance Support initiative (CCSI) which provides training to code officials and buildings professionals with the intent to improve compliance with building energy codes. The study found that compliance attributable to the CSSI was 5-6% improvement.

Table 9. MA Stretch Energy Code Compliance

Reported in % of applicable buildings for each year after implementation.

	Year 1	Year 2	Year 3	Year 4	Year 5
Energy Code Compliance Trends [34]	82	76	85	87	88
Compliance estimate with CSSI [35]	93	94	94	95	95
Compliance estimate without CSSI ever existing [35]	81	82	83	84	84

7.2 STATE POLICIES

7.2.1 MassSave

MassSave offers a wide range of services, rebates, incentives, trainings, and information to assist residents, businesses, and communities to make energy efficient upgrades. MassSave is a collaborative of natural gas utilities, electric utilities, and energy efficiency services providers, including Berkshire Gas, Blackstone Gas Company, Cape Light Compact, Columbia Gas of Massachusetts, Eversource, Liberty Utilities, National Grid, and Utiliti [36].

In the City of Boston, Renew Boston is the incentive program associated with the Utilities. As identified in the policy adoption research, incentives have an important role to play in driving behavior and it is anticipated this will continue as Boston moves to decarbonize by 2050.

The City of Boston, through its Renew Boston program, has set a goal to increase residential participation in all residential energy efficiency programs including MassSave, rebates for Energy Star appliances, and Low-Income and Multifamily programs. The data represents the percentage of households participating each year and as such, duplicates will be present as households can participate multiple years.

Table 10. Prescriptive Incentive Adoption Rates

Reported in % of applicable buildings for each year after implementation.

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Boston Renew Boston Participation	2.4	3.3	3.3	4.4	7.4	8.7
LED Lighting - MA	1	2	3	6	12	18

The Massachusetts Energy Efficiency Advisory Council (EEAC) also provides data on the effectiveness and progress of efficiency programs across the state. A June 2017 briefing [37] looked at the residential upstream lighting program which provides for retrofitting of lighting with LED lamps. As the data shows, this program has yielded much higher participation than Renew Boston. The ease of obtaining the incentive can be a barrier to participation in these types of programs. While these two data sets provide very different results, at the macro scale, the overall penetration remains low at less than 20%.

7.2.2 Energy Code & Stretch Energy Code

The Energy code and the Stretch Energy Code is outside the direct control of the City of Boston and is controlled by the State via administration of the State Building Code by the Board of Building Regulations and Standards (BBRS). In accordance with the Green Communities Act of 2008, Massachusetts is required to update its building code every three years to be consistent with the most recent version of the International Energy Conservation Code (IECC).

780 CMR Ninth Edition via Chapter 13: Energy Efficiency Amendments, the energy code regulates energy performance (not emissions) of buildings for both new construction and existing buildings. The Stretch Code is optional by going above the State Energy Code. It is updated less frequently but needs to be refreshed in order to maintain its “stretch” status over the Base Energy Code. Municipalities choose to adopt it by vote of the City Council or Town Meeting. Adopting the stretch code is a necessary criterion for designation as a Green Community and therefore be eligible for grants from the State to pay for energy saving projects in municipal buildings. Boston’s adoption of the stretch code became effective July 1, 2011. Boston can work with state agencies to advance the energy code at triennial revisions and introduce net-zero stretch energy code options.

In its current form, new residential construction needs to follow the Performance Path of the Base code and achieve a HERS (Home Energy Rating System) rating of 55. The Stretch Code also applies to new commercial buildings over 100,000 square feet. Additions, renovations, and repairs to residential or commercial buildings are not applicable to the updated Stretch Code, only the Base Energy Code is applicable.

7.3 OTHER PROGRAMS

These programs include A Better City’s Sustainability Challenge locally and nationally, DOE’s Better Buildings Challenge. These organizations establish programs based on performance that provide leadership recognition and awards for participants. As such, these participants are typically early adopters, or the first movers.

Boston’s Green Ribbon Commission commissioned a study to look at the largest property owners in the City. This analysis found that the top fifty property owners in the City control 28% of the overall square footage in Boston, over 176,000,000 square feet. These owners include public, commercial and non-

profit organizations such as: the City of Boston, the Massachusetts Port Authority; Boston University; Northeastern University; the Archdiocese of Boston; the Boston Medical Center; Avalon Bay Communities; and Boston Properties. The largest segment is public entities followed by real estate and higher education. The research showed that most of these entities have commitments around GHG emissions and energy reductions. As such, they are already working towards the City's goals to varying levels.

This cohort is important for demonstrating the feasibility of new technologies or novel approaches to GHG reduction. Often their financial capabilities or public responsibilities facilitate the implementation of newer technologies. This increases market knowledge about technology design and implementation, such as building electrification or comprehensive energy conservation measures. This knowledge helps to reduce technology and implementation costs for others, subsequently opening the door to policies aimed at implementing such actions across the entire sector.

7.4 POLICY IMPACT ANALYSIS: ROOFTOP SOLAR

Building-scale solar can help contribute to Boston's carbon neutrality goals. Its adoption by both residential and commercial building owners in recent years reflect a confluence of incentive-focused policies, lowering prices, and increasing consumer interest. For building-scale solar, rooftop solar photovoltaic (PV) electricity generation ("rooftop solar") is the most significant technology being deployed. Through the generation of solar energy, such systems can provide power to the buildings that underly the panels, power to the grid through net metering, and lucrative solar-renewable energy credits (SRECs) that can be transferred to other entities [38]. Rooftop solar also provides a green-status to buildings that can increase asset values. Despite the benefits of solar electricity, the installation of these systems presents a large up-front cost that many residents and businesses are not financially capable of covering. To alleviate this financial burden, various financial incentives (e.g., rebates, low-interest loans, tax credits, etc.) are available at the state- and federal-level to make solar electricity a viable and affordable energy option.

The Massachusetts Clean Energy Center (MassCEC) offers incentive programs to help residents and businesses throughout Massachusetts to adopt clean energy technologies and is responsible for tracking solar installations through its Renewable Energy Production Tracking System (PTS) [39]. The analysis presented below utilizes the MassCEC's PTS solar installation data to evaluate how this technology has been adopted over the last decade.

7.4.1 Solar Electricity - Massachusetts

As of mid-2018, approximately 83,000 rooftop solar installations have occurred across 351 municipalities in Massachusetts, amounting to nearly 2.14 GW of total solar capacity. About 95 percent of these installations were on residential buildings. Solar electricity adoption was slow at the beginning of the century with less than 3,000 solar installations statewide within the first decade. Statewide solar installations began to rapidly pick up between 2011 and 2016, adding an additional 64,000 solar electric systems and exceeding 20,000 installations per year in 2015 and 2016 (Figure 1). Solar installations dropped drastically in 2017, decreasing by nearly 50 percent of 2016's total. Cost has been a key driver in the adoption of solar electricity across Massachusetts. The average cost per watt has decreased over time, increasing the affordability and accessibility of this clean energy technology (Figure 28).

Figure 28. Annual Solar Installations in Massachusetts

Source: Data from Massachusetts Clean Energy Center.

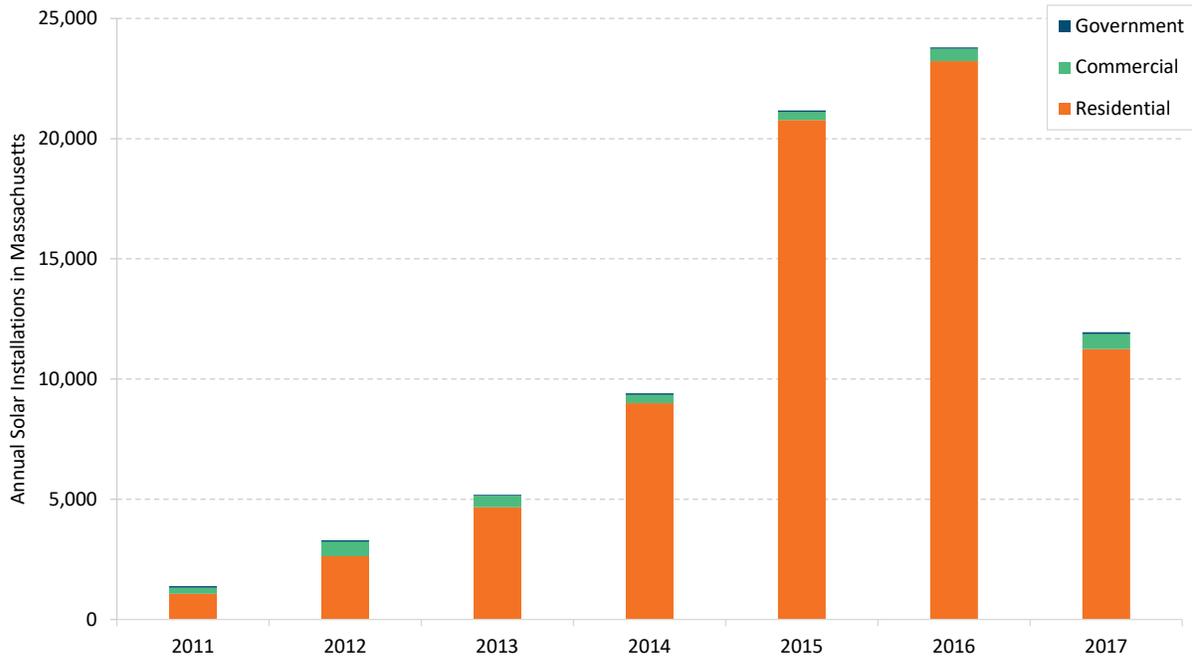


Figure 29. Average Cost per Watt in residential installations

Source: Data from Massachusetts Clean Energy Center.

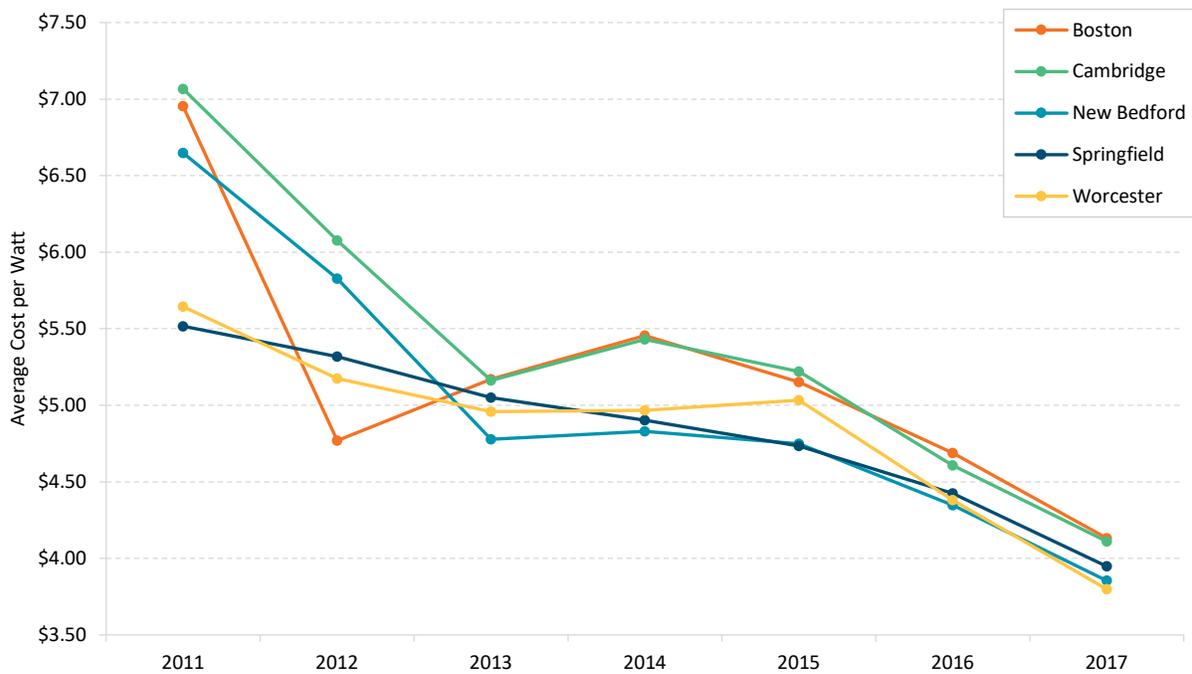
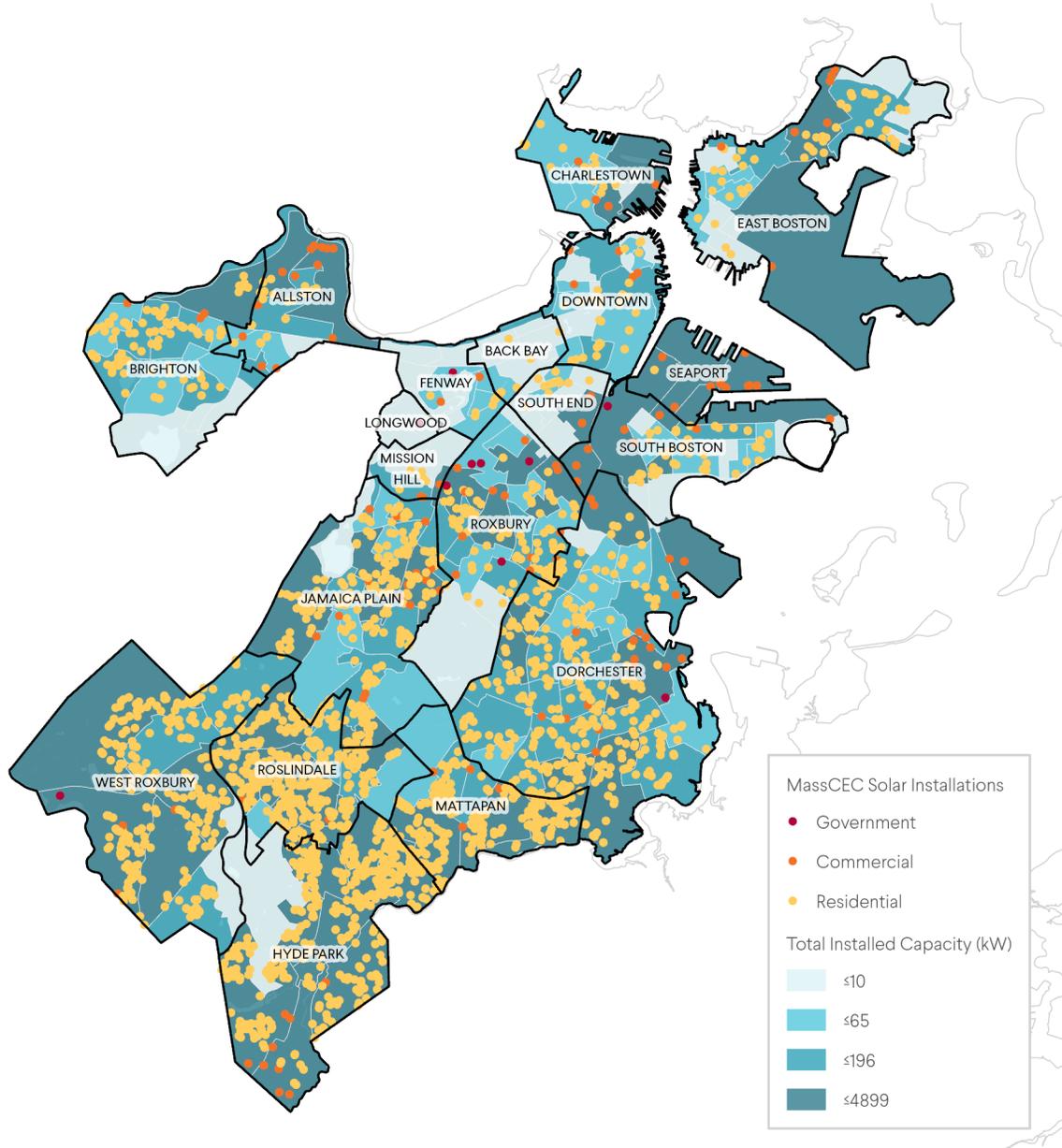


Figure 30. Rooftop Solar in Boston

Solar installations and total installed capacity by census tract in Boston through June 2018 that were funded by Massachusetts Clean Energy Center programs. Source: Data from Massachusetts Clean Energy Center.



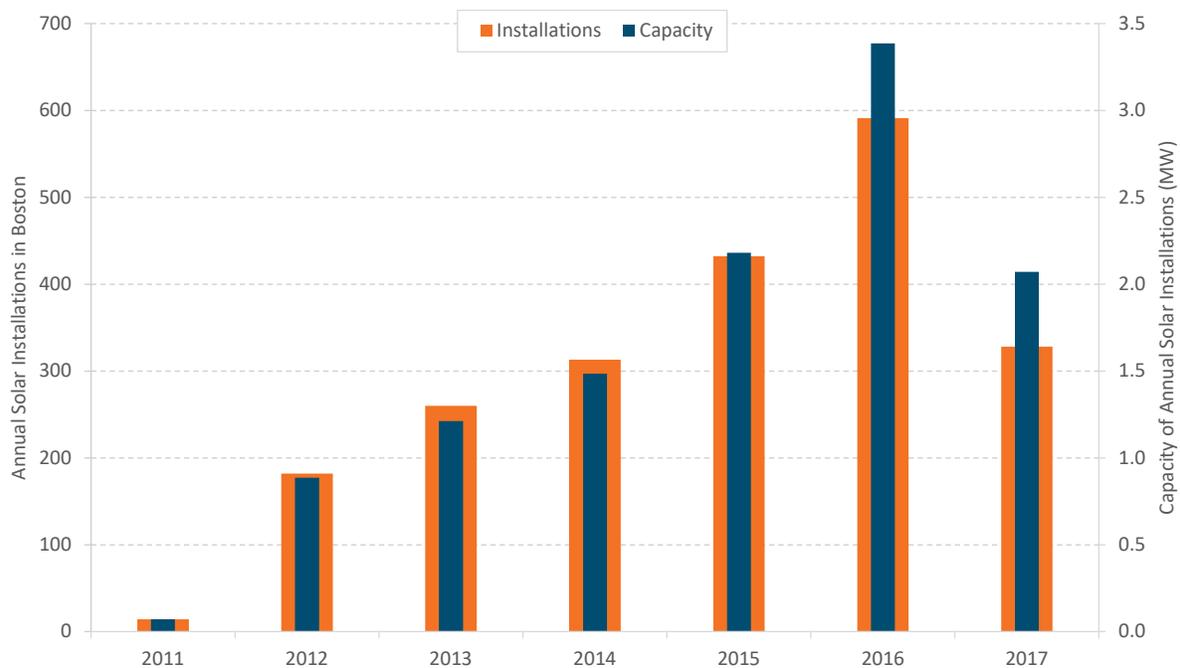
7.4.2 Solar Electricity - Boston

Through mid-2018, about 2,450 solar systems have been installed in the city, amounting to nearly 36 MW of total solar capacity (Figure 29). Boston's solar electricity portfolio is by far the largest out of any municipality in Massachusetts with Worcester and Springfield following behind with only about 1,300 installations each. Like Massachusetts, Boston's solar installations have mainly taken place on residential buildings.

In addition to the number of annual installations, the installed capacity of these solar electric systems can provide important information about how solar electricity adoption has evolved over time (Figure 31). Between 2011 and 2015, the average installed capacity ranged between 4.7 and 5.0 kW per installation. In 2016 and 2017, the average installed capacity increased to 5.7 and 6.3 kW per installation, respectively reflecting an improvement in cost, technology, and installation approaches.

Figure 31. Annual Solar Installations and Capacity in Boston

Note decline in 2017 is also observed in City of Boston permit data. Source: Data from Massachusetts Clean Energy Center.



Although Boston's residential buildings account for most solar installations in the city, solar installations have only occurred on about 3 percent of Boston's residential building stock. Rates of installs differed starkly amongst the 3 different ownership structures for residential buildings (condo, owner-occupied and rentals). Owner-occupied buildings account for most residential solar installations in Boston, both overall and as a proportion of buildings in each cohort (Figure 31). The lower installation rates for rental and condo units suggest potential barriers to adoption in these groups. For condo associations such barriers may include organization hurdles and lack of models for implementation. For rentals, the financial benefits of solar generation could provide additional revenue, but landlords may be limited by capital constraints and knowledge.

Solar roofs may have become as much as an element of personal identity as owning a hybrid or an electric vehicle. Such consumer behavior would likely be one of the reasons why owner-occupied homes

tend to have higher rates of adoption than other ownership classes. Such behavior may also explain the recent drop in adoption, which could indicate a saturation in the type of owner who will likely be an early adopter. At this point about 3-3.5% of residential buildings have rooftop solar. While some early incentive programs have promoted some to adopt, more aggressive policy action will be needed to get close (Figure 32) to achieving the full technical potential of 1.2 TWh (Google Project Sunroof).

The ownership aspect of having access to renewable energy has likely been a driver of rooftop solar uptake. If community choice aggregation (and city wide 100% carbon free procurement in the long term) comes online this may lower the desirability of installing a rooftop solar: *If one can check a box on their utility bill for 100% renewable energy, why go through the hassle of installing solar?* Thus, for rooftop solar to reach its city-wide technical potential there must be either a clear financial incentive to install panels or a clear policy mandate to spur action.

The financial incentive of rooftop solar will lag other renewable options, due to its high installation costs. In Massachusetts on-shore wind is typically the lowest cost renewable energy, followed by utility scale solar, and then rooftop solar. Once developed at scale, offshore wind may become cheaper than rooftop solar. Solar on new construction is generally cheaper than installations in existing buildings, but as buildings grow larger and taller, the proportion of solar available to the building is smaller and smaller. This would suggest that rooftop solar may be a misallocation of capital, at least in the near term. However, if time of use pricing was implemented broadly, rooftop solar may provide significant cost savings if integrated with on-site battery storage allowing residents to store energy during peak production (e.g., day time, when a home is unoccupied) to be used during period of peak demand (e.g. nighttime heating or cooling). Additionally, if integrated into a local microgrid, such integrated solar-battery systems could provide a source of resiliency during critical events. Roof-top solar thus need to provide location- and time-specific value. Identifying such value will be necessary in future policy design to promote more rooftop solar generation.

Achieving this such installations will require a mix of financial and regulatory incentives. Financial incentives include both subsidies and time of use pricing. Regulator incentives could support microgrid development or require the installation of rooftop solar. California has implemented the latter regulation, requiring all new residential homes up to three stories to have solar roofs installed. This may be feasible for similar homes in Boston but may be infeasible for larger buildings that may require the use of roof space for heat pumps. Solar regulations should also consider the importance of trees in an urban environment and avoid trading current and potential future foliage for rooftop solar generation. Promoting rooftop solar is an essential element of creating carbon neutral buildings, but will require a flexible mix of polices and incentives to accelerate adoption and innovation in the space.

Recent residential installation rates hover at around 300 per year. This is a large increase from just a few years ago, but is well below the installation rate needed to realize the full rooftop PV potential in Boston of about 1 TWh, equivalent to about 15 percent of current electricity demand (Figure 26). The work required to achieve this scale of rooftop PV deployment provides an excellent opportunity to implement in-city workforce development.

Figure 32. Annual Residential Solar Installations in Boston by Owner Classification

Source: Data from Massachusetts Clean Energy Center.

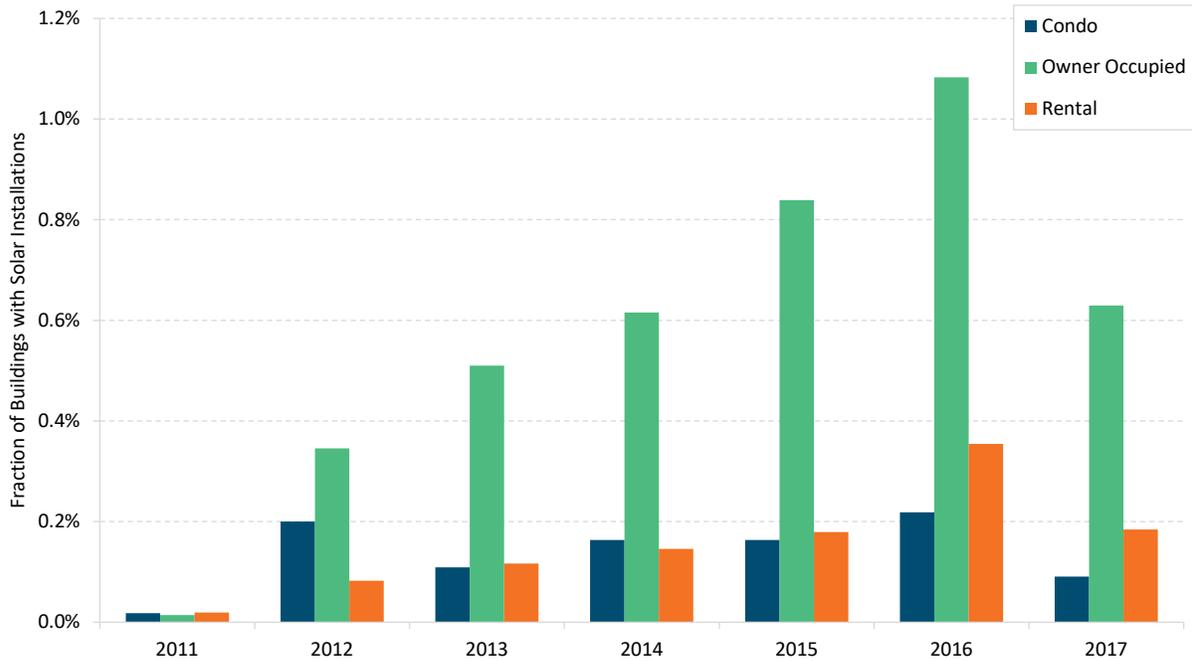
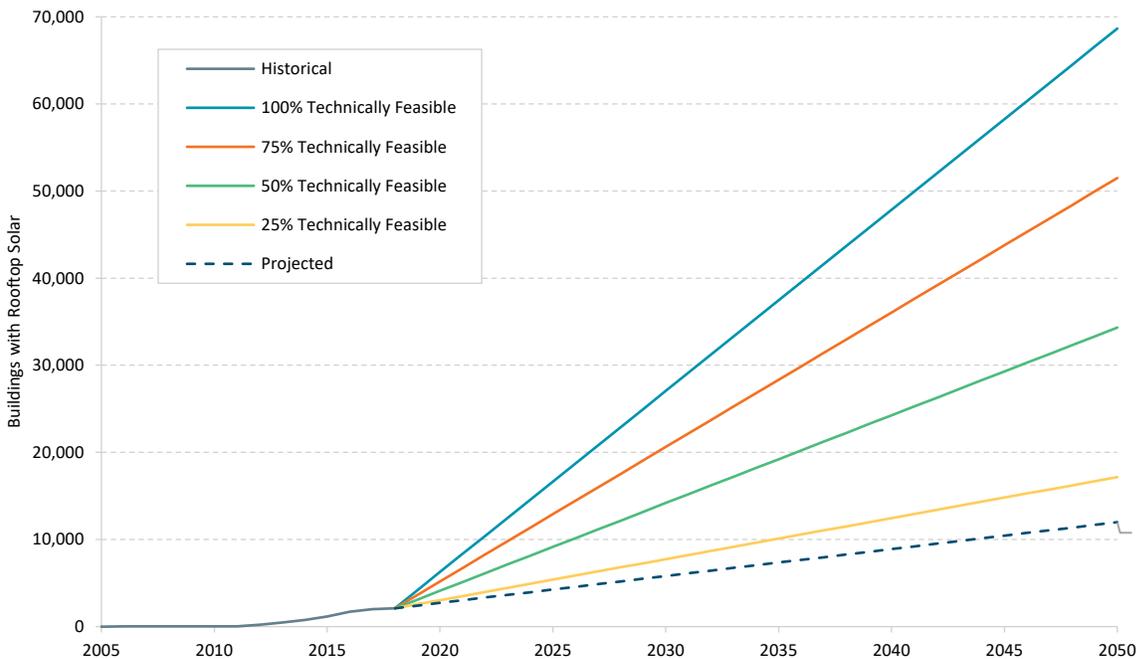


Figure 33. Possible Future Installations of Rooftop Solar in Boston

Historical installs of rooftop solar electric systems in the residential building sector, with forecasts representing various rates of potential citywide adoption, and the number of annual installations required to achieve each respective level of adoption. Source: Historical data from Massachusetts Clean Energy Center; forecasts from Institute for Sustainable Energy model calculations.



7.5 POLICY ADOPTION

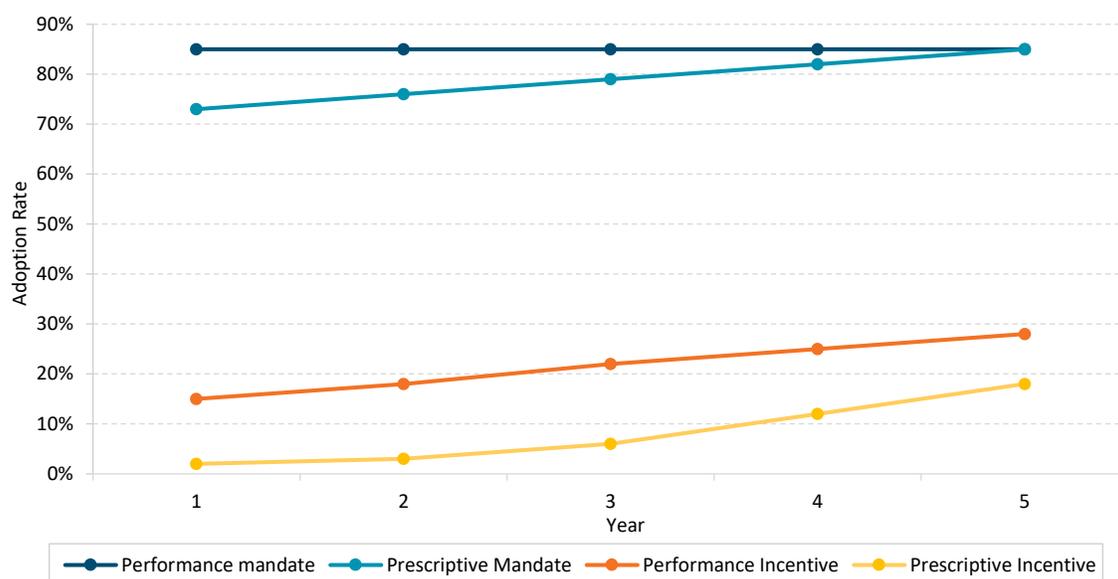
Predicting how building owners, managers and residents will respond to various, untested policy mechanisms is challenge and wrought with uncertainty. Due to knowledge limitations, regulatory barriers, perceived resource and capital constraints, uncertain and variable time horizons, and other factors, decision makers in this sector tend not to behave as classical rational agents compared to other sectors. This may suggest that more direct regulatory action, such as an emissions-focused policy regime, can help to reduce the social consequences of poor-performing and fossil-fuel emitting buildings. These social consequences go beyond those associated with carbon emissions and include climate resiliency and public health.

Using the policy framework listed earlier in Table 7, a range of policies were defined that included both incentives and requirements on a prescriptive and performance basis. The important distinction is that policy is the legal mechanism to achieve a desired outcome (e.g., emissions mitigation) while the strategy analysis establishes the impact of a particular action. To model the impact of a policy, the strategy or combination of strategies were combined with the appropriate adoption rate, defined intervention and implementation timeline. Policies were developed for new construction, existing buildings or applicable to all buildings.

Based upon the background research of policies from Boston and other cities, adoption rates were identified based on the policy classifications (Figure 34). These adoption rates would define at what rate a defined policy would be adopted for the applicable building segments. Overstating the adoption of policy could set unreal expectations and would ignore the reality that not all policy can achieve the technical potential. Mandates are expected to have a higher rate of adoption than incentives. Performance requirements, due to their flexibility, are anticipated to have a higher rate of adoption than prescriptive polices.

Figure 34. Policy Adoption Time Series Curves Used in This Study

From the background research described above, local and state data on existing programs and policies in addition to national research of similar programs and policies were categories into adoption curves. After year five, adoption is anticipated to remain steady at the year five value.



8 POLICIES FOR CARBON NEUTRAL BUILDINGS

Combining the building-level strategies and the policy-framework's adoption rates, illustrative policies were modeled to evaluate their potential impact. Summaries and definitions of these policies are included in the Policy and Strategy Appendix Excel file.

8.1 NEW CONSTRUCTION

Boston is in the midst of a major building boom, adding 4 to 6 million square feet per year of new building space since 2014. Advancing new buildings to high energy performance, including net zero or net positive standards, will reduce emissions and prevent the need for future retrofits in these buildings. While the Commonwealth administers the State Building Code, Boston can take leadership in working with state agencies to advance Energy Code standards at triennial revisions and introduce net zero energy Stretch Code options. Another option is to enact new Zoning Code carbon emissions performance standards, including phasing in net zero emissions requirements starting with residential multifamily low-rise buildings.

Figure 34 shows the potential emissions reductions under alternative electricity-supply scenarios. While single measure policies and requirements can reduce emissions, only building-wide *net zero* and passive house policies were capable of reducing emissions significantly. Similar to the strategy analysis results, individual building specific incentives for lighting, HVAC equipment or building envelope do not make significant impacts to further reduce GHG emissions. The baseline assumption for an ever-increasing energy code makes these targeted and incremental measures less impactful.

Performance based new construction policies focused on accelerating the baseline scenario of an increasingly stringent energy code which resulted in Net Zero Energy performance in 2045. Both Net Zero Energy and Net Zero Emissions policies were part of the analysis to determine if there is material difference between regulating energy performance or emissions performance. Currently codes regulate energy as a proxy for realizing emissions reductions. A passive house standard for residential buildings, another performance-based standard, was also included in the analysis. Each of these three policies are performance based which builds off the current energy code and provides flexibility to define what the right combination of efficiency strategies is for a specific building. These policy options also align with larger national organization and state government proposals for new construction such as the Zero Code, an Architecture 2030 initiative, and Title 24 in California.

Additional policies applicable to new construction included incentives and requirements for energy storage, rooftop solar photovoltaics and single-action strategies like lighting enhancements, cooking, equipment and appliance efficiency (Figure 35). While the strategy analysis demonstrated these had low to moderate potential for energy and emissions reductions and the policy analysis is consistent with these results, they can contribute to emissions reductions. Both energy storage and solar PV can be important and possibly necessary contributors or enablers for a carbon neutral building sector. Policies to continue to incentivize and require these systems were considered.

Figure 35. Impact of selected new building policies on emissions under alternative renewable electricity scenarios

ZNE = Zero Net Emissions. Source: model calculations.

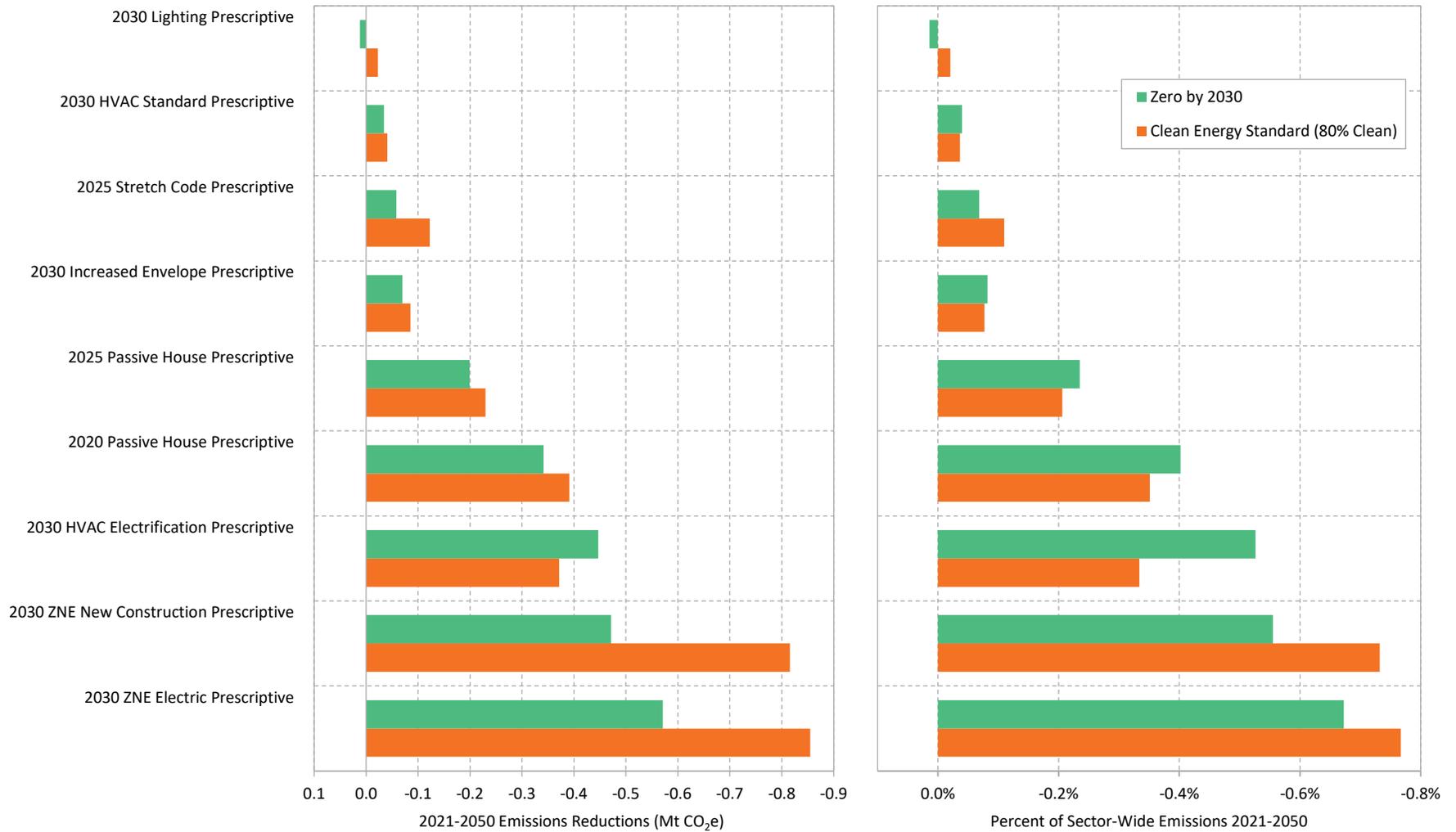
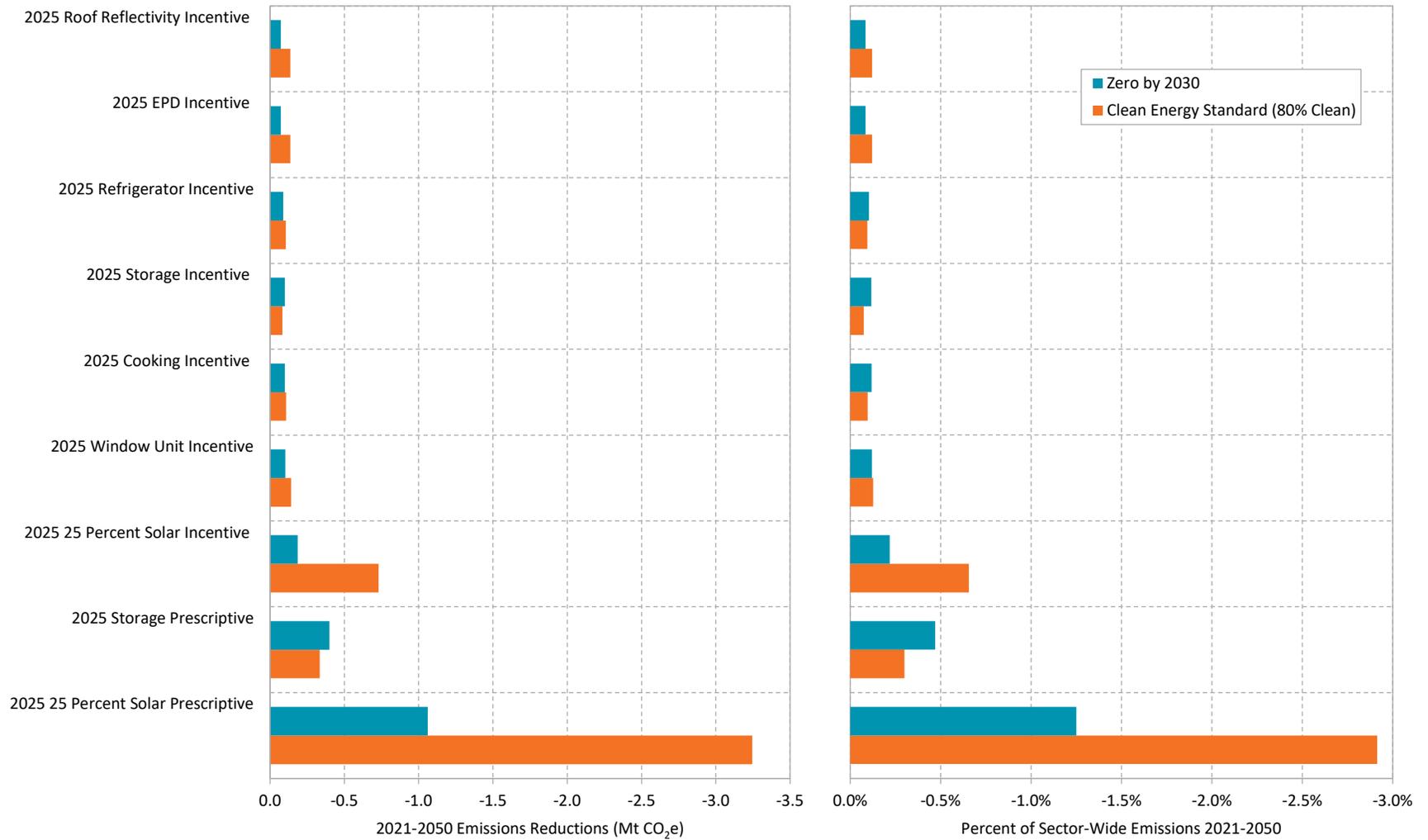


Figure 36. Impact of selected (new and existing) building intervention policies on emissions under alternative renewable electricity scenarios



8.1.1 Performance Standards

The timelines identified for new construction policies start as soon as 2020 as additional action is needed in the near term. The policies that were considered as soon as 2020 were to require Passive House Performance Standard for residential buildings, which are expected to experience the most growth, and to continue to incentivize solar PV and energy storage systems. The strategy analysis demonstrated that Passive House provided significant energy savings and when implemented with a heat pump system could realize significant emissions savings. This was prioritized as it is a known performance standard that has been implemented and can be accelerated.

Both the Net Zero Energy and Net Zero emissions timelines phase in the requirement in five-year increments over a ten year timeline starting in 2025. Achieving Net Zero Energy or Emissions across the Commercial building sector remains a challenge in knowledge and technology for many buildings as compared to Passive House. The intent for the initial timing and phasing of the requirement recognizes these realities and that this performance requirement is much more challenging for some building typologies than others. It also builds on precedent that the City would lead by example requiring the performance standards of its own facilities first, then starting to phase in residential and commercial construction with the Med/Lab/Production segment the last segment to be applicable. The timeline also recognizes that these performance requirements represent a step change in how buildings are designed, built and operated and that knowledge gaps exist across stakeholders within the built environment, i.e. Owners, tenants, designers, builders and operators. The timeline also leaves the highest energy intensive buildings as the last to phase into the requirements in order to allow stakeholders and technology additional time to develop.

It is important to highlight that several building segments are currently able to achieve these levels of performance. Single family and smaller residential and commercial buildings, e.g. multifamily residential, office, and K-12 schools have already achieved Net Zero Energy or Energy Positive performance in Boston and Massachusetts.

These high performance standards for buildings also offer many additional benefits besides reduced and/or very low utility bills and reduced maintenance. Thermal comfort for occupants improves as building envelope designs become more insulated and allow less air infiltration which makes them less reliant on mechanical systems. These buildings can better moderate the impacts of extreme heat and cold spells on its occupants, delivering resiliency benefits in a changing climate. Indoor air quality is improved, and daylight is typically enhanced to offset electric lighting use.

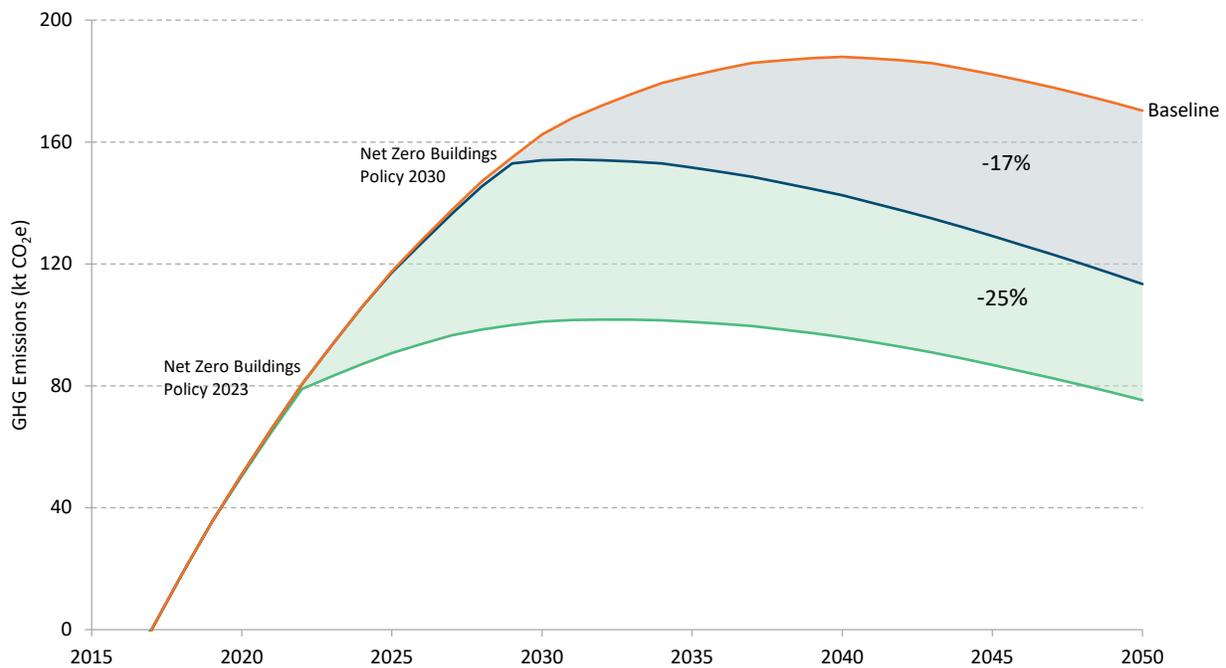
The Passive House Standard also has limited aggregate impact since it is only applicable to residential buildings, or 66% of new construction where Net Zero Energy and Emissions policies are applicable to all new construction buildings. The implementation timing of these policies limit their aggregate impact to offset emissions associated with growth since the last segments of buildings being phased in between 2035-2040. As this analysis has demonstrated timing matters greatly in determining the magnitude of emissions reductions in new construction.

Timing determines the magnitude of emissions reductions in new buildings. The implementation of a net zero policy for all new buildings by the City in 2030 reduces cumulative emissions by 17 percent (Figure 37). Earlier implementation of the same policy reduces emissions by an additional 25 percent.

This is a consistent theme that emerges from our analysis in every sector: early action builds on itself and makes it easier to reach an emissions target.

Figure 37. Reducing GHG Emissions in New Buildings

Early action to reduced emissions yields a large reduction the long run. This chart shows annual emissions from cumulative new building construction: without a new buildings performance policy (Baseline), from a net zero policy implemented in 2030, and from a net zero policy implemented in 2023. In the baseline, emissions increase with the growing stock of new buildings, but eventually level off and decline. The baseline scenario is based on our assumptions that the state building code will strengthen, and that the grid becomes cleaner due to the Massachusetts Clean Energy Standard. A net zero buildings policy instituted in 2030 will reduce cumulative emissions through 2050 by 17 percent. A net zero buildings policy instituted in 2023 will reduce cumulative emissions through 2050 by 42 percent. Source: model calculations



8.1.2 Solar Incentives

Solar PV opportunities on buildings should continue to be encouraged as they produce carbon-free electricity and help reduce demand on the electricity grid, particularly at peak times. Their impact on a buildings' total energy consumption varies widely depending on the scale of the project, building massing and use. For instance, a rooftop solar PV system on a single family or small multi-family residence can fully offset energy consumption or even generate more energy than the building consumes while a solar PV system on a hospital or laboratory building will make a very small contribution.

Energy storage systems are still in their infancy but are expected to advance rapidly in the near future. As discussed, they help reduce demand on the electricity grid, particularly at peak times. With increased electrification, demand on the electricity grid will increase, not only in the summer but will also transition the peak to winter. Energy storage can play a significant role in managing the peak demand by providing dispatchable energy on-site.

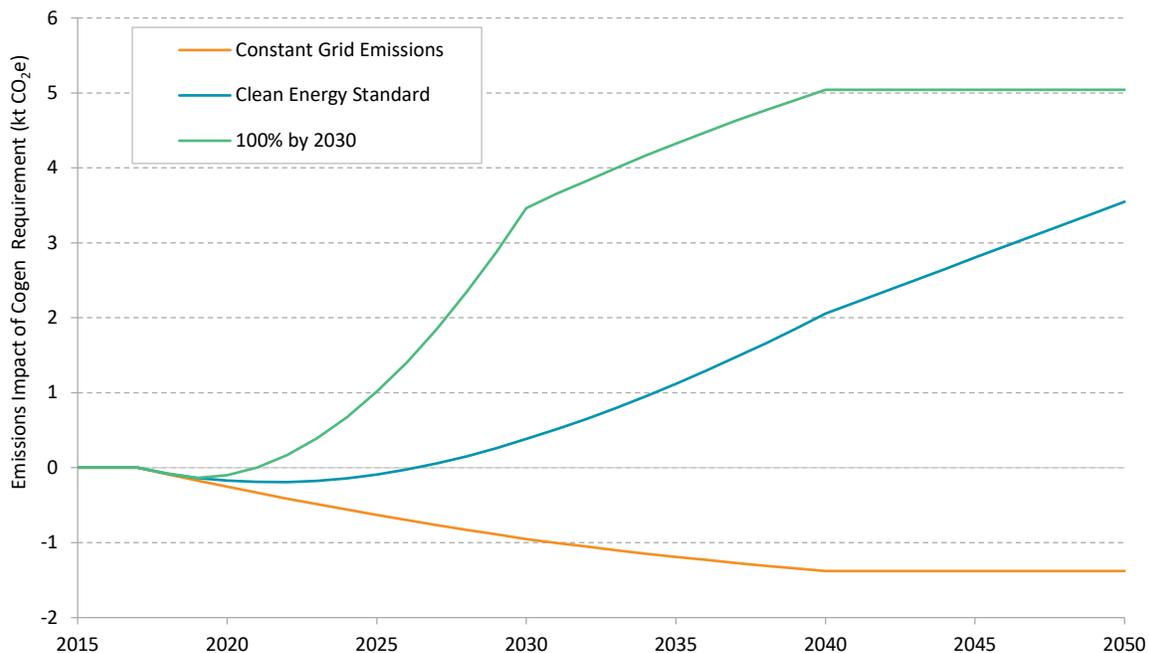
The policy options for both Solar PV and energy storage systems explored the continuation of incentives for these technologies and then requirements for these systems starting as early as 2025 for municipal buildings to 2040 for all buildings. Given that one aim of rooftop solar PV is to help supplement renewable energy on the grid, it can be viewed as a step in providing 100% renewable generation for

the city. Viewed in this vein, rooftop PV is unlikely to be the most cost-effective path to achieve carbon neutrality; in most electricity markets nationwide, distributed renewables tend to have a premium relative to grid-scale renewable power. Additionally, as a building strategy, if the grid moves to 100% renewable energy, rooftop PV becomes less valuable as a decarbonization measure, and the required investment may be better placed in transitioning remaining fossil fuel load to electricity.

8.1.3 New District Energy

Figure 38. GHG Emissions from New District Energy Systems in Boston

Net emissions change from the implementation of a combined heat and power system in every large new building project (about 1 million square feet per year from 2020 to 2040). Each emissions profile represents alternative grid or electricity procurement scenarios. “100% by 2030” means that the City procures enough clean electricity such that its total supply (grid purchases plus procurement) is 100% zero-carbon by 2030. Source: Institute for Sustainable Energy model calculations.



The *Boston Community Energy Study* and the *Cambridge Low Carbon Energy Supply Study* identified high-density zones where district energy could feasibly provide heating and cooling for both new and existing buildings. New district systems could utilize storage facilities that enable thermal energy to be stored at times of low demand, and then utilized when demand is higher. New district systems could also generate electricity that is distributed via a local microgrid that enhances the resiliency of electricity supply. The *Smart Utilities Policy* adopted by the Boston Planning and Development Agency in 2018 aims to leverage the resiliency and efficiency benefits of district energy into the planning and design process for large new developments.

The emissions reductions associated with new district energy systems will be short lived if fossil fuels are used (Figure 38). Under the GHG intensity of today’s grid, a district energy system would measurably reduce emissions compared with independent gas and electricity services to buildings. But as the GHG intensity of electricity declines, the GHG benefits of district energy also declines, and eventually results in greater emissions compared with independent gas and electricity services to buildings.

Climate neutrality requires that at some point in the future district energy must use GHG-free fuels. These could include sustainably-sourced renewable natural gas or solid biomass, however sustainable supplies of these resources are uncertain. Hydrogen generated from renewable electricity has much higher costs and would require new pipeline infrastructure. New district energy systems can leverage heat sources other than fuels, such as heat pumps that utilize waterbodies, sewage lines, subway systems, data centers, industrial processes, and the ground. While a full assessment of the potential of these systems was outside the scope of our analysis study, these potential resources merit deeper investigation and are discussed in the Carbon Free Boston Energy Sector Chapter.

8.2 EXISTING BUILDING POLICY

Policies for existing buildings ranged from prescriptive to performance based and focused on accelerating the baseline scenario of driving energy efficiency through the current BERDO regulation. A greater number of policies were explored for existing buildings as this analysis has demonstrated that achieving emissions reductions in existing buildings is the most important. The 2050 baseline assumed the current BERDO thresholds for buildings would achieve a 5% energy savings during the first energy action period and 2.5% energy savings in each subsequent five-year period.

8.2.1 Prescriptive Policies

The prescriptive policies included in this analysis explored incentives for isolated building components such as windows/glazing, wall and roof insulation, air infiltration, lighting and HVAC system equipment efficiency. Each is assumed to go beyond current prescriptive code requirements for performance. Given the limited scope of each of these policies their emissions reductions were relatively low.

8.2.2 Performance Policies

The performance base policies included in this analysis explored requirements for ongoing energy efficiency and GHG emissions reductions over time, primarily extending existing policies (e.g., BERDO). This approach eases the process with which to implement changes as they require an amendment rather than a completely new regulation or regulatory structure.

The policies included a range of options for amending BERDO as this policy is focused on existing buildings and already has an actionable component to the ordinance. The first options was under existing BERDO reporting to change the current guidance on what constitutes an energy action by requiring energy savings of 5%. On average, over a five year period, this equates to 1% sustained savings annually. This is an incremental increase from the baseline assumption, i.e. half of buildings achieve 2.5% every 5 years to 5% energy 5 years. These small incremental efficiency requirements can be implemented currently to start to move the most important segment of the city's emissions profile.

The next policy focused on the lowest performers under existing BERDO reporting to require the bottom quartile to improve out of the bottom quartile every 10 years starting in 2030. This seeks to require continual improvement in the worst-performers to realize a more energy efficient building stock but does not further expand the buildings covered in BERDO. Additionally, since it is only implemented in 10 year increments, it would only have 2-3 cycles limiting its overall impact. Differentiation in current performance may still be a valid policy approach for future requirements.

Additional policy options sought to expand the number of buildings that participate in BERDO by lowering the reporting threshold. This approach brings more buildings into disclosing performance

which builds a more robust database for the City and more importantly, requires energy actions to be taken in a greater number of buildings. Two increments were defined to lower the reporting threshold, to buildings greater than 20,000 SF or 20 units, and to include all buildings in Boston.

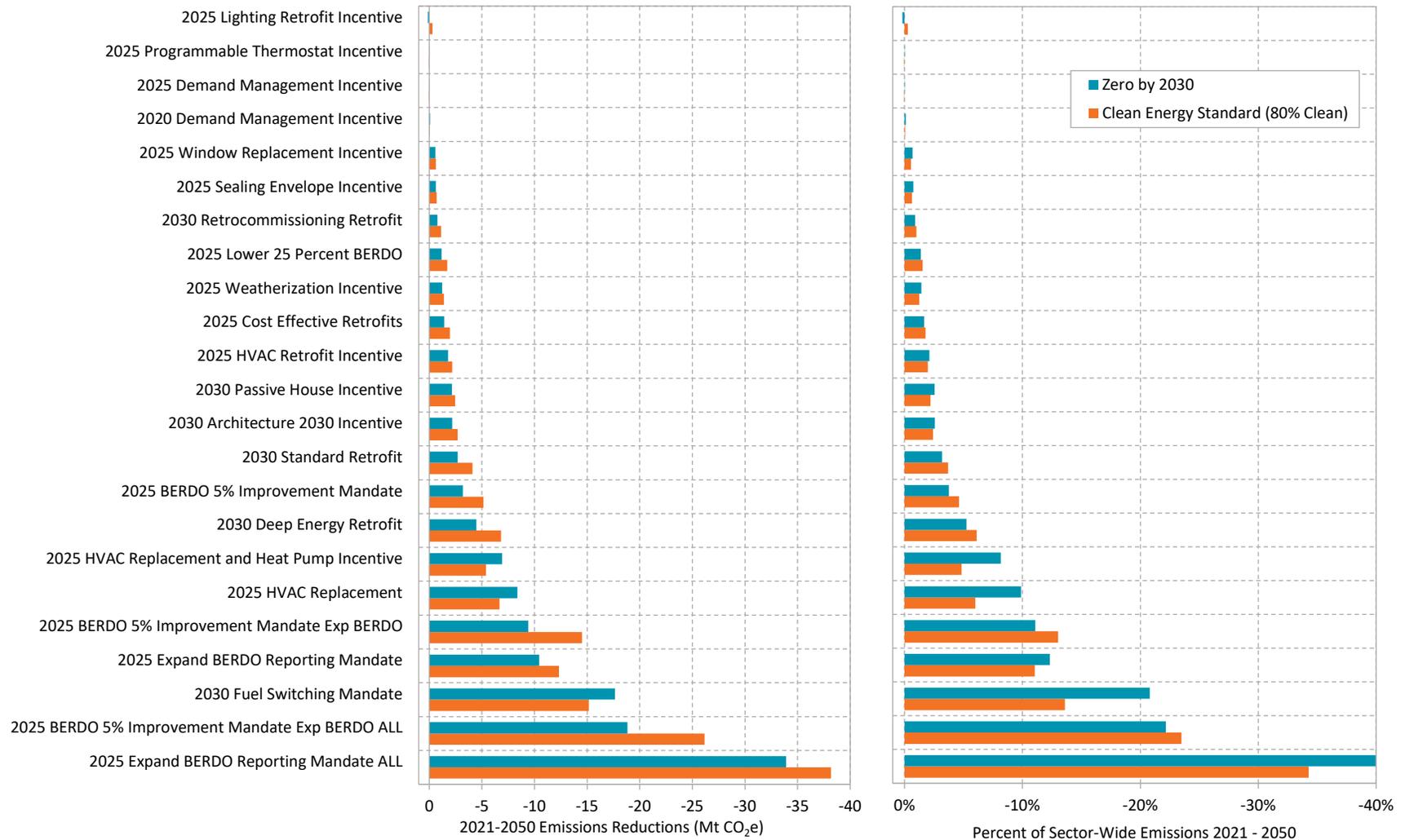
At 20,000 SF or 20 units, these buildings are not too dissimilar from those at 35,000 SF or 35 units and adds a manageable number of buildings to the ordinance. However, the City would need to assess its capacity to implement and enforce requirements across an increased quantity of buildings and a considerable outreach effort would be required to educate new building Owners of the requirements.

Including all buildings has a higher impact on emissions reductions but has much greater implications to make this largely not viable. This would add an additional 76,000 buildings which has implications on the City in its capacity to implement and enforce the ordinance and level of effort needed for outreach. As such, a different policy approach is likely needed for this segment of the building stock, which is predominantly residential, both single family and small multifamily.

In addition to changes to BERDO, policies explored in this analysis looked to other triggers to require performance improvements. Requirements for deep energy and/or emissions retrofits when buildings undergo major renovations, similar to performance-based policies for new construction. Major renovations were assumed to be applicable to 3% of buildings per year, which is small but accrues over time to make it a meaningful policy option.

While not included in this analysis, there are other points of intervention or triggers that are recommended to be studied further. These include triggers such as point of sale, point of lease, and as part of refinancing for both residential and commercial buildings. Refinancing events realize capital for Owners, and a portion of the proceeds could be reinvested in the building for GHG emissions reduction. It is important to note that these triggers are also subject to larger macro-economic and market trends that have the potential to underperform depending on economic activity in Boston over the next thirty years. Ongoing requirements as studied under BERDO are not subject to such trends.

Figure 39. Impact of selected existing building retrofit policies on emissions under alternative renewable electricity scenarios from 2021-2050



8.2.3 Decarbonization Policies

Policies specifically targeting on-site fossil-fuel combustion through reduction and elimination were also evaluated. The first was fuel switching with the intent of eliminating fuel oil as a heating source by 2030. This was defined as switching from fuel oil to natural gas for all buildings except for single family and small multifamily residential where it was assumed these buildings would install a heat pump (electric) based heating system, rather than the incremental step to natural gas. Fuel switching from oil to natural gas is a known strategy that has been successfully implemented over the past decade (+) across all building types.

The second fuel-switch based policy was to eliminate the sale of fossil-fuel based heating systems over time starting in 2030 and being fully implemented by 2040. This only regulates the sale of equipment and would not require buildings to retrofit or replace fossil-fuel based boilers until their useful life was reached. As mentioned, the most effective strategies at reducing emissions are those that specifically target fossil-fuel based energy consumption since the emissions associated with electricity decrease by at least 80% by 2050 in all scenarios. The timelines for this policy is phased as it recognizes there are limited options currently available and that advances in technology are needed. Single Family and Small Multifamily have current, proven technology options available to be fossil-fuel free and therefore were identified as the initial segment for this policy starting in 2030. Larger buildings do not have as many options available and specific building types with process requirements in Hospitals, Laboratories and others are the most challenging to phase out fossil fuel use. Recognizing this, this segment of buildings the latest timeline for compliance by 2040 assuming technology will be available over the next two decades.

The results of individual policies show a wide range of impact across the building stock from minimal to significant. Even highly effective policies that are targeted to a small segment of buildings, e.g. passive house retrofits for residential buildings, yield a limited impact in the context of the entire building stock. Only the policies that encompass the largest segments of the building stock addressing both energy efficiency and decarbonization make a significant impact in reducing the city's GHG emission profile.

The policy analysis has demonstrated that requiring ongoing energy and GHG emissions reductions under BERDO's energy action requirement can have the largest impact on the city's GHG emission profile. The analysis at its most aggressive action required 1% savings per year over the next 20-30 years. Further expansion of BERDO by reducing the reporting threshold further expands the impact of the policy in GHG emissions reductions. By lowering the threshold, it also makes a statement that carbon neutrality is not only the responsibility of the city's largest buildings, it is the responsibility of all buildings in Boston.

8.3 ENABLING POLICIES

Substantially increasing the regulation of the built environment will need to be supported by a number of enabling policies to spur innovation, work force capacity, and provide project financing. These enabling policies will need to be crafted in collaboration by the City, other municipalities, the state, local educational institutions, property owners and corporate partners. Their inclusion in building retrofit and electrification programs will help to accelerate progress, keep costs low, stimulate local economic development and reduce burdens on stakeholders.

8.3.1 Knowledge and Innovation

Education has a key role to play in making such policies effective and maximizing potential emissions reductions. Many property owners and occupants are not aware of the numerous benefits associated with deep energy efficiency and electrification measures. Increasing awareness of these benefits will be essential to ensuing wide program adoption. Further, retrofitting an average of 2,000-3,000 buildings a year will require a trained workforce educated by new programs in the city's vocational programs, community colleges and universities. In the meantime, building retrocommissioning and operator training programs that seek to optimize building energy use without major interventions, can deliver measurable reductions, at very low costs.

The collection and analysis of data related to building performance is essential for effective performance policies and sharing best practices. Boston's Building Energy Reporting and Disclosure Ordinance (BERDO) established a foundation for bringing attention to energy use, efficiency and emissions in Boston's buildings by requiring building owners to report energy use data. BERDO currently covers approximately 2,000 large commercial and large multifamily residential buildings, nearly half of the built environment in the city. This program will be essential for tracking the success of performance-based policies. Improving the quality and types of data (smart meters, audits) collected by BERDO will also enable a better understanding of building energy use.

Retrocommissioning and Building Operator Training

The City of Boston has worked with its electric and gas utilities, Eversource and National Grid, to develop an initiative for Building Operator Certification (BOC) training. BOC training is a 74-hour program that covers best practice in operations and maintenance of facilities to promote improved occupant comfort and energy efficiency. Each class covers a different building system, such as HVAC, lighting, controls, or electrical. Students are asked to evaluate their own buildings' operational systems as homework for each class. In the first round, completed this month, 30 municipal employees from Boston and surrounding municipalities participated, with utility sponsorship.

A 2017 NEEC study¹ estimates that BOC training results in an average savings of more than 100,000 kWh (0.3 kWh/sqft) and 1,400 therms per participant per year. Such savings in Boston's 2,200 largest buildings, approximately 258 million square feet, would reduce annual electricity use by 77 million kWh. Demand response, taught in these courses, has the added benefit of reducing load on the grid during peak hours when the grid emissions factor is higher. In 2016, ISO New England's average marginal emissions rate was 710 lb/MWh while the LMU marginal emissions rates were 807 lb/MWh (off-peak), 892 lb/MWh (on-peak) and 968 lb/MWh (high electricity demand days).

The City of Boston is working with their utility partners to promote and expand this program to train all municipal facilities operators, to see regular and widespread participation. The program could also be opened to building operators working in buildings covered by Boston's Building Energy Reporting and Disclosure Ordinance.

There is substantial opportunity for innovation in the buildings space, although it is often overlooked. Smart meters, connected systems, air recycling, pre-fabricated envelopes, and other emergent technologies have the potential to provide novel emissions reduction strategies. Performance mandates encourage the application of such innovative approaches.

8.3.2 Financing

Deep energy retrofits require significant upfront capital investments and some thermal electrification measures may increase lifetime energy costs. Historically, these have been considered obstacles to intervention. There are a couple of reasons that this mode of thinking may be outdated. First, tying deep energy retrofits to an intervention point such as a major renovation lowers their potential costs as many building components undergo replacement at this point anyways. Second, energy cost savings are substantial despite having long payback periods. Finally, deep energy retrofits deliver health and quality of life benefits that are harder costs to realize. Such benefits need be considered when pursuing a retrofit.

Despite these potential benefits, the upfront costs of interventions can remain prohibitive, especially for residential homes. Financing programs need to provide the capital necessary at low costs to avoid burdening building owners who may be mandated to implement costly investments.

8.3.3 Keeping people in place

Such significant investment in Boston's buildings will increase asset value and potentially rental prices. This may lead to the displacement of many low-income and vulnerable populations. Enabling new, zero-emission, construction will lower stress on the housing market. Ensuring that residents can benefit from lower utility costs and be empowered in conserving energy will help to lower the cost burden of energy, which can be significant for some low-income populations.

8.3.4 Foster Leadership

200 Clarendon Street, formerly the John Hancock Tower, underwent a major energy modernization effort in 2012. HVAC and operational upgrades to the 40-year-old icon of Boston's skyline reduced energy use intensity by 23 percent and emissions by 38 percent. Boston Properties, the building's owner, aims for a 45 percent reduction in emissions by 2025.

The path to carbon neutrality will be accelerated if the City leads by example with its own building stock; it is already doing so on multiple fronts. Ultra-efficient municipal buildings with rooftop PV provide a strong message to everyone that Boston is firmly committed to its climate goals. The City has undertaken lighting and heating improvements to the Central Library in Copley Square and to City Hall and added rooftop solar to other facilities. Leading by example also bolsters the City's national and international reputation as a leader on addressing climate change.

Across Boston, other building owners are stepping forward. Boston University recently committed to achieving carbon neutrality by 2040 with an anticipated one-third of emission reductions coming from building energy-efficiency measures. Residents across the city are installing solar on their rooftops and implementing home energy-efficiency measures. These leaders are demonstrating that meaningful progress is possible and cost-effective and helping to mature the market, thereby paving the way and reducing costs for others to act.

The City has supported market development for high performing new buildings by proving their feasibility and demonstrating their benefits. In 2011, the City of Boston launched the E+ Green Building Program, a design competition and development initiative, to pilot the use of high-performance standards in multi-unit residential buildings in Highland Park, Jamaica Plain, Mission Hill, and Dorchester.

The City can further drive emissions reductions in the building sector and accelerate market transformation towards carbon-neutral buildings by advocating for a more stringent state energy code. In addition to Commonwealth staff, working directly with representatives from the utilities, real estate industry, affordable housing organizations, green building and environmental justice organizations, and other groups in the setting of objectives and drafting of language can help to cultivate support, or at least minimize opposition, to the ambitious and transformational requirements. The development of clear and targeted communication strategy to accompany the roll out of draft standards and codes will also strengthen the implementation of these policies.

9 PATHWAY TO CARBON NEUTRALITY

The above evaluation of individual policies shows the limited impact of incremental increases in building energy and emissions regulation at the city and state level. On the low-impact end, a series of incentives can continue the success of programs such as MassSave to increase efficiency and reduce costs. On the high-end, building on BERDO, more aggressive wide-reaching emissions performance requirements can achieve material reductions in the city's emissions.

While important, incentive-based policies and programs alone do not provide the market penetration needed to make a significant impact on reducing GHG emissions towards carbon neutrality. Incentives are useful and important to gain acceptance of a new technology or system, enable early adoption, demonstrate leadership and/or reward good behavior. Required policies (i.e. mandates) provide the level of penetration required to make a significant impact on reducing GHG emissions towards carbon neutrality. But mandates can take as much as 5 years to reach full potential and require significant regulatory oversight. As new policies are implemented these challenges need to be factored into policy planning.

Ultimately decarbonization will require a transition from the use of fossil fuels in buildings. In the absence of sufficient state and federal policy to achieve deep decarbonization the City will likely need to require the phaseout of fossil fuels in the next 30. This requires a policy regime that facilitates electrification to the greatest extent feasible and mandate the use of renewable fuels where fuels are used. An effective policy would this seek to pursue two objectives

1. Buildings must shift to non-fossil fuel-based energy systems.
2. Buildings energy demand should be reduced to enable the implementation of non-fossil fuel energy systems.

In effect this is a prescriptive mandate to decarbonize that would necessitate buildings performance to meet potential cost and feasibility constraints of electrification and fuel decarbonization.

Figure 40 and Figure 41 reflect an aggressive an illustrative deep decarbonization pathway in the buildings sector. Here new construction is assumed to meet net zero requirements phased in across building classes throughout the 2020's. Building electrification and deep energy (50% EUI reductions) retrofits are assumed to proceed at a rate of 3% of the building stock per year starting in 2020 reaching a maximum penetration of 85% by 2050. Electrification with no grid improvement has the potential to increase emissions (hence the observed crossover in Figure 40) due to the current higher carbon intensity of electricity than natural gas. However, a cleaner grid such as the one imposed by the Clean

Energy Standard, or a 100% renewable procurement strategy can unlock significant efficiency savings. For Boston to achieve its interim goals of 50% GHG reduction by 2030, an earlier procurement strategy will be necessary due to the limitations of decarbonization in the transportation and buildings sectors. Figure 42. Shows the impact of such a procurement on the emissions trajectory.

In any scenario, getting off of fossil fuels will be a challenge for some buildings. These may include historic buildings, deeply entrenched energy equipment or systems, such as district energy, backup services, cooking, aesthetic uses of natural gas, or other processes. Either renewable fuels or offsets will be needed to decarbonize these systems.

Figure 40. Illustrative Pathway to Eliminating Carbon Emissions in the Buildings Sector

The key to carbon-neutrality in buildings is the combination of deep energy efficiency and the electrification of heating and cooking with clean electricity. Wedges represent the impact of specific, consecutive actions starting from today's conditions (Baseline (Current Grid)), which reflects expected growth in buildings and current policies in place. Deep efficiency performance requirements (light blue) include strong new building performance standards, and deep energy retrofits aligned with a critical intervention point (e.g., major renovation) in a building's life cycle. Deep energy retrofits target a 50% reduction in energy use per square foot. Electrification includes the deployment of heat pumps in residential and some commercial buildings, electric boilers in larger buildings, and the electrification of most hot water and cooking services. *Source:* model calculations

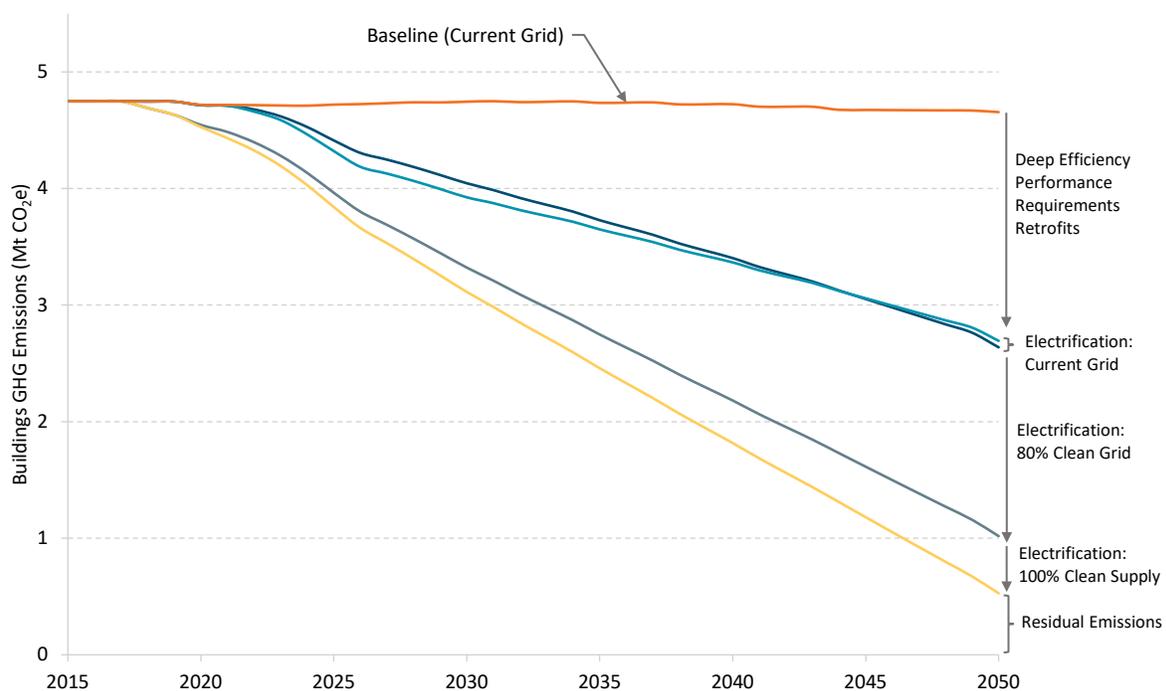


Figure 41. The Steps to Carbon Neutrality in Boston’s Buildings

The steps reflect the GHG reduction potential of specific consecutive actions starting from today’s conditions. *Source:* model calculations

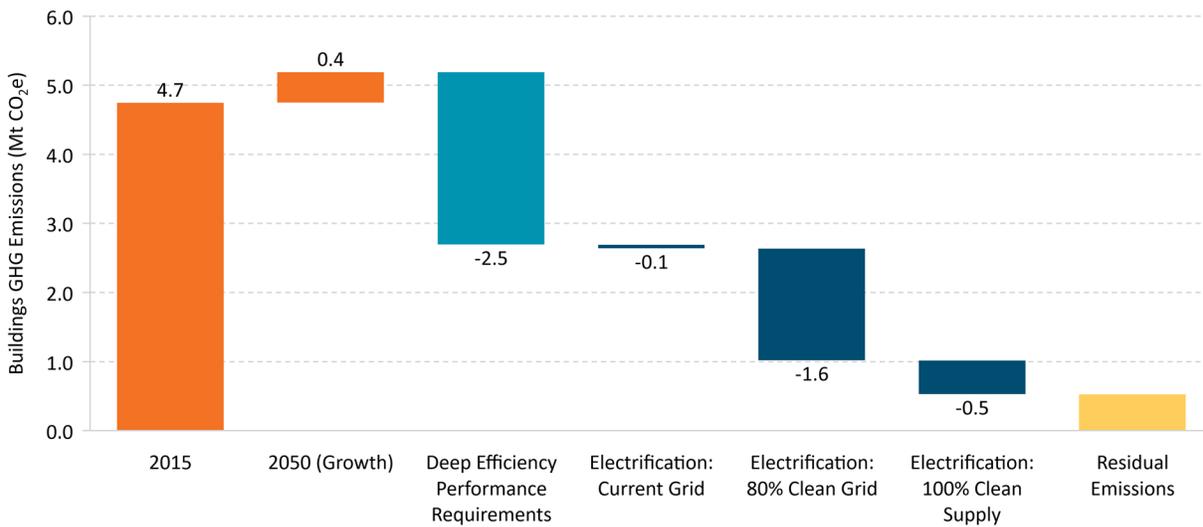
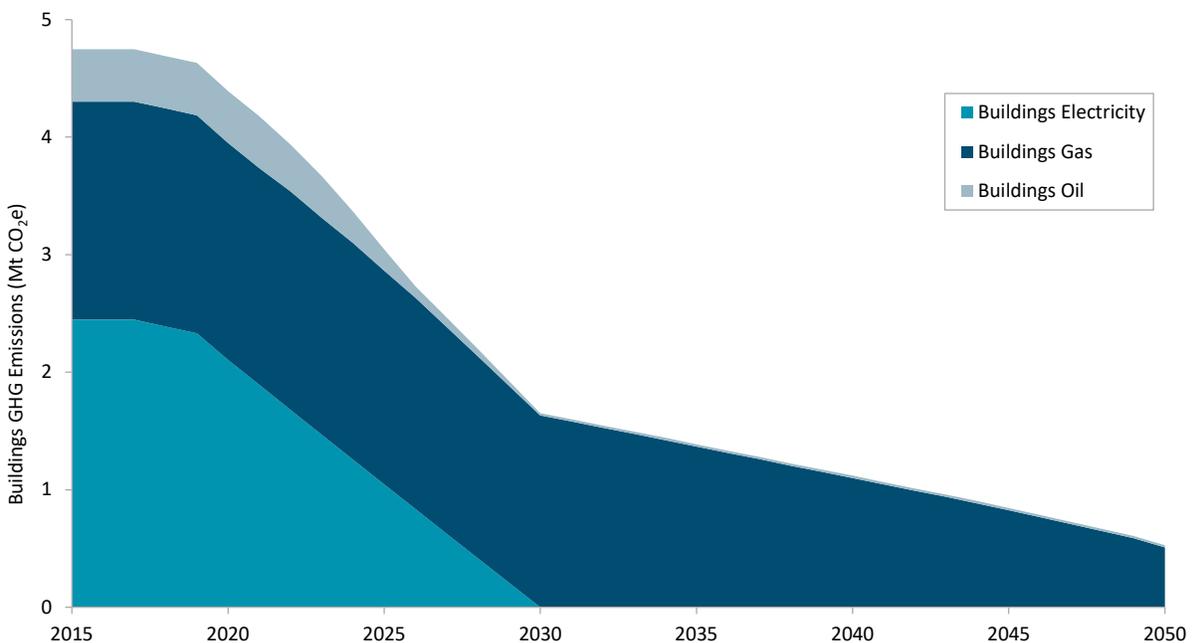


Figure 42. Illustrative pathway for buildings sector decarbonization under an early (Zero by 2030) electricity procurement strategy

Source: model calculations



9.1 THE CHALLENGE AND OPPORTUNITY OF COMPREHENSIVE ELECTRIFICATION AND EFFICIENCY

The decarbonization of the city's electricity supply is an *a priori* requirement for carbon neutrality. This transition will result in electricity becoming a less carbon intensive fuel. A city-wide renewable procurement strategy can by itself cut emissions in the building sector in half. What remains is a dependence on fossil fuels, mostly natural gas and a nominal fraction of oil. Decoupling the city from fossil fuels will require electrifying a good portion of the buildings stock's thermal demand and procuring renewable fuels for those which cannot be easily electrified. The impacts of electrification on the demand for electricity are briefly addressed here, but is evaluated in detail in the Carbon Free Boston Energy Sector Report, which also discusses potential supplies of renewable natural gas and hydrogen.

A challenging aspect to electrification is its potential to significantly increase the demand for electricity. This has consequences in the actual supply of electricity and delivery. Table 11 shows changes in energy consumption by fuel type as a result of a thermal electrification strategy and a strategy that combines deep energy retrofits with electrification. Under both scenarios, natural gas and oil fuel use drops considerably. The remaining fuel use is predominantly for cooking, backup, and supplemental heating services. Some of these services could conceivably be electrified now. The increase in electric demand is a fraction of the removed heat. This is a testament to the potential of highly efficient heat pumps which are modeled to provide 3.2 times the thermal energy than the electricity required to operate them. Under the electrification measure, a small number of typically-large building types are assumed to have been converted to electric boilers (99% AFUE). This significantly increases demand for these building types. The small increase in electricity, relative to the decline in fuel use, is also attributable to the conversion of electric-resistance heating systems to the air source heat pumps, and the inefficiency of older fuel-based boilers.

Table 11. 2050 Impacts of Energy Demand under a full implementation of thermal electrification and deep efficiency measures

Source: Energy data is from Institute for Sustainable Energy model calculations. Energy cost estimates are obtained from [23]

	Electricity (GWh)	Natural Gas (GWh)	Oil (GWh)	City-Wide Energy Cost (\$ bn)
2050 Baseline	7,200	10,040	1,689	2.11
2050 Electrification Only	9,340	3,272	317	2.17
2050 Efficiency + Electrification	6,452	2,878	24	1.50

Under the electrification only scenario electric demand increases by about 30%. This increase is significant, but not divergent from historical trends in electric demand growth. Deep efficiency measures can unlock substantial energy cost savings. Building electrification increases peak electricity demand drastically on cold days (see Energy Chapter), even under deep efficiency measures. These two scenarios thus represent potential extremes in which electrification would necessitate investment in either transmission, distribution, storage and generation capacity (electrification only) or into energy conservation measure. The former strategy reflects small incremental investment with no-long-term cost savings, while the latter reflects large upfront investment that results in long-term cost savings.

The optimal strategy is likely somewhere in the middle, as even deep energy conservation efforts will still require the management of peak electricity demands on cold days that currently exceeded the low-carbon capacity of the regional grid.

The capital costs of electrification are expected to be relatively small, especially if treated as incremental. The cost of heat pumps and electric boilers are comparable to natural gas furnaces and boilers. Despite this small cost, subsidies could be effective at ensuring uptake and technology acceptance, especially if policies prohibiting the replacement of fossil fuel thermal systems are put into place. However, to achieve deep penetration additional requirements are needed.

Our illustrative example factors in a phase out of oil by 2030. These buildings are assumed to be electrified, but represent a small part of the stock and one that is predominantly residential. These residences will likely have modestly cheaper energy bills as a result and represent a priority target for electrification and efficiency efforts. Phasing out natural gas will at some point require a significant incentive for electrification at the end of life of existing systems or a mandate prohibiting the installation of new systems in buildings that can be feasibly electrified. Such an approach could also be applied to cooking and hot water equipment in addition to heating systems.

Feasible electrification will require buildings to be retrofitted with ECMs to complement of heat pumps in a way that ensures their functionality, keeps operating costs low and can ensure high levels of air quality. The core concern is functionality, which is steadily improving for heat pumps and is likely to be sufficient in the future. The operational costs of thermal electrification, are going to be influenced by how future increases in peak electricity demand gets passed on to the ratepayer. As these costs increase, the potential benefits of building energy conservation measures will also increase.

Such action may not require achieving the 50% target associated with a deep energy retrofit, but comprehensive energy conservation efforts that are less than 50% can still reduce costs and improve building health. The costs of comprehensive or deep energy retrofits are uncertain. Our incremental cost estimates (6-8 \$/sf) suggest a relatively low price for such actions. Other estimates on the cost of deep energy retrofits range dramatically and often do not report the incremental or marginal cost of energy efficiency measures [40]. It is thus difficult to get accurate estimates of the true cost of deep energy efficiency measures. A joint effort by National Grid and NREL to deep energy retrofit single family and small multifamily homes in the region resulted in total costs of \$16-\$54 per square foot. The Department of Energy's Advanced Energy Retrofit Guidelines modeled 50% EUI reduction targets at a cost of \$4-6 per square foot for office and retail spaces [12], [13].

Achieving such costs is a likely best-case scenario that is only feasible if comprehensive energy conservation actions were conducted at a significant building intervention point such as a major renovation. Timing comprehensive action with such an intervention point can also minimize disruption. Typically, such interventions happen on a 30-year cycle or at a rate of 3.3% a year. For Boston this would amount to nearly 3,000 buildings a year, most of which would be residential. Table 12 lists a number of alternative intervention points which may be used to reduce potential disruption.

Conceivably, a mandate to couple a deep energy retrofit with such an intervention that is supported by financial incentives to cover the gap such actions would require a minimum \$4-5 billion of funding support, but costs likely become higher. There is reason to assume that the cost of deep energy retrofits can decline substantially to reach economical price targets. Currently, deep energy retrofits are rare, in part, due to the concerns about the cost. As the industry scales up, knowledge about building behavior and best practices will increase and drive down costs. Additionally, new methods may be developed. For example, the *EnergySprong* approach developed in partnership with the EU's Transition Zero programs is seeking to use prefabrication methods to lower the cost of deep energy retrofits. Such

a manufacturing-based approach reduces the labor-demanded by retrofits and thus the cost. Such cost reductions have been observed in other industries such as solar and wind. Unlocking this potential requires early investment into process development and technological learning.

Table 12. ADEG’s Identified Opportunities in a Buildings Life to Perform a Deep Retrofit

Source: *Advanced Energy Retrofit Guide: Office* [13]

Building Event	Opportunity
Roof, window and siding replacement	Planned roof, window and siding replacements provide opportunities for significant improvements in daylighting and efficiency at small incremental costs. These improvements in turn allow for reduced artificial lighting, and a smaller, more efficient HVAC system.
End (or near end) of life major equipment replacement	Major equipment replacements provide an opportunity to also address the envelope and other building systems. After reducing thermal and electrical loads, the marginal cost of replacing the major equipment with smaller equipment, or no equipment at all, can be negative, as seen in the Empire State Building Case Study.
Upgrades to meet code	Life safety upgrades may require substantial disruption and cost, enough that the incremental investment and effort to radically improve the building efficiency becomes not only feasible but also profitable.
New owner or refinancing	New ownership or refinancing can include building upgrades as part of the transaction. This may offer a lower interest rate than is normally available for upgrades, which improves the cost-effectiveness of a deep retrofit.
Major occupancy change	A major occupancy change presents a prime opportunity for a deep retrofit, for two reasons. First, a deep retrofit can generate layouts that improve energy and space efficiency, while creating more leasable space by downsizing mechanical equipment. Second, owners may be able to leverage tenant investment in the fit-out.
Building greening	An owner or tenant-driven desire to achieve green building or energy certification may require significant work on the building and its systems, which may then make a deep retrofit economical.
Large utility incentives	Many utilities will subsidize the cost for a deep retrofit. In some regions, the incentives might be large enough to make the deep retrofit economical.
Fixing an “energy hog”	Upon examination, some buildings are found to have such high energy costs the deep retrofits have good economics without leveraging any other building event.
Portfolio planning	The cost-effectiveness of a deep retrofit may be improved when many similar measures are implemented across a portfolio of buildings. This is particularly true when buildings in the portfolio share similar characteristics, allowing both the design and construction teams to achieve some efficiencies of scale.

9.2 HOLISTIC APPROACH TO POLICY IS NEEDED TO ACHIEVE NEUTRALITY

Boston’s building stock is old and diverse. To make the buildings stock last though the 21st century and its challenges, significant investment and comprehensive action will be needed to make these buildings more energy efficient, carbon neutral, healthy, and affordable. Comprehensive, deep or holistic actions have the potential to deliver these benefits. Generally, the city’s building stock can be divided into two categories: the mid-size to large size commercial and residential which comprise the bulk of the city’s floorspace; and the small residential which dominate the city’s individual buildings (Figure 43). These two segments will need to be regulated differently.

Since the large buildings stock tends to have more potential time points of intervention (e.g., those listed in Table 12), this stock may be best suited for medium-term electrification and performance requirements. Here, the City could target its poorest performing buildings first, but set additional targets for ensuring that the commercial stock would be electrified to the greatest extent practical. Some building classes may need more time: laboratory and hospital buildings may be the hardest building segment to achieve these goals in. However, the commercial space represents much of the city’s low

hanging fruit in terms of economically reducing energy consumption. This space could also include a number of City owned buildings and public housing. The retrofit of these buildings could provide significant ancillary benefits in terms of municipal cost savings and health outcomes.

Figure 43. Illustrative policies for regulating residential (left building) and commercial (right building)



The small residential stock will be more of a challenge due the smaller building size – where an action will typically have a smaller impact. Economies of scale for comprehensive building retrofits and electrification could be achieved if a local industry was fertilized by pilot projects and workforce development. It would likely take a longer time for this industry to get off the ground for the small residential stock, but it could leverage the capacity of the industry developed for the large building stock. In the near term, thermal electrification can be pursued by encouraging the deployment of heat pumps in the residential sector to supplement existing systems.

To manage growth associated with projected new construction, it is imperative that these new buildings achieve net zero emissions, not net zero energy. This requires both energy efficiency and electrification. Until a net zero emissions policy is implemented, new construction will continue to add to the city's GHG emissions profile and will require these buildings be decarbonized in the future likely at a higher cost than if it was done now.

The pathway to carbon neutrality is not easy and requires a level of commitment and action by all building types and actors in the city. The technology, systems and strategies that currently exist, when accelerated, can make a considerable contribution to lowering the city's GHG emissions despite a projection for continued growth. However, those alone will not meet the goal. While the challenge is daunting, the end result are buildings that are dramatically more energy efficient than today and use fossil-fuel free electricity for their energy needs. These buildings are healthier, more resilient and require less money to operate and maintain.

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PEOPLE AND ORGANIZATIONS

Technical Advisory Group for Buildings

Name	Organization
Kalila Barnett	Alternatives for Community and Environment
Francis Boucher	National Grid
Amy Laura Cahn	Conservation Law Foundation
Dennis Carlberg	Boston University
James Cater	Eversource
Hong-Hanh Chu	Commonwealth of Massachusetts
Bronwyn Cooke	City of Cambridge
John Dalzell	Boston Planning & Development Agency
Manuel Esquivel	Boston Planning & Development Agency
Seth Federspiel	City of Cambridge
Matt Foran	National Grid
Michael Gevelber	Boston University
Katie Gonzalez	Boston Properties
Stephanie Horowitz	ZeroEnergy Design
David Ismay	Conservation Law Foundation
Jonathan Lee	Boston Planning & Development Agency
Harvey Michaels	Massachusetts Institute of Technology
Benjamin Miller	Commonwealth of Massachusetts
Benjamin Myers	Boston Properties
Galen Nelson	Massachusetts Clean Energy Center
Jim Newman	Linnean Solutions
Kathleen Pedersen	Boston Planning & Development Agency
Cammy Peterson	Metropolitan Area Planning Council
Alex Pollard	Commonwealth of Massachusetts
Karthik Rao	Enel X
Chris Schaffner	Green Engineer
Jhana Senxian	Sustainability Guild

Northeastern University, School of Public Policy and Urban Affairs

David Snowdon

Jiaqi Lui

Moire Loftus

Hannah Lyons

Yuwei Zou

Conflict of Interest Disclosures

Rebecca Hatchadorian, Rob Best, Katie Wholey, Alexandra Calven, Erica Levine, Sara Tepfer, Brian Swett, Michael Walsh, Adam Pollack, Taylor Perez, Joshua Castiglieno, and Cutler Cleveland declare that they have no affiliations with or involvement in any organization or entity with any financial or non-financial interest in the subject matter or materials discussed in this report.

ABBREVIATIONS

AEDGs	Advanced Energy Design Guidelines
BBRS	Massachusetts Board of Building Regulation and Standards
BEM	Building Energy Modeling
BERDO	Building Energy Reporting and Disclosure Ordinance
BOC	Building Operator Certification
BPDA	Boston Planning and Development Authority
Btu	British Thermal Unit
CB ECS	Commercial Buildings Energy Consumption Survey
CCSI	Code Compliance Support Initiative
CES	Massachusetts Clean Energy Standard
CO₂	Carbon Dioxide
CO_{2e}	Carbon Dioxide Equivalent
COP	Coefficient of Performance
CV[RMSE]	Coefficient of Variation of the Root Mean Squared Error
DOE	US Department of Energy
EBCx	Existing Building Commissioning
ECM	Energy Conservation Measure
EEAC	Massachusetts Energy Efficiency Advisory Council
EUI	Energy Use Intensity
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, and Air Conditioning
IECC	International Energy Conservation Code
IGBC	Interagency Green Building Committee
ISD	Inspectional Services Department
LEED	Leadership in Energy & Environmental Design
MassCEC	Massachusetts Clean Energy Center
NMBE	Normalized Mean Bias Error
PTS	Renewable Energy Production Tracking System
PV	Photovoltaic
RECS	Residential Energy Consumption Survey
t CO_{2e}	Tonne (Metric ton) of CO _{2e}
TMY	Typical Meteorological Year
W	Watt
Wh	Watt-hour

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