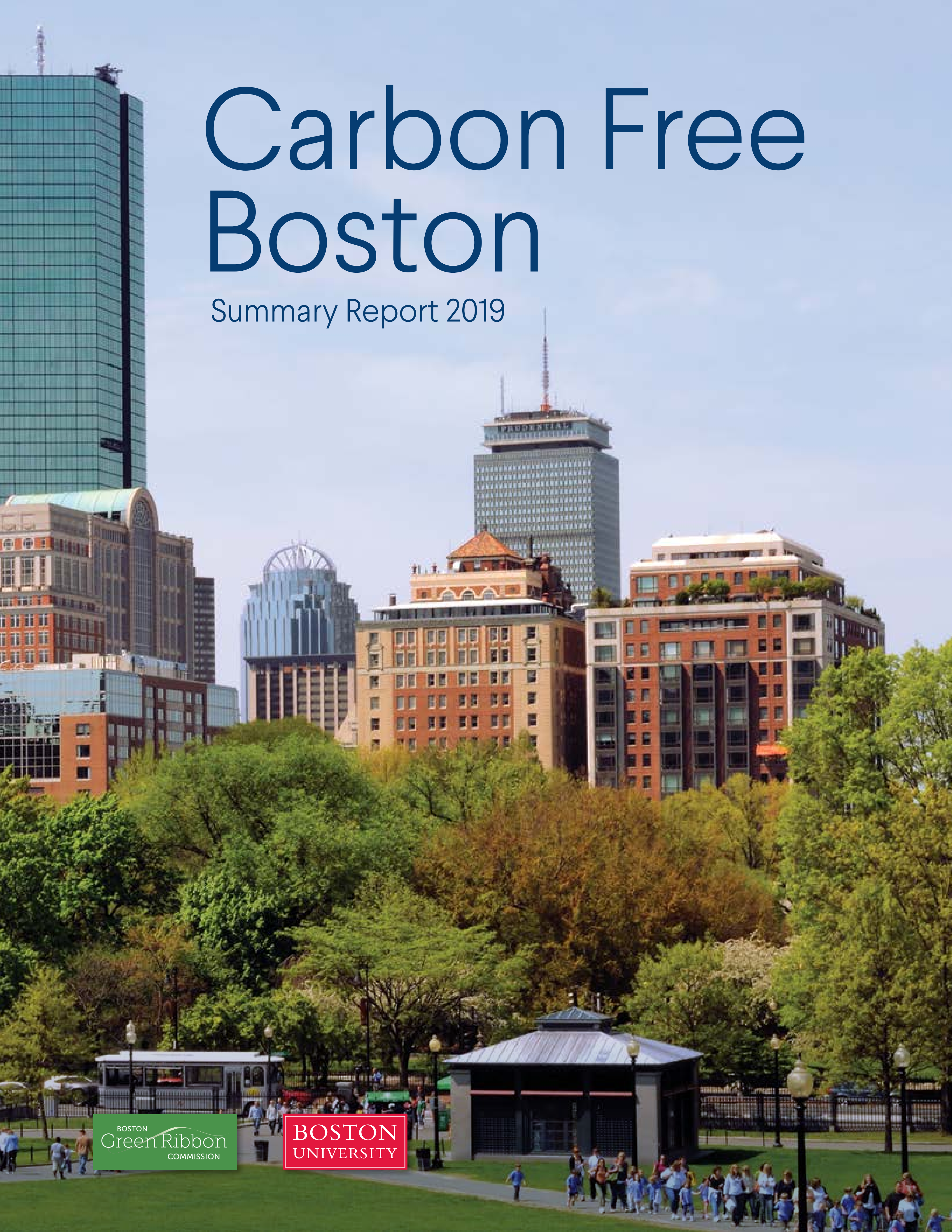
Carbon Free Boston

Summary Report 2019



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Project Support

The work of Carbon Free Boston was made possible by the generous support of these organizations:

Sherry and Alan Leventhal Foundation
Barr Foundation
The Grantham Foundation
William and Flora Hewlett Foundation
Henry P. Kendall Foundation
City of Boston
Commonwealth of Massachusetts
National Grid
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Dear Mayor Walsh,

On behalf of the Boston Green Ribbon Commission (GRC) and its Carbon Free Boston Working Group, we are honored to present you with our Carbon Free Boston report. This report quantifies the most effective combinations of strategies to reduce greenhouse gas emissions across our energy, buildings, transportation, and waste sectors. It is intended to provide an analytical framework for the City of Boston and its key stakeholders to use in making choices about which specific strategies and policies to pursue to achieve the goal of being carbon neutral by 2050.

The good news is that by taking ambitious steps to reduce its greenhouse gas emissions, the City of Boston can also improve the quality of life for its residents – reduce congestion, make our streets safer, improve transit access, create more green space, reduce noise and air pollution and improve public health. We are proud to note that our Carbon Free Boston report explicitly addresses the potential impacts of different policies on social equity and acknowledges that socially just solutions are as important as technically efficient solutions.

In 2016 you signed the Metro Mayors Climate Mitigation Commitment, committing the City of Boston to achieving carbon neutrality by 2050. In that same year, you asked the Green Ribbon Commission to establish a Working Group to support the City in the development of strategies to achieve those ambitious targets. In response, we set up the Carbon Free Boston Working Group, comprising GRC members and other leaders in the energy, finance, and communications sectors. We subsequently partnered with Boston University's Institute for Sustainable Energy (ISE) to develop a sophisticated analytical platform to assess the impact of a broad range of strategies and policies on the City's emissions. The Boston University team worked with a team of consultants and five different Advisory Groups representing more than 120 experts in the fields of energy, transportation, buildings, waste and social equity. These experts came from a wide variety of organizations, including city and state government, regional planning organizations, non-profits, higher education, health care, commercial real estate and private business.

The report's analysis makes clear the great magnitude of the change needed to achieve carbon neutrality. It requires an electricity grid that is powered by renewable sources of energy and a large-scale reduction in the use of oil and natural gas for transportation, space heating, and hot water. It requires immediate and dramatic efforts to make buildings more energy efficient. It entails replacing travel in personal vehicles with greater use of public transportation, cycling and walking, while eliminating the use of internal combustion engines for remaining vehicles. And it necessitates sending zero-waste to landfills and incinerators. These necessary achievements will require innovation and transformation in our city's core systems. And we will need to make these changes in a way that is cost effective, that equitably distributes benefits and burdens, and that does not unduly disrupt ongoing operations.

We know that the delivery of this report is just one step on the City's road to carbon neutrality. As your administration translates this analysis into concrete implementation strategies, the members of the GRC stand with you to provide support and expertise, to test concepts and help scale those that make sense for the City, and to reach deep into our sectors to muster support for the transition that you will lead. Please call on us. We look forward to continuing our deep and productive partnership as Boston moves toward carbon neutrality.

Sincerely,

Amos B. Hostetter, Jr.
Co-Chair, Boston Green Ribbon Commission
and Trustee, Barr Foundation

Mindy A. Lubber

Mindy Lubber
Vice Chair, Boston Green Ribbon Commission
and CEO & President, Ceres

> “Climate change is not a narrow issue, but one that affects the social and economic vitality of our city.”
>
> *Climate Ready Boston, 2016*

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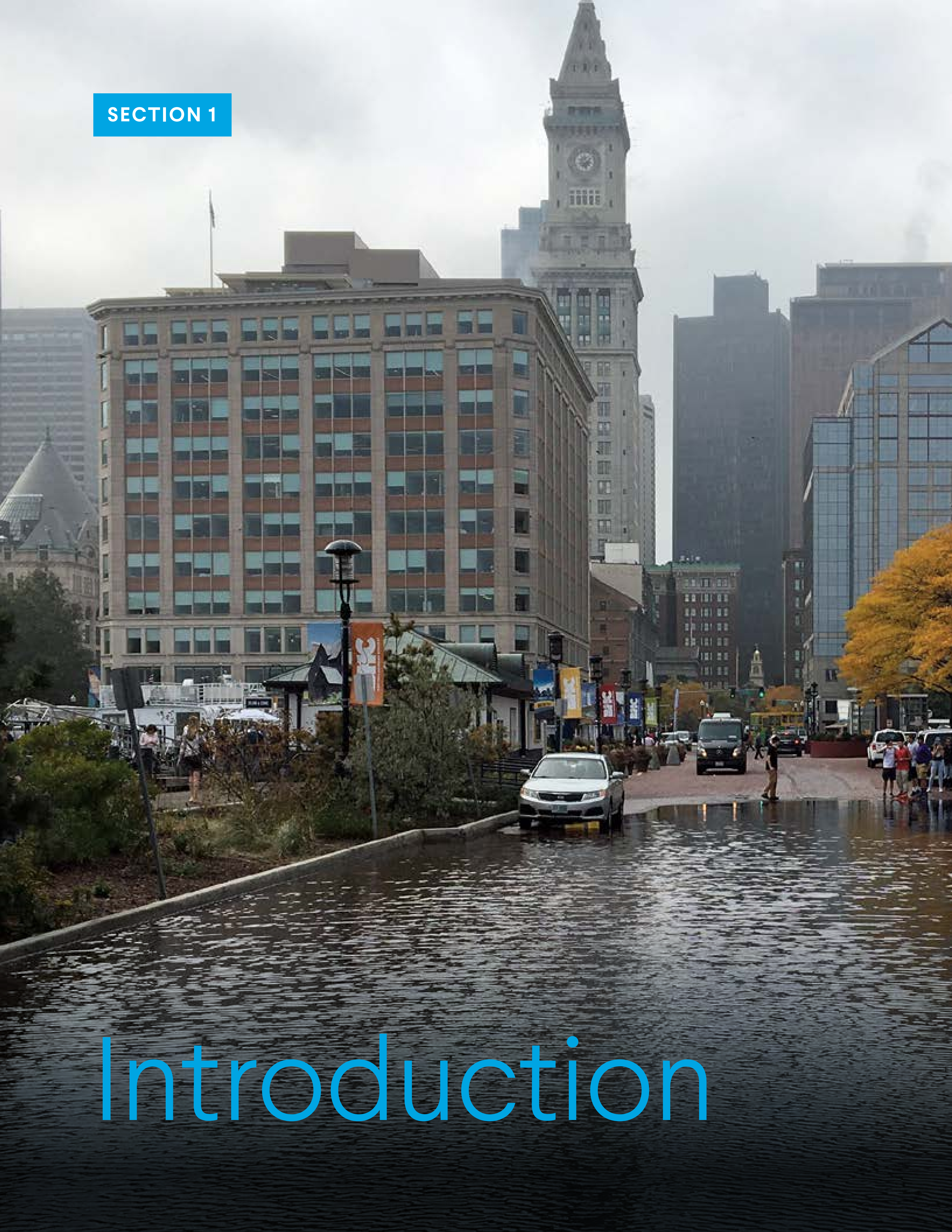
SECTION 1

Introduction



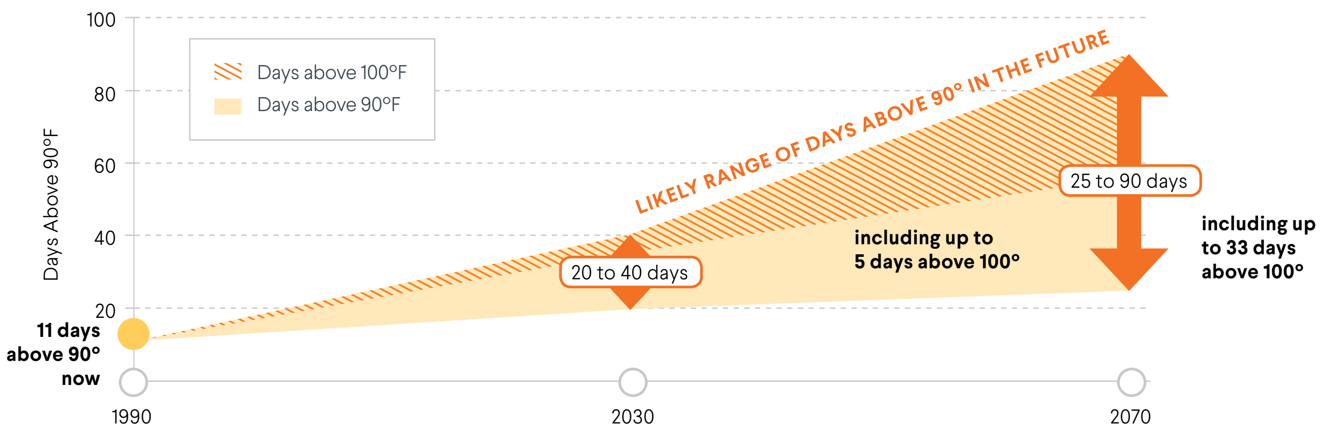
Project Overview

In 2016, Mayor Martin J. Walsh signed the *Metro Mayors Climate Mitigation Commitment*, pledging to make Boston carbon neutral by 2050,[1] and asked the Boston Green Ribbon Commission (GRC) to establish a Working Group to support the City in the development of strategies to achieve carbon neutrality. In response to the Mayor's request, the Green Ribbon Commission collaborated with the Institute for Sustainable Energy at Boston University to develop Carbon Free Boston, a long-term framework for a carbon-neutral Boston that also supports short- and medium-term action.[2]

Carbon Free Boston was developed through comprehensive engagement with City staff, utilities, neighboring municipalities, regional authorities, state agencies, industry experts, and community representatives, among others, and was supported by comprehensive analysis using models that project feasible pathways to carbon neutrality by 2050. To ensure meaningful and actionable outcomes, we looked across scales and considered opportunities and challenges associated with specific actions at the city, state, and regional levels. We also addressed disparities in communities' capacity both to mitigate climate damages and to benefit from the transition to a carbon-neutral city.

The *Fourth National Climate Assessment* by the U.S. Global Change Research Program reports that the northeast will be especially hard-hit by climate change. By mid-century, there will be 20 to 30 more days per year with a maximum temperature of more than 90°F (32°C), and the amount of precipitation in extreme events will increase by as much as 20 percent. The projected increases in extreme heat, intensive storms, and flooding will impact people's health, property, and livelihoods, especially in socially vulnerable communities.[3] To avoid the worst of these impacts, climate scientists call for a reduction in the greenhouse gas (GHG) emissions that drive climate change to a pace that keeps global temperature increases below 1.5°C, the highest increase that the Earth's natural systems can tolerate before severe and irreversible changes occur. Meeting this commitment will require cities, including Boston, to achieve carbon neutrality,[4] which means a 100 percent reduction in net GHG emissions by 2050.[5]

Figure 1a. Projections of Climate Change in Boston Adapted from *Climate Ready Boston*



THE NUMBER OF VERY HOT DAYS WILL INCREASE

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1 http://www.mapc.org/wp-content/uploads/2017/09/FINAL-Metropolitan-Mayors-Climate-Mitigation-Commitment.pdf

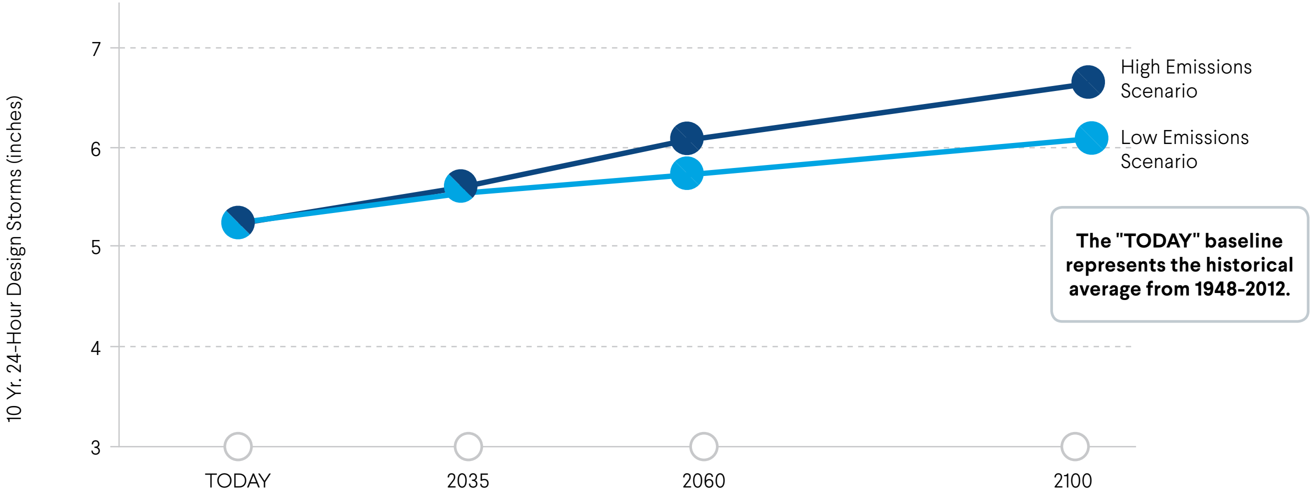
2 Carbon Free Boston refers to both the City's commitment and the process to develop the framework.

3 For a full review of expected future climate impacts to the City, please refer to the *Climate Ready Boston* report: https://www.boston.gov/departments/environment/climate-ready-boston

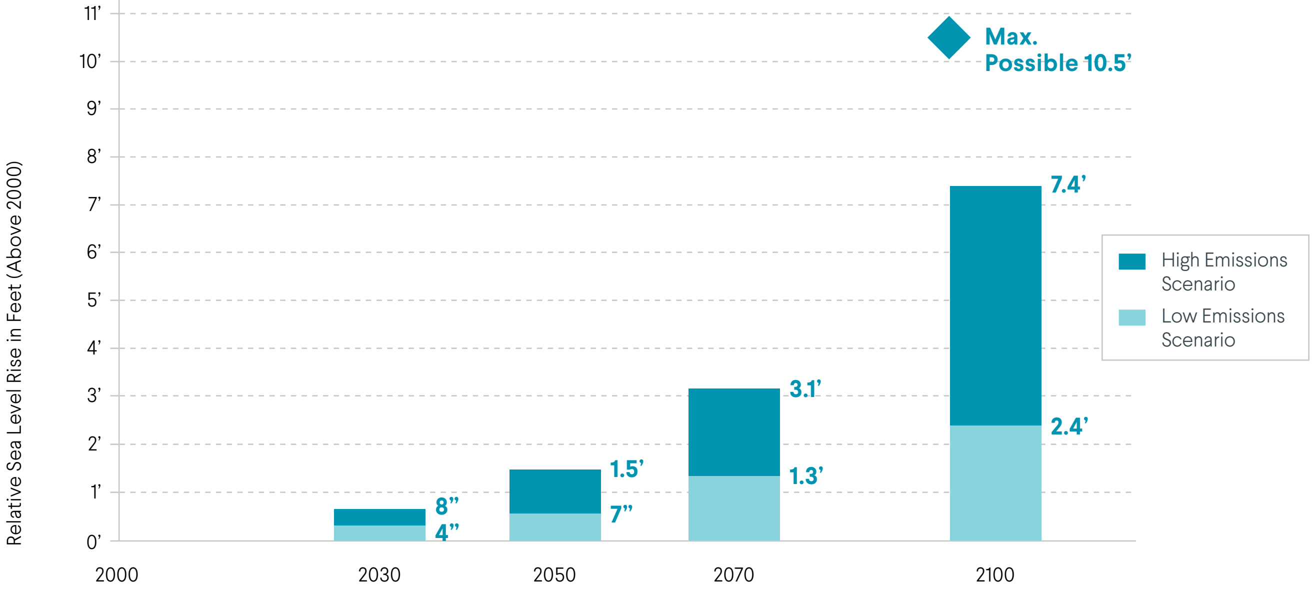
4 A carbon-neutral city is one that reduces the net effect it has on climate from human activity to zero. Here "carbon" refers to carbon dioxide (CO_2), but also other gases such as methane (CH_4) and nitrous oxide (N_2O) released by human activity that contribute to the greenhouse effect.

5 Even after aggressive action reduces emissions citywide, residual emissions may exist. Under these conditions, appropriate, and limited, third-party verified offsets will be needed to address residual GHG emissions.

Figures 1b and 1c. Projections of Climate Change in Boston Adapted from *Climate Ready Boston*



RAINFALL FROM STORMS WILL INCREASE



SEA LEVELS IN BOSTON WILL CONTINUE TO RISE

Source: BRAG Report, 2016.

City of Boston's Climate Action Timeline

2000

Boston joins the Cities for Climate Protection Campaign of ICLEI—Local Governments for Sustainability

2005

Boston adopts the U.S. Mayor Climate Protection Agreement

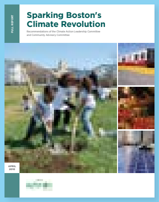
2007

Executive order by Mayor Menino commits Boston to 80x50 reduction in GHGs

Boston releases first climate action plan: *Climate: Change* https://www.cityofboston.gov/climate/pdfs/CAPJan08.pdf

2010

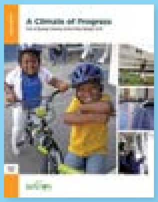
Sparking Boston's Climate Revolution



Green Ribbon Commission launched

2011

Climate of Progress



2014

Greenovate Boston 2014 Climate Action Plan Update

Boston joins *C40*

2015

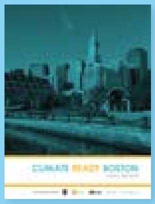
Boston joins the Carbon Neutral Cities Alliance

Metropolitan Mayors Coalition adopts the Metro Boston Climate Preparedness Commitment

2016

Mayor Walsh elected to the C40 Cities Climate Leadership Group Steering Committee

Climate Ready Boston

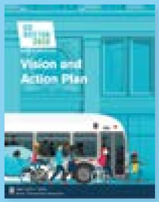


Metropolitan Mayors Coalition adopt the Metro Boston Climate Mitigation Commitment

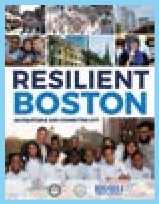
2017

Imagine Boston 2030

Go Boston 2030



Resilient Boston



2019

Carbon Free Boston Report

Climate Action Plan update

Contributions to a Just and Sustainable City

Carbon neutrality is not merely about tracking GHG emissions to meet a numerical goal; it is a public health, economic, and social equity imperative. Climate change affects everyone. The projected impacts of climate change are intrinsically linked to health and economic outcomes, and they will likely fall disproportionately on the City's most-vulnerable populations. The strategies to reduce GHG emissions ("decarbonize") offers opportunities to address historic disadvantages and create positive outcomes for all.

Climate solutions that enhance social equity are not only the most effective at reaching their goals; they are mandated by the Commonwealth. In 2014, Executive Order 552 established that "all people have a right to be protected from environmental pollution and to live in and enjoy a clean and healthy environment regardless of race, income, national origin, or English language proficiency," and that "all residents of the Commonwealth should be involved in the development, implementation, and enforcement of environmental laws, regulations, and policies, as well as equal beneficiaries of them."[6] The 2017 *Environmental Justice Policy*[7] that followed made these requirements Massachusetts law.

Every action to reduce GHG emissions has the potential to increase or reduce inequity. The key to realizing benefits from these opportunities lies in how each action is designed, implemented, tracked, and evaluated. To capture both the potential challenges and opportunities that will arise through implementation of these strategies, we evaluated potential actions with an equity framework. Our evaluation included a

Neighborhood youth at the official opening of the Erie-Ellington Playground in Dorchester. Photo credit: City of Boston

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[6] Executive Order 552. November 25, 2014. https://www.mass.gov/files/documents/2016/08/su/eo552.pdf

[7] Environmental Justice Policy of the Executive Office of Energy and Environmental Affairs. January 31, 2017. https://www.mass.gov/files/documents/2017/11/29/2017-environmental-justice-policy_0.pdf

variety of actions—such as regulations, incentives, and investments—that the City and its partners could pursue, and based on those outcomes identified specific equity considerations, issues, best practices, and opportunities that, if adequately addressed, will put Boston in the best possible position to be a carbon neutral, just, and sustainable city.

We found that actions to reduce carbon emissions in Boston would pay significant health dividends for the people who live and work here, now and in the future. In particular, the near elimination of fossil fuels would produce immediate local health benefits through improvements in air quality and more active lifestyles. More public transit, biking, and walking makes people safer and healthier. Energy-efficient, well-run buildings improve comfort and indoor air quality. In the longer-term, global efforts to avoid the most-extreme climate changes would have a big impact on Bostonians' health. This includes the adverse health effects of climate change driven by extreme events, such as unprecedented heat waves, long periods of intense rain or drought, and those associated with climate change's impacts on food supply, insect-borne diseases, and other indirect potential consequences.

Businesses, residents, the City, and the Commonwealth will need to invest in new urban infrastructure, including bike lanes, bus rapid transit, electrified trains, solar photovoltaic (PV) panels on building rooftops, battery storage, charging stations for electric vehicles (EVs), and more energy-efficient buildings. These investments will spur innovation and job creation. Employment opportunities span the entire supply chain: research and development; product manufacturing and distribution; project development; construction, installation and deconstruction; and operation and maintenance. The integration of local training and hiring opportunities into programs that reduce GHG emissions can strengthen the connection between climate action and equity and continue the momentum of economic growth in the region.

Bike lane on Boston University Bridge. Photo credit: Jorge Salcedo/Alamy Stock Photo

What it Takes to Achieve Carbon Neutrality

About two-thirds of Boston's GHG emissions come from buildings, including the electricity used in the buildings and the heating oil and natural gas burned to supply heat and hot water. The bulk of the remaining emissions comes from the energy used to move people and goods. For Boston to be carbon neutral, we must rethink the way we design and operate our buildings, heat our homes, power our businesses, and get from place to place. Every Bostonian must work with the City government, state and regional planners, designers, building owners, and energy utilities to make it happen.

The fundamental characteristics of a carbon-neutral city are clear:

- **Maximizes Efficiency:** A carbon-neutral city minimizes the demand for energy. Every building is a high-performance building; travel shifts from single-occupancy vehicles to public transit, biking, walking, and shared modes; and waste diversion is maximized.
- **Electrifies Activity:** A carbon-neutral city converts most systems that currently run on fossil fuels, such as cars, furnaces, and stovetops, to use electricity instead. Heating systems are converted to heat pumps and electric boilers where feasible. Light- and medium-duty vehicles are powered by electric motors.
- **Runs on Clean Energy:** A carbon-neutral city purchases electricity that is 100 percent GHG-free, and it fully utilizes the potential for in-city renewable generation, such as rooftop solar. Sustainably sourced renewable fuels are used in highly efficient district energy systems, emergency backup energy systems, and heavy-duty vehicles.

Boston's successful transition to a carbon-neutral city will require not only technically efficient and far-reaching solutions, but also a social-equity ethic implemented every step of the way. Both the impacts of climate change and the choices made regarding how best to reduce GHG emissions are inseparable from historical disparities in communities' access to resources and vulnerability to crises. A companion report on social equity presents a detailed analysis of equity considerations, challenges, and opportunities in Boston's energy transition.[8]

Our analysis confirms that Boston needs to embrace efficiency and clean energy in all sectors—without exception—to achieve carbon neutrality. It also revealed that early action makes it easier to reach the carbon-neutral target. Many of the technologies we need already exist. But large changes are required in the region's economic, social, institutional, and regulatory systems to enable the adoption of new technologies at sufficient scale. Energy and transportation systems are large and extremely complex, and changes to these systems will be difficult and require time. However, incremental change will not produce the GHG reductions required to avoid the most severe impacts of climate change, and it will not enable Boston to reach carbon neutrality by 2050.

Boston's ability to simultaneously become carbon neutral and advance its social equity, economic, and public health goals depends on *how* change is pursued. This effort will require a diverse set of actions in the near and medium term—some led by the City and others supported by the City. The design of each specific action must not only reduce GHG emissions, but also align with the City's goals and priorities and its communities' needs.

Solar Installation on Bethel AME Church in Jamaica Plain.
Photo credit: Resonant Energy

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[8] The companion report on social equity is scheduled for release in March 2019.

Boston's Roadmap to Carbon Neutrality

Efforts are already underway that will reduce GHG emissions in Boston. Existing regulations and investments, trends in technology, and current programs are expected to reduce GHG emissions by 40 percent by 2050 relative to 2015 (Figure 3, top). Most of that decline is attributable to state energy regulations coupled with a decline in the cost of renewable electricity, federal energy and emissions standards for vehicles, and by various City initiatives to improve the energy efficiency of buildings.

We expect a large fraction of the reduction in Boston's GHG emissions to come from the New England electric grid. The Commonwealth's Clean Energy Standard requires that 80 percent of electricity delivered to customers in 2050 be generated by low- or zero-GHG sources. There are many reasons to believe that this target will be achieved: the large decline in the capital cost of wind and solar energy, the expansion of offshore and onshore wind generation, utility-scale solar, increased distributed solar generation, and the expected increased transmission of hydropower from Quebec.

These reductions are significant, but they will not result in a carbon-neutral Boston by 2050. There are forces working against achievement of this goal, such as the closure of the Pilgrim Nuclear power plant in May 2019, which may be replaced in part by new or existing fossil fuel plants that increase emissions, or the growing popularity of ride-hailing services (e.g., Uber and Lyft) in place of public transit. Federal regulations requiring power plants to emit fewer GHGs and vehicles to be more energy efficient may be weakened. Gasoline prices are not expected to rise significantly through 2050, which will slow both the adoption of electric vehicles and the shift of people out of cars to transit, walking, and biking.

To bridge the GHG emissions gap and address these challenges, we assessed a number of scenarios and actions that can accelerate Boston toward carbon neutrality (Figure 3, bottom). Despite the expected decarbonization of the New England grid, natural gas may still generate some electricity used within Boston on the path to 2050. If so, the City can lead efforts to allow Bostonians to easily purchase GHG-free electricity. The City can accelerate the regional deployment of renewable energy by facilitating 100 percent zero-GHG electricity at a reasonable cost through a combination of procurement strategies.

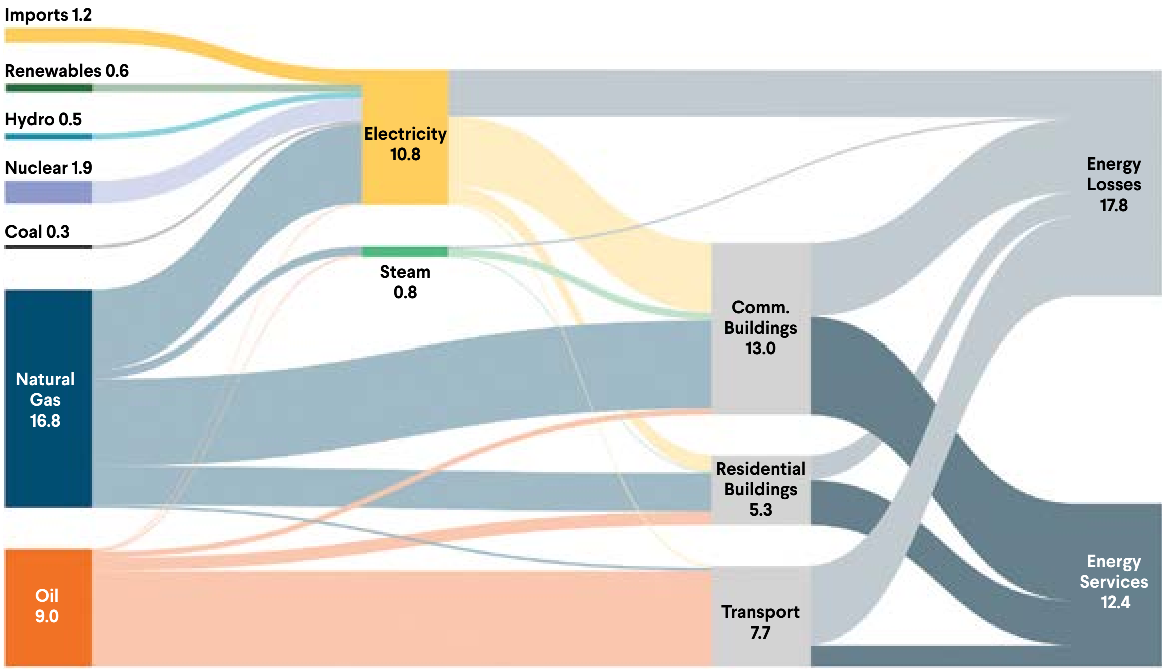
A clean electric grid alone will not get Boston to carbon neutrality. Buildings in Boston rely heavily on the combustion of oil and natural gas for space heating, cooking, and hot water. This makes the combination of building energy efficiency and the use of low- to zero-GHG fuels and electricity important changes to make. Accordingly, new buildings can be designed to achieve net-zero/net-positive performance by prioritizing passive building strategies, well-insulated and air tight envelopes, and orientation and massing, while at the same time employing smaller high efficiency heating, cooling, and lighting systems.

Existing buildings pose a greater challenge; 85 percent of projected building square footage in Boston in 2050 exists today. For carbon neutrality, nearly all of the existing buildings in the city will need to undergo deep energy retrofits that are designed and implemented with a "whole building" approach. A piecemeal approach—e.g., a more-efficient boiler only—will not result in the necessary emission reductions. Rather, a whole-building approach improves both the building envelope—its roof, walls, windows, and doors—and replaces heating/hot water systems that currently rely on gas and oil with systems that run on increasingly zero-GHG electricity, like heat pumps. Consistent with the City's priorities, the design of programs to promote existing building retrofits will need to ensure that socially vulnerable populations can afford such upgrades, reap the benefits of lower utility bills, and not be displaced as a result of higher housing costs. Achieving these objectives while also stimulating market development will require the City, the Commonwealth, and other partners to accelerate programs that provide technical and financial support, technology deployment, and workforce training. To further drive market adoption and the full transformation of the building stock, these programs will need to work in conjunction with appropriately timed building performance standards and other regulations.

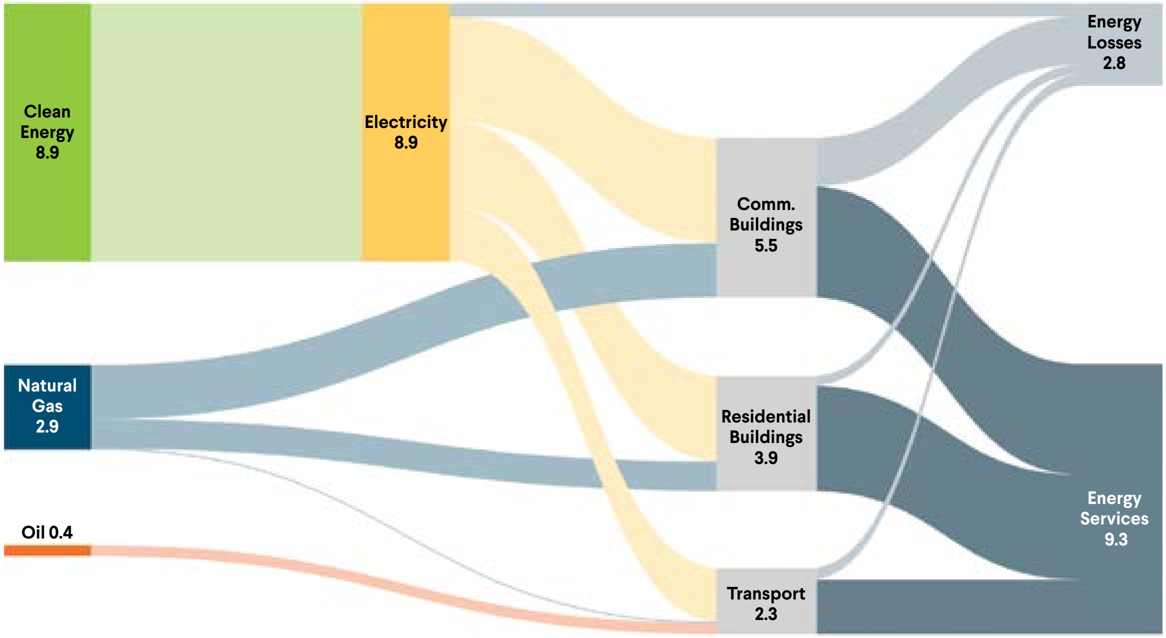
Similar to buildings, the reduction of transportation GHG emissions is dependent on the decisions of Bostonians as well as commuters who live outside the city. It requires them to shift

Figure 2. Current and Future Energy Use in Boston

Top: In 2015, fossil fuels dominate total energy use, and energy is used inefficiently. **Bottom:** In 2050, clean fuels and electricity dominate energy use, and little energy is wasted. On the left are energy sources used in the City. The height of a bar indicates the relative quantity of energy used. On the right are energy services such as mobility, heating and cooling, lighting, etc. Also shown are energy losses, i.e. the energy consumed in buildings and transportation that does not provide a useful service, such as the heat released by car engines and leaky windows. In the middle are the sectors that transform the energy inputs into the energy services. Steam from district systems could play a role in 2050 but is not explicitly assessed. Sources: Boston Community Greenhouse Gas Inventory and Institute for Sustainable Energy model calculations.



Boston 2015—Energy Use (TWh)



Boston 2050—Energy Use (TWh)

travel from cars—the largest source of transportation-related GHG emissions—to public transit, biking, and walking. The benefits of this approach are clearly laid out in *Imagine Boston 2030,* Boston's citywide development plan, and *Go Boston 2030,* the City's long-term transportation plan: safer streets, improved public health from cleaner air and more physical activity, equitable access to mobility, and more connected communities. These 2030 Boston plans also emphasize the importance of addressing social equity as a central theme in planning and decision making, including economic inclusion, anti-displacement policies, bringing transit to under-served neighborhoods, and valuing health benefits in decision making.

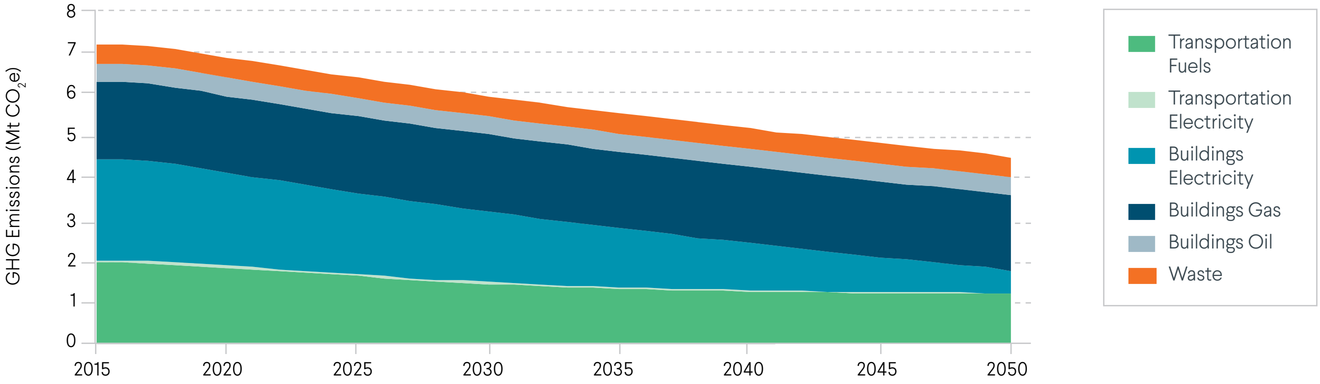
People make transportation choices based on access, convenience, cost, and personal preference. Getting residents and commuters to change their transportation modes of choice will require making transit, biking, and walking more convenient, less expensive, safe, and practical, while also making driving and parking more expensive.

Any remaining cars and trucks driving into and around Boston in 2050—including ride-hailing services—must run on low- or zero-GHG fuel or electricity. The City, region, and Commonwealth, along with utilities and other private sector partners, must help accelerate an affordable market transformation

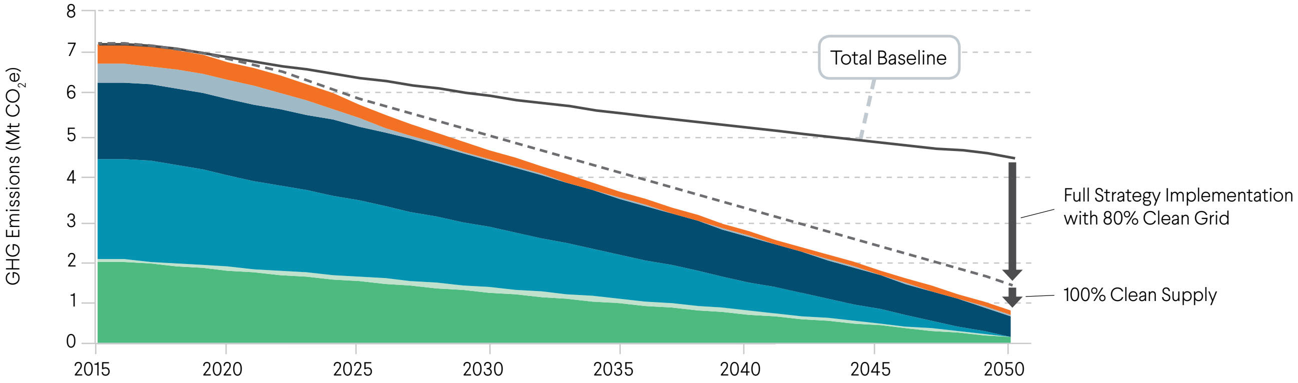
Figure 3. Boston's Roadmap to Carbon Neutrality by 2050

Top: Emissions forecast for a baseline scenario with no additional City action in which emission reductions are primarily driven by increasing efficiency in transportation due to federal vehicle fuel efficiency standards, and a reduction in the GHG intensity of the electricity grid caused by the Massachusetts Clean Energy Standard (80% low- to zero-carbon electricity by 2050). **Bottom:** Emissions forecast for a scenario that represents forceful city action on GHG mitigation across all sectors ("Full Strategy Implementation"). The solid line is the baseline scenario in the top figure. The dashed line indicates the impact of efficiency and electrification measures alone, while additional reductions are achieved by the City's procurement of 100% zero-GHG electricity by 2050. Source: Institute for Sustainable Energy model calculations.

Boston's Current Path



Boston's Path to Carbon Neutrality by 2050



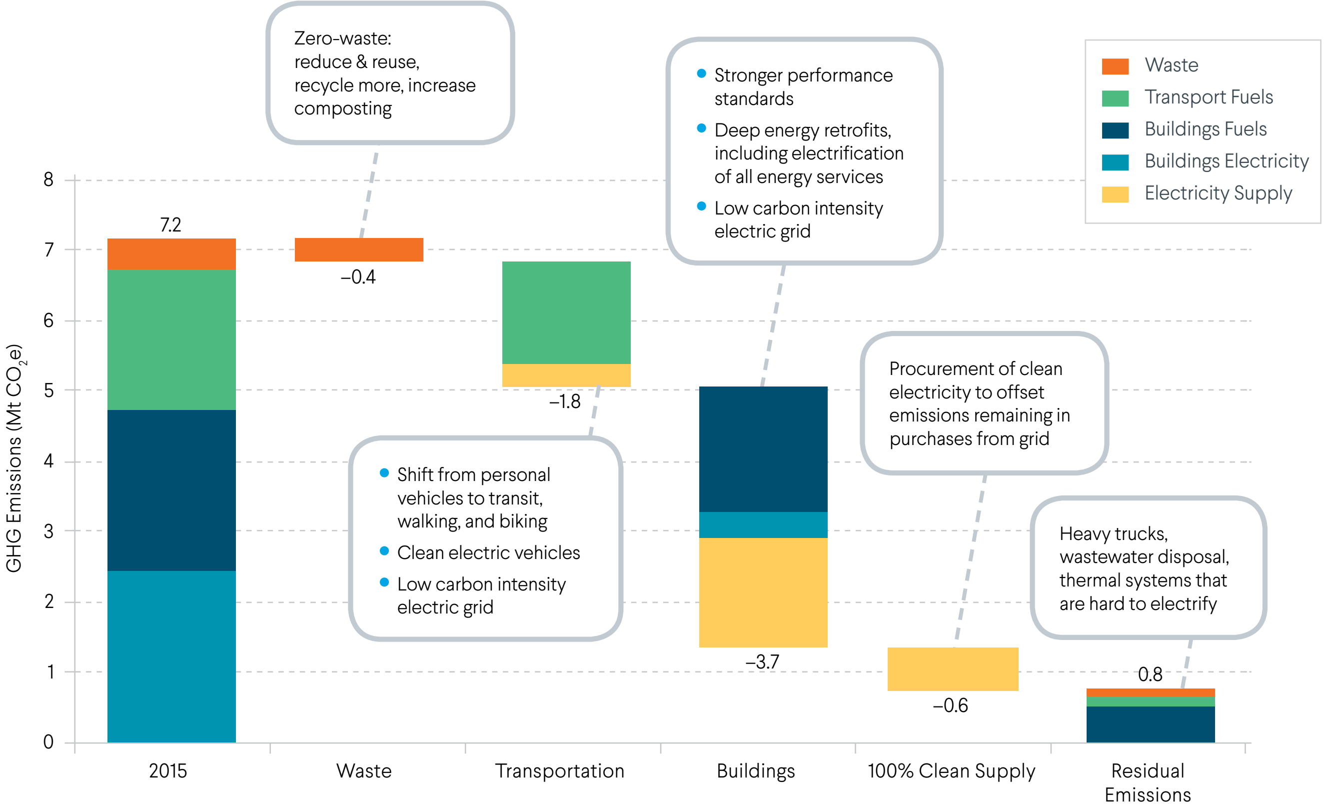
toward electric vehicles. Programs to support electric vehicle purchases and to build out local and regional electric vehicle infrastructure will help make EVs a more economic, convenient, and accessible solution. Charging fees or restricting city access of cars with internal combustion engine vehicles would accelerate market transformation toward electric vehicles. Achievement of Boston's long-term climate, transportation, and equity goals will also require the City to manage the growth of ride hailing and prepare for the commercial availability of autonomous vehicles.

In addition to climate strategies that focus on energy supply, buildings, and transportation, actions to reduce GHG emissions from solid waste and to attain the City's zero-waste goals are necessary for carbon neutrality. Less waste generation combined with more recycling and reuse will reduce GHG emissions and foster companies that reprocess recyclables and reuse these materials in their products. The capture of methane for reuse as a renewable energy source is a key component of a zero-waste strategy. Expanding renewable energy deployment at the Deer Island Sewage Treatment Plant will further reduce GHG emissions from treatment of the City's wastewater.

Even after comprehensive and aggressive action, some of Boston's building, transportation, and waste management systems may still emit GHGs. These may include emergency management systems, or simply buildings and systems that are expensive or difficult to decarbonize with available technologies. Under these conditions, after the City has exhausted its other strategies, verified carbon offsets will be necessary to get to carbon neutrality. Therefore, limited, strategic offsets should be part of the City's dialogue with stakeholders in its climate action planning.

Figure 4. Steps to Carbon Neutrality in Boston

In 2015, GHG emissions in Boston were about 7.2 Mt CO$_2$e. Each subsequent column indicates reductions in each sector that are possible by 2050. In the transportation and buildings columns, the yellow portion reflects the reduction in emissions caused by the expected contribution of the Massachusetts Clean Energy Standard (80% clean electricity by 2050). "100% Clean Supply" refers to the emissions reduction associated with the procurement of 100% GHG-free electricity. Residual emissions are generated by sectors that are difficult to fully decarbonize and will likely require the use of low-carbon fuels or offsets. Source: Institute for Sustainable Energy model calculations.



The Key Takeaways

Rooftop photovoltaic installation. Photo credit: City of Boston

The results of our assessment demonstrate that carbon neutrality in Boston depends on three self-reinforcing strategies, all of which must be pursued in a synergistic and socially equitable manner:

- Improve the energy efficiency of all activities;
- Electrify activities to the fullest extent feasible;
- Purchase 100 percent GHG-free electricity and sustainably sourced fuels.

Pursuing these strategies and accelerating movement to carbon neutrality requires a comprehensive set of actions occurring in parallel and phased in over time, across different sectors and levels of government. The City will need to be intentional in its design and implementation of these actions to integrate positive equity, public health, and economic outcomes, especially for historically disadvantaged and vulnerable populations. This will require close collaboration with businesses and communities, especially when it comes to the structure of necessary regulations and pricing policies because voluntary programs alone will not achieve the scale of change required. This will also help to foster trust, even as decisionmakers need to act with imperfect knowledge about costs, consumer behavior, and the pace of technological innovation, while also considering time and budget constraints.

The City will not be able to achieve carbon neutrality on its own, and the coordination and design of actions must extend beyond Boston. The private sector owns and operates the vast majority of buildings and vehicles. The Commonwealth of Massachusetts sets building and energy codes, regulates utilities, runs the regional transportation systems, and has authority over state and local tax rates and related fees. Regional entities control the port, airport, public transit, water supply, and wastewater treatment infrastructure, and the federal government has oversight over a number of emission standards. Climate action will be most effective when it is done in partnership with other sectors and levels of government, and is included in the City's state and federal legislative agendas.

Effective climate action also fosters an informed and engaged constituency that demands—and votes for—decisive action and accountability over time. For this advocacy to occur, these actions must align with Bostonians' priorities and therefore must reinforce the expansion of economic opportunities for all, improved public health, and stronger social and climate resilience.

In short, carbon neutrality requires a strong, long-term commitment and leadership from City Hall that will support action and coordination across all agencies. It demands a shared vision, set of objectives, and commitment to act across different levels of government and sectors. It will entail both acting on its own and expanding partnerships with the private sector and communities. And it will only be possible with an informed and engaged constituency calling for continued action, follow through, and accountability over time.

This hard work will generate rich dividends. A carbon-neutral city is healthy, safe, and resilient in the face of climate change. The investment that underpins the transformation of Boston will create enormous opportunities for entrepreneurship and workforce development. The collaboration required to reach carbon neutrality will improve the connection between the City, neighboring communities, the state, the business community, and, most importantly, the people of Boston. That collaboration will ensure that every person that lives, works or visits Boston has equitable access to the benefits and opportunities of a carbon-neutral city.

SECTION 2

Approach

Rooftop solar installation in Dorchester. Photo credit: National Renewable Energy Laboratory

Organization and Process

The work described in this report required data, analysis, and review from diverse groups of people and organizations (Figure 5). The advisory and engagement process is described below. The individual people and organizations who contributed time and expertise are listed in Appendix A.

Steering Committee

The Steering Committee provided strategic direction for the Carbon Free Boston project. The Committee ensured that the project's scope aligns with the City's climate goals, prioritized the work of the project, and monitored the project timeline. The Committee included stakeholders from the City, the Commonwealth, the GRC, and key project funders.

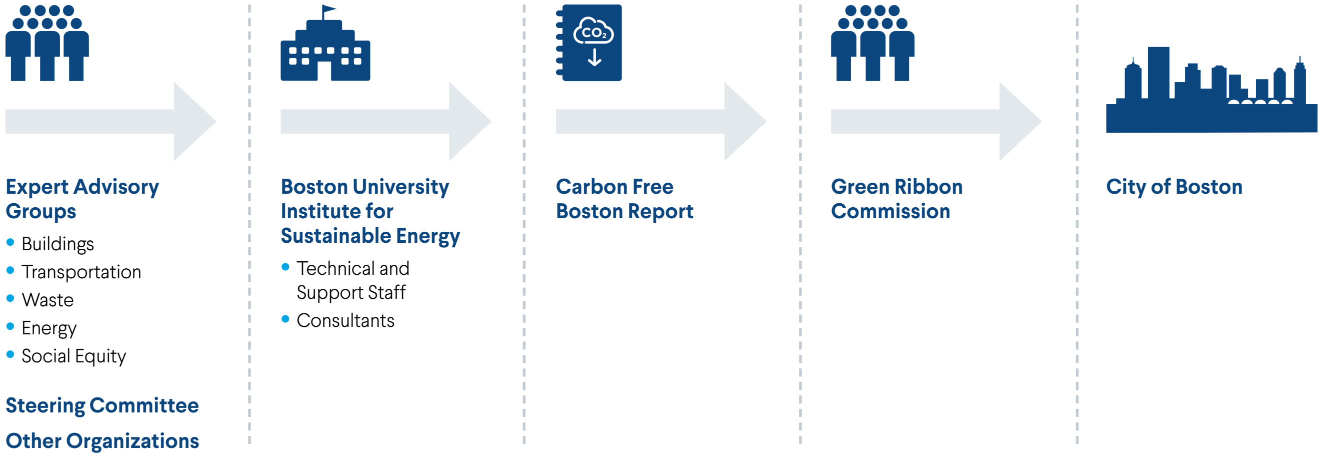
Advisory Groups

Technical Advisory Groups (TAGs) were formed for the buildings, transportation, waste, and energy sectors. The TAGs comprised 90 individuals from 50 organizations, including the City of Boston, the Commonwealth, energy utilities, energy consulting firms, developers, real estate firms, non-governmental organizations, and academia. The TAGs included experts in the area of social equity.

The role of the TAGs was to provide guidance on each sector's analysis and review the overall technical quality of the work in each sector. Specific responsibilities included identifying policies to assess, discussing issues related to the reduction of GHG emissions in each sector in an open and transparent manner, and reviewing content for the final report.

The Social Equity Advisory Group provided guidance and feedback on the integration of social equity into the technical analysis and implementation options. The group's meetings created an open and transparent forum to discuss issues related to social equity in conjunction with reducing GHG emissions as members assessed the social equity costs and benefits associated with specific policies. Members of the Social Equity Advisory Group were drawn from the TAGs, as well as equity-focused community groups and experts.

Figure 5. The Organizations Involved in Carbon Free Boston



Analytical Approach

Charging the battery of an electric car. Photo credit: National Renewable Energy Laboratory

The assessment of strategies to reduce GHG emissions in Boston requires a comprehensive analysis of the key drivers of emissions and alternative technology and policy choices. We focus on energy demand from buildings and transportation, energy supply, and waste. These represent the most well-quantified sources of emissions in the city, and they align with the focus of most other urban climate action plans.[9] Our analysis notably omits air travel at Logan airport and the consumption of goods and services. Emissions from these activities are significant and can be reduced, but are outside the scope of the City's GHG accounting. Future work could quantify such consumption emissions and seek to educate the public and relevant authorities on potential mitigation options.

We used a systems-modeling approach to evaluate GHG reduction pathways in the buildings, transportation and waste sectors (Figure 6). Our models characterized how Boston's residents, businesses, workers, and visitors use buildings, travel, and generate waste. From this data, we calculated their energy needs and emissions. We then assessed a range of specific strategies and actions in terms of their effect on energy use and GHG emissions.

Many of the parameters in a forward-looking model rest upon uncertain assumptions about future technology, costs, human behavior, and policies. For important activities such as public transit, renewable electricity, building energy use, waste disposal, and personal vehicles, we characterized historic trends in people's behavior and technological progress in our modeling framework. While the technology exists today for a city like Boston to eliminate most of its GHG emissions, reaching carbon neutrality by 2050 will require additional technological development as well as an acceleration of efforts that exceed historical behavior.

In this report, we distill our findings from the technical analysis and input from the TAGs and Social Equity Advisory Group into a "Pathway to Carbon Neutrality by 2050" for each sector. These pathways represent our judgment regarding an effective, efficient, and equitable reference point for the City to develops its *Climate Action Plan.* They are not predictions of the future. Rather, they are descriptions of the underlying driving forces, feedbacks, sensitivities, and bounds.

This summary report will be complemented by two companion reports. A Technical Report will provide greater detail on the data and methods used to analyze the City's options for mitigating emissions. A Social Equity Report will expand our analysis on the opportunity at hand to improve the quality of life for all Bostonians while simultaneously moving Boston toward carbon neutrality.

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[9] The industrial sector in Boston contributes a very small fraction of overall GHG emissions, so emissions from industrial buildings are included in the commercial sector.

Sectors That Drive GHG Emissions

Buildings

In the buildings sector we modeled energy conservation and electrification strategies in 15 building use classes (single-family, multifamily, office, etc.) over five vintages representing period-specific advances in building construction. We frame the adoption of these strategies with policies (e.g., mandates vs. incentives) to show the citywide potential of building intervention measures.

Transportation

In the transportation sector we assessed emissions associated with on-road vehicles (cars and trucks), rail, and local waterborne navigation (ferries). Our assessment of strategies to reduce on-road household vehicle emissions was based on a coupled approach to model travel mode choice and electric vehicle adoption. The mode choice model represents the factors (cost, travel time, traveler preference) that influence a decision to take a particular mode of transportation (personal vehicle, walk, bike, public transit). This enabled the evaluation of travel pricing and transit improvement policies that act to shift a trip's mode of travel. Additionally, an electric vehicle adoption model was used to explore how various incentives could increase adoption rates.

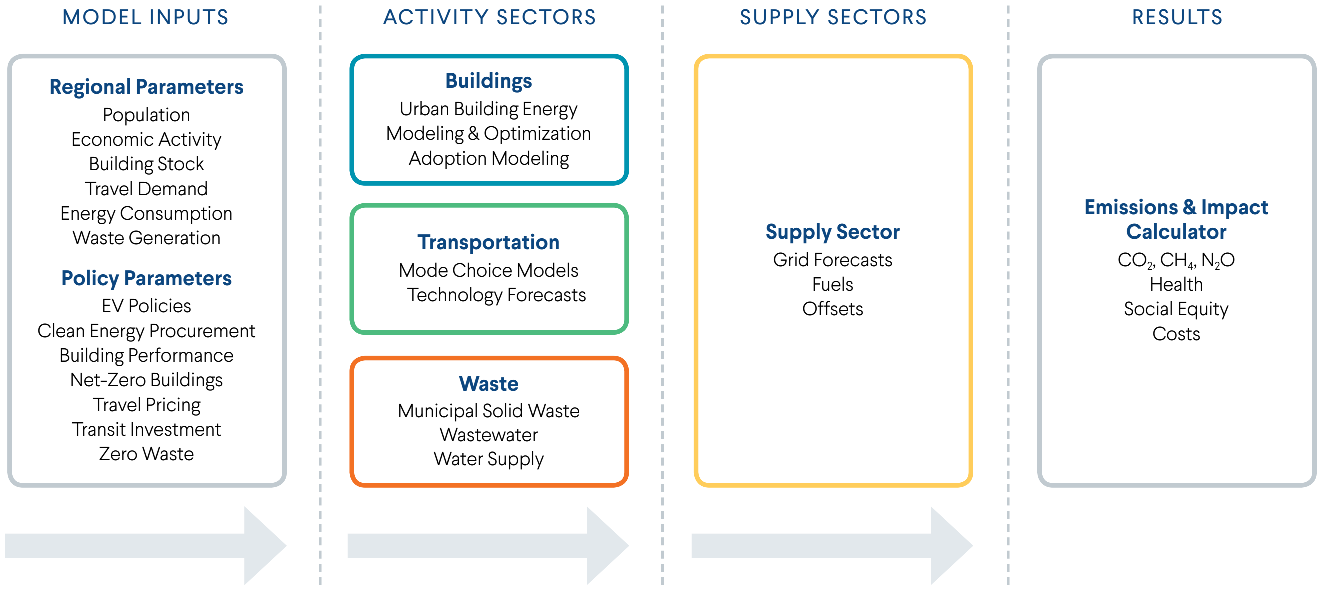
Waste

Waste reduction strategies proposed by the *Zero Waste Boston* initiative are evaluated for their impact on emissions. We assessed how these policies reduce and divert different types of waste materials (organics, glass, plastics, etc.) from combustion to other processes. We also assessed emissions from wastewater treatment at the Deer Island treatment facility, which processes wastewater from the City and surrounding region.

Energy Supply

Our analysis of the energy sector focused on three elements of supplying GHG-free electricity. First, we assessed the impact of electrification in the buildings and transportation sectors by evaluating the resulting changes in electricity demand. We then evaluated the options for in-city energy systems such as rooftop solar energy and district energy. Next, we assessed the options available to Boston to acquire GHG-free electricity. Finally, we assessed the potential of low- and zero-GHG fuels to reduce emissions where electrification is impracticable.

Figure 6. Modeling Framework for Carbon Free Boston



Integrating Social Equity

Our analysis used a criteria-based framework to evaluate and prioritize strategies and actions to reduce GHG emissions in the context of how each intersects with social equity (Figure 7). Specifically, strategies are examined to determine their implicit equity considerations, challenges, and opportunities; using examples of best practices or lessons learned from experiences elsewhere in the country and the world as appropriate. The forthcoming Social Equity Report will include definitions, assessments, and mapping of key performance indicators presented in the context of their impacts on socially vulnerable populations. That report is intended to generate actionable insights for the design and implementation of specific carbon-neutral policies in Boston.

We define "socially vulnerable populations" as those communities that are more likely to suffer disproportionately because of their existing social circumstances, such as those associated with age, gender, race, medical illness, disability, literacy, and English proficiency. All neighborhoods contain some residents from each of these groups; Figure 8 shows the distribution of socially vulnerable populations in Boston.

We use this social vulnerability framework because of the observed sensitivity of those populations to changes in the cost of energy, access to and uptake of energy efficiency and renewable energy incentives, and their access and use of transportation services that may be affected by action taken to reduce GHG emissions. These are the same populations that *Climate Ready Boston* identified as vulnerable to the impacts of climate change itself, such as increased flooding and more extreme temperatures. The equity framework explicitly calls out the needs of Boston's most vulnerable, while simultaneously improving the quality of life for all residents.

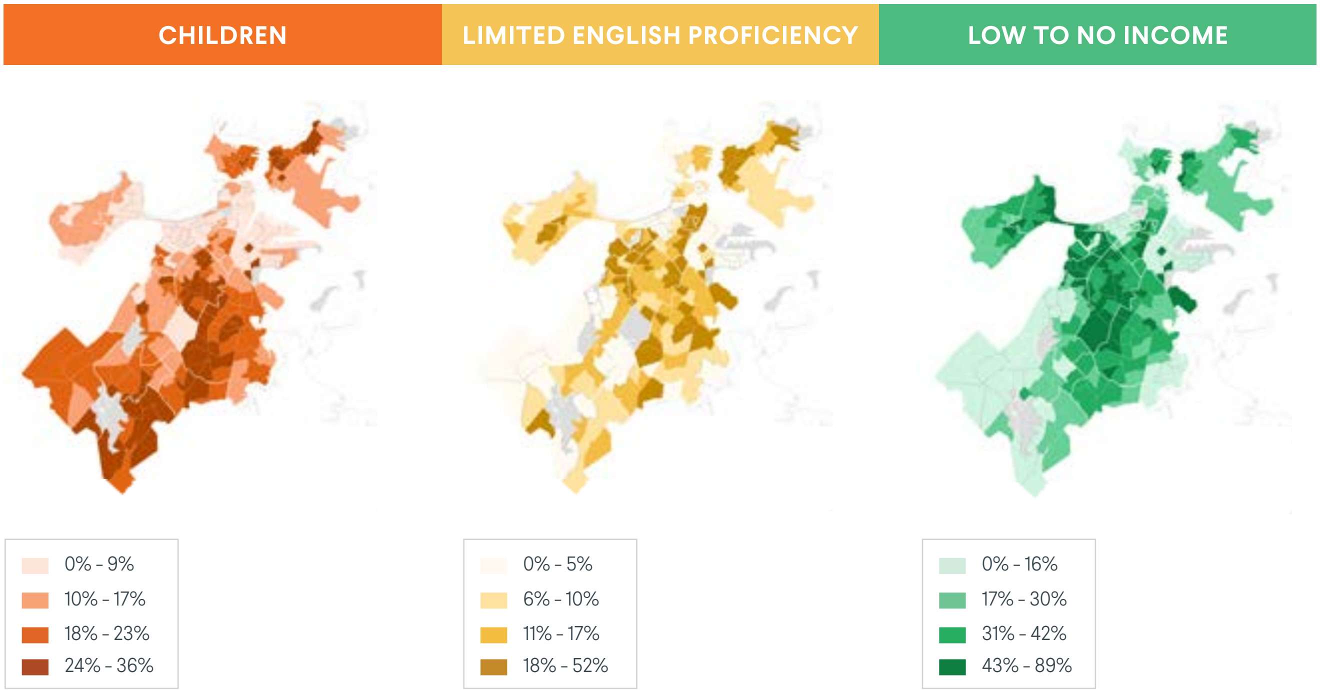
Mayor Walsh visits the Haynes Elementary School in Roxbury. Photo credit: Jeremiah Robinson/Mayor's Office

Figure 7. Equity Scorecard: Social Equity Framework

Components	Evaluation	
Is it green?		
Is it GHG-free?	Reduces GHG emissions: electrification, active transport, lower non-CO_2 emissions	Yes / No / Depends
Is it environmentally sustainable?	Less energy used or fewer GHGs emitted to provide the same energy service; other environmental considerations: land and water use, pollution, etc.	Yes / No / Depends
Does it promote smart behavior?	Use or behavior is altered in ways that accomplish more than GHG reductions: i.e., better timing or siting for congested resources, smarter use of resources, waste reduction	Yes / No / Depends
Is it fair?		
Is it accessible?	Available to and beneficial for all communities; addresses historical disparities and cultural differences	Yes / No / Depends
Is it affordable?	All private residents can afford it; limits negative impacts on public sector	Yes / No / Depends
Are workforce opportunities just?	Fairness and balance in workforce and contractor diversity; addresses historical disparities	Yes / No / Depends
Who gets to decide?		
Is it inclusive?	Impacted or socially vulnerable communities have an active and meaningful role in decision-making	Yes / No / Depends
Are values considered?	Decision-making processes go beyond dollars and cents to address shared values and cultural differences	Yes / No / Depends
Is it measurable?	Quantity and quality of service provided and community impacts can be measured quickly and continually in order to provide important performance feedback	Yes / No / Depends

Figure 8. Socially Vulnerable Populations in Boston

Populations are mapped by quartile to show relative concentrations in each census tract. Sources: Data from U.S. Census Bureau, 2012-2016; American Community Survey 5-Year Estimates.



CHILDREN AND ADOLESCENTS (108,939 people)

Children and adolescents are especially vulnerable to both indoor and outdoor air pollution. Reduced fossil fuel combustion in transportation will improve health outcomes for this population. Transit, biking, and walking produce safer streets, improve children's navigation skills and knowledge of their neighborhood, and increase physical activity. Energy-efficient buildings reduce mold and allergens that cause asthma and other respiratory illnesses.

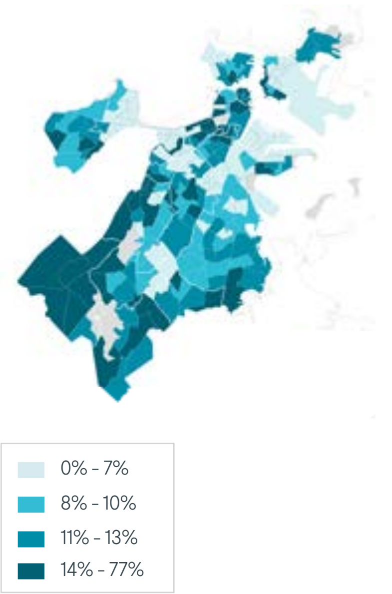
PEOPLE WITH LIMITED ENGLISH PROFICIENCY (31,796 households)

Thirteen percent of Boston's population have limited English proficiency. This population will need targeted information on proposed actions to reduce GHGs. Among those with limited English proficiency, the most common languages spoken in Boston are Spanish or Spanish Creole (17%), Chinese (5%), French Creole (4%), and Vietnamese, Portuguese, and Portuguese Creole (3%). Linguistically appropriate and culturally relevant training and education materials will support efforts on waste reduction, increased residential energy efficiency, and active transportation.

PEOPLE WITH LOW TO NO INCOME (187,515 people)

People with low to no income spend a large fraction of their household income on energy and rely heavily on public transit. Energy-efficient buildings will lower household energy bills. Action to improve building energy efficiency should help this population pay for the upfront costs of building retrofits. Investment in transit will reduce GHG emissions and benefit low-income populations. Fees levied to reduce GHG emissions in transportation must be accompanied with action to offset the impact on this population. Equitable access to electric vehicles, smart mobility, and other new technologies should be prioritized.

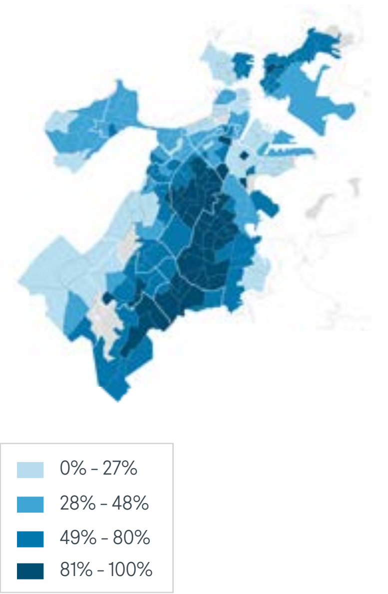
OLDER ADULTS



OLDER ADULTS (70,229 people)

People over the age of 65 have physical and social vulnerabilities in the context of climate change and mitigation. They suffer from higher rates of medical illness than the rest of the population, are often socially isolated, and can have functional limitations that impede mobility. Energy efficient buildings will improve indoor air quality and reduce thermal stress in winter and summer. Investments in transit, biking, and walking directly address this population's mobility and access challenges, and improve health outcomes via more physical activity.

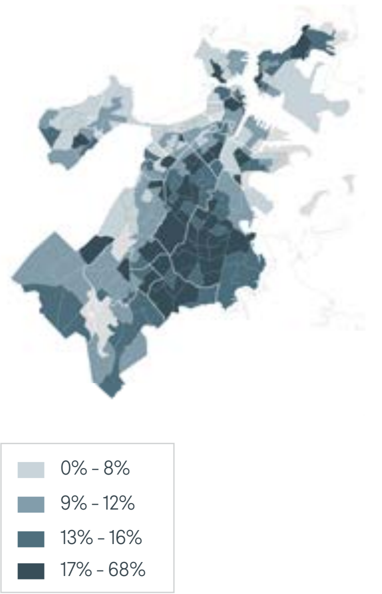
PEOPLE OF COLOR



PEOPLE OF COLOR (359,738 people)

A majority of people of color (55.3%) make up Boston's residential mix; 19.5% of residents are Latino/x, 22.9% are Black, 9.5% are Asian, and 2.5% are multiracial. Action to reduce GHG emissions has the potential to decrease the burdens these communities bear on a daily basis by establishing pathways to equitably distribute benefits and increase resilience. This requires an intentional effort to remove historical barriers and include people of color in the decision making that impacts their lives.

PEOPLE WITH DISABILITIES



PEOPLE WITH DISABILITIES (80,101 people)

One in 10 people in Boston has a disability and may face challenges around mobility, resources, and social connection. Investment in public transit and active transport can simultaneously reduce GHG emissions and improve mobility for this population. Similarly, building retrofits can simultaneously increase energy efficiency and increase access to buildings.

Defining Emissions Sources and Boundaries

We used the *Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories* (GPC) framework as the basis for our GHG analysis. We quantified emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), the primary GHGs released in Boston. The bulk of emissions is CO_2 from the combustion of natural gas and fuels derived from petroleum, such as motor gasoline, diesel fuel, and home heating oil. Smaller quantities of GHG emissions arise from waste collection, waste combustion, wastewater treatment, and leaks in the natural gas distribution system that runs through the city. To estimate total GHG emissions, we converted emissions from each of these gases into carbon dioxide equivalent (CO_2e) units by multiplying them by their global warming potential, which is an index that measures each GHG's effects on the Earth's warming relative to CO_2.[10]

Geography and Emissions Scope

Our analysis included both direct and indirect GHG emissions. Direct emissions are from activities that take place within the city limit of Boston. This may include emissions from vehicles making trips into the City from outlying cities and towns. The majority of direct emissions are from the combustion of fossil fuels such as natural gas, gasoline, and diesel fuel. Much smaller quantities of direct emissions are associated with methane-leakage or N_2O generation from wastewater.

Indirect GHG emissions result from the generation of electricity, heat, or steam purchased from a utility provider for use within the city. The generation, however, does not necessarily take place in the city. Our electricity, much of which is generated from turbines that combust natural gas, is purchased from the ISO-New England grid. Steam is imported from the Veolia-Kendall generation station in Cambridge, which is also powered by natural gas. Natural gas is supplied and distributed by National Grid and Eversource.

Within Boston, we distinguished between residential and commercial activity to demonstrate the relative contribution from each sector. This also allows us to distinguish policies that would separately apply to these sectors. We use "commercial" to loosely describe all non-household activity that could include retail, services, hospitals, industrial facilities, non-profit institutions, and government operations.

GHG Accounting Differences Between the Carbon Free Boston Report and the City of Boston

This report uses a broad analytical framework for accounting emissions that differs from the methodology used in the City's *Community Greenhouse Gas Inventory* in a couple of notable ways, although both approaches follow the GPC.

For transportation, the City's *Community Greenhouse Gas Inventory* captures all vehicle activity occurring inside Boston's geographic boundaries, whereas the Carbon Free Boston analysis assessed trips that have at least one endpoint within these boundaries. This trip-focused approach enabled us to evaluate the impact of policies that intend to shift both residents and commuters from one mode of transit to another, or from an internal combustion vehicle to an electric vehicle. Our approach assigned half of emissions associated with a trip to the origin and half to the destination. Due to the number and distance of commuter trips, our analysis captured more miles traveled and emissions than the *Community Greenhouse Gas Inventory,* and allowed us to assess the effectiveness of strategies to reduce emissions from regional travel.

In the waste sector, we evaluated the impact of policies on downstream emissions associated with the final disposition of solid waste and wastewater. Most of Boston's solid waste is combusted to generate electricity (waste-to-energy). The *Community Greenhouse Gas Inventory* follows the GPC guidance on emissions from waste-to-energy plants and attributes them to regional electricity generation. We took a different approach by assessing emissions associated with alternative waste management strategies. These included direct emissions from collection, combustion, composting, as well as avoided emissions via energy recovery, material recovery, and carbon storage.

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[10] Specifically, the Global Warming Potential (GWP) is an index that measures the radiative forcing that follows the emission of a gas, accumulated over a chosen time horizon, relative to CO_2. CO_2, as the reference gas, has a GWP of 1.

Future Assumptions

Population and Economic Growth

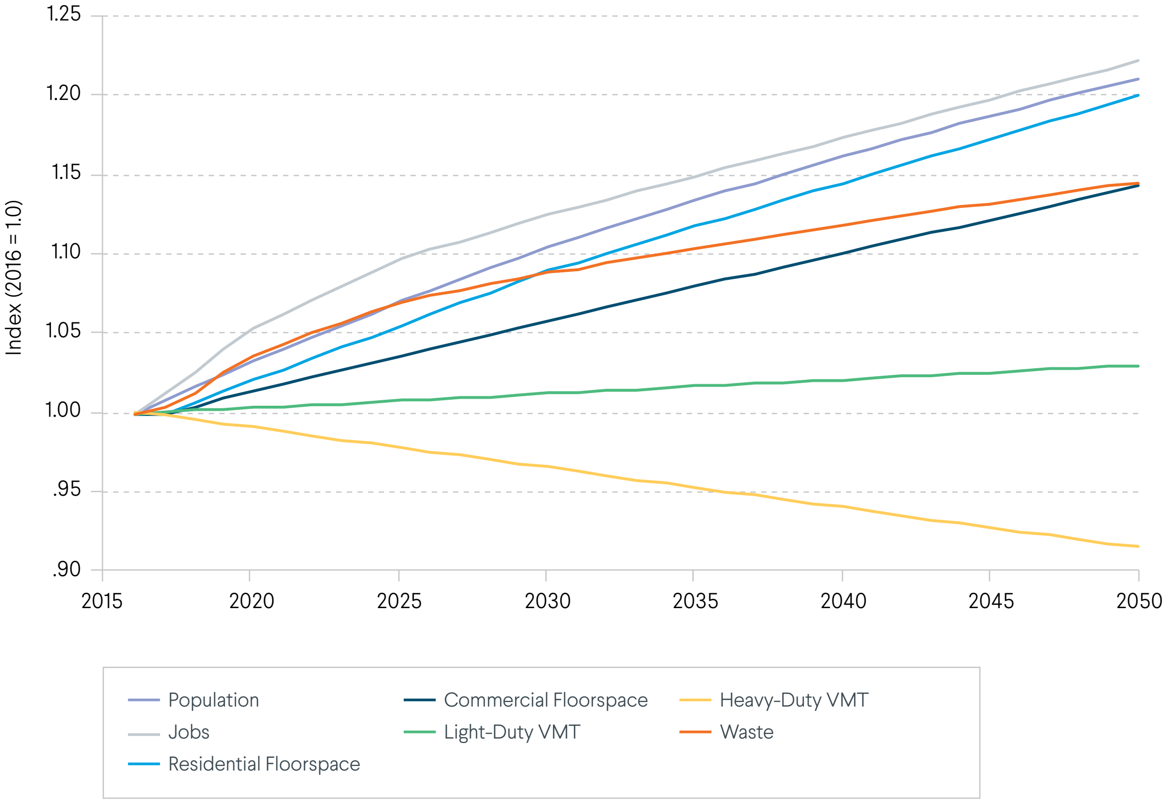
We derived growth forecasts (Figure 9) defining future population, building stock growth and transportation demand from the Metropolitan Area Planning Council's *2014 Regional Growth Projections, CTPS Charting Progress to 2040: A Long-Range Transportation Plan for the Boston Region,* and *Imagine Boston 2030* reports. Further detail on building stock and transportation systems were derived with guidance from the Boston Planning and Development Agency and projections from *Go Boston 2030.* Appendix B contains more detail on the data used in our analysis.

Electricity Supply

Electricity is used in buildings for lighting, cooling, heating, appliances and various plug loads. It will play an increasingly important role as heating systems depend more and more on electric heat pumps and automobiles, trains, and trucks are electrified. A key aspect of Boston's electricity supply is the GHG intensity of the regional electric grid. That intensity is measured as metric tons of CO_2e released per unit of electricity generated (t CO_2e/MWh). We assumed that the future GHG intensity of the electricity consumed in the city will meet the requirements of the Massachusetts Clean Energy Standard

Figure 9. Projections of Key Drivers in Carbon Free Boston

In a business as usual scenario, population growth, new buildings, and overall economic growth increases the demand for energy, thereby increasing GHG emissions. But the implementation of existing and new policies, emerging technologies, and behavioral change are potential counterweights to those forces. An index value of 1.0 signifies that a metric is expected to remain constant at 2016 levels over time, and higher (lower) index values mean that the metric grew (shrank) over time. VMT refers to vehicle miles traveled. Waste refers to the municipal solid waste generated by the residential and the commercial sectors. Sources: Metropolitan Area Planning Council's *2014 Regional Growth Projections, CTPS Charting Progress to 2040: A Long-Range Transportation Plan for the Boston Region,* and *Imagine Boston 2030.*

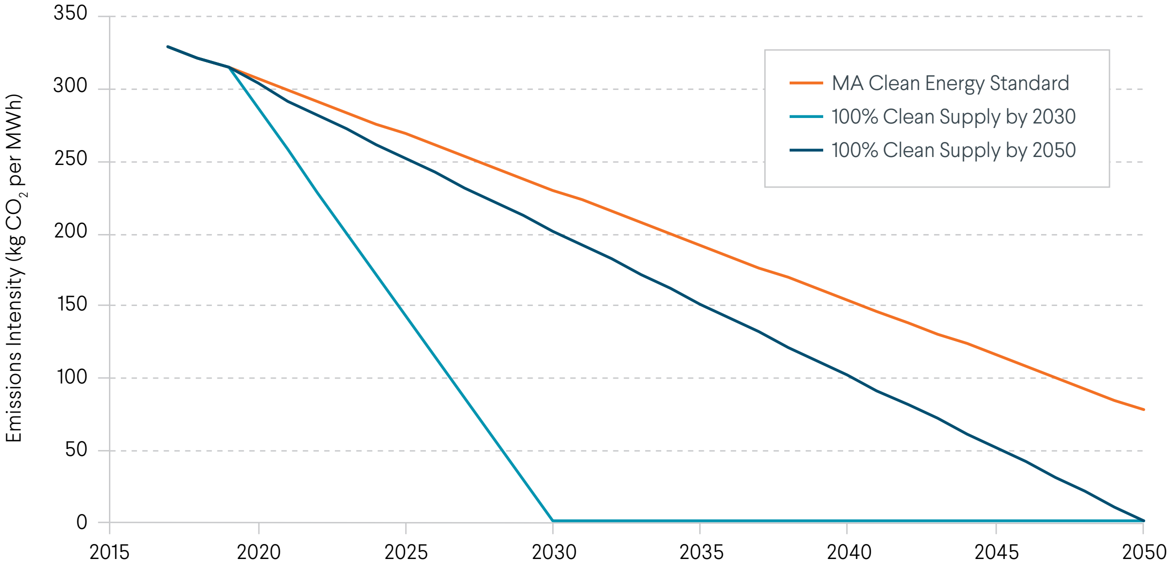


(CES), which requires that 80 percent of all electricity sold in Massachusetts be generated from low- to zero-carbon energy sources by 2050. The CES specifies a linear increase in the provision of clean energy use from current levels to the 2050 target, which, in turn, implies a linear decrease in the carbon intensity of electricity (Figure 10). We also assessed the effects of the procurement of zero-GHG electricity in quantities such that Boston's total supply (grid purchases plus procurement) is 100 percent zero-GHG by either 2030 or 2050.

The 2030 or 2050 endpoints are consistent with ongoing efforts in other states and cities. In May 2018, the City of Atlanta adopted a resolution to achieve 100 percent renewable electricity by 2035. Legislation in Washington, D.C., to attain 100 percent renewable energy by 2032 recently passed. Moreover, these alternative scenarios enable a comprehensive analysis of possible futures for Boston. While they are a high-level representation of generation technologies, legal requirements, distribution capabilities, and procurement strategies, they enable a comprehensive review of the impacts of demand-focused policies in the transportation and buildings sectors.

Figure 10. Carbon Emissions Intensity of Electricity Purchased by Boston

The orange line is the estimated intensity (kg CO_2e/MWh) that will occur under the Massachusetts Clean Energy Standard that requires that 80% of all electricity sold to Massachusetts customers to generated from renewable or clean sources by 2050. The two blue lines represent trajectories of electricity procurement by the City that achieve 100% GHG-free electricity by 2030 or by 2050. Source: Institute for Sustainable Energy model calculations.



Identifying the Pathways to Carbon Neutrality by 2050

Strategies to reduce GHG emissions across Boston's buildings, transportation, waste, and energy sectors can be combined in different ways to reduce emissions along a particular pathway. Each combination of strategies—and the specific actions to implement them—has a unique impact on emissions, cost, public health, social equity, and other aspects of life in the city. There is no single "best" pathway. We believe, based on the outcomes of our modeling and input from our advisory groups, that the pathway to carbon neutrality described in this report is a credible and proactive blueprint to inform the City's development of specific climate action policies.

The strategies and actions we included in this pathway do more than just reduce GHG emissions. We evaluated them to consider market readiness, job creation, equity outcomes, and the ability for the City and other stakeholders (e.g., the Commonwealth) to implement them. For example, we emphasize energy efficiency and electrification because most of the necessary technologies are available and cost-effective today, and the remaining enabling technologies are likely to become economical at scale before 2050. While there are still challenges related to costs, financing and implementation, we believe the solutions to them are within the span of control of the City, the Commonwealth, the business community, and other partnering organizations.

Clean Electricity in New England. Clean Energy projects in Maine such as the 42-megawatt Mars Hill wind farm help the New England electricity grid reduce its carbon intensity. Photo credit: National Renewable Energy Laboratory

Scenario Analysis

To form the pathway to carbon neutrality described in the subsequent chapters, we conducted a sequence of assessments for each sector:

1. Baseline

First, we defined a *baseline pathway* for future GHG emissions that incorporates the projected changes in energy consumption and energy efficiency caused by existing and planned action at the city, state, and federal level. These included the City's green building and large-building energy efficiency requirements, and federal vehicle fuel-efficiency standards. The baseline also included projections of future economic conditions and population growth in the city. Appendix B provides more detail on the baseline pathway.

2. New Action on Energy Efficiency (Current Grid)

We then assessed how additional, new action by the City can further reduce the demand for energy and improve energy efficiency as means to reduce GHG emissions, using the current (2017) GHG intensity of the regional grid.

3. New Electrification Action (Current Grid)

Next, we evaluated the impact of electrification of buildings and transportation under the current grid emissions intensity.

4. Massachusetts Clean Energy Standard

We then applied the efficiency and electrification strategies in (2) and (3) with the grid intensity that will exist in each year through 2050, assuming compliance with the state's clean power law. We separated this effect to illustrate the influence that this important state action has on Boston's energy decisions.

5. 100 Percent Clean Supply

Next, we assessed the impact of the purchase of a quantity of GHG-free electricity such that, when combined with the electricity purchased from the grid, Boston's total supply of electricity is effectively 100 percent free of GHGs.

6. Residual Emissions

Finally, we calculated and discussed a set of residual GHG emissions that remain after implementation of steps (2) through (5). Some uses of fossil fuels may be very difficult to eliminate, such as diesel fuel in heavy-duty transportation and emergency backup energy services, and natural gas used in district energy and heating in some buildings. Residual emissions from waste and wastewater treatment have no ready technological solution. In the Offsets chapter, we discuss how the City could address residual GHG emissions to reach carbon neutrality.

Photo credit: City of Boston

SECTION 3

Buildings

Background

Boston is known for its iconic historic buildings. These include the Paul Revere House in the North End, City Hall in Government Center, the Old South Meeting House in Downtown Crossing, the African Meeting House on Beacon Hill, 200 Clarendon (formerly the John Hancock Tower) in Back Bay, and the Museum of the National Center of Afro-American Artists in Roxbury. In total, there are more than 86,000 buildings in Boston, comprising more than 647 million square feet of area.

Boston's buildings are used for a diverse range of activities: homes, offices, hospitals, factories, laboratories, schools, public service, retail, hotels, restaurants, and convention space. These activities strongly influence energy use; for example, restaurants, hospitals, and laboratories have high energy demands compared with other commercial uses. Floorspace (square footage) is almost evenly split between residential and nonresidential uses, but residential buildings account for nearly 80,000 of the 86,000 buildings.

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. Today, Boston is in the midst of another boom in building construction that is transforming neighborhoods across the city.

The age of the building stock is important. Many residences were built before the 1950s and the establishment of the first building energy codes. These buildings typically have less insulation, are less airtight, and use older, inefficient equipment, all of which result in higher energy use and GHG emissions compared with newer buildings. Newer 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.

Achieving carbon neutrality will require Boston's buildings to be highly efficient and to move away from fossil fuel use for heating and other services. New buildings can 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. This transformation of the building stock will require a synergistic mix of regulatory requirements to drive performance, financial assistance to cover upfront costs where necessary, and workforce training to expand the labor force able to do this work. The design of these programs will need to ensure all communities have access to information, technical assistance, and financial resources. It will also need to prioritize the needs of Boston's socially vulnerable populations to ensure that they have the opportunity to accrue the benefits that residents of new, efficient buildings have; are able to receive energy efficiency retrofits to their homes that result in lower utility bills; and are not displaced by rising housing costs.

Old South Meeting House in Downtown Crossing, Boston. Photo credit: By Sean Pavone/Shutterstock

This chapter presents the results of a citywide building energy simulation to assess strategies, supported by a set of demonstrative policy actions, to achieve the goal of carbon-neutral buildings by 2050. It builds upon the work of the *Boston Community Energy Study's* exploration of Boston's building stock and the visioning process of *Imagine Boston 2030.*

Drivers of GHG Emissions

The GHG emissions from the use of electricity, heating oil, natural gas, and steam in Boston's buildings account for more than two-thirds of the city's total emissions. These emissions come mostly from the use of natural gas (41 percent), heating oil (10 percent), and electricity (47 percent).[11] Oil and natural gas are used primarily to produce space heat and hot water, while electricity is used primarily for cooling, lighting, and plug loads (Figure 11). The remaining GHG emissions (2 percent) is associated with steam imported from the Kendall Generation Station in Cambridge.

Baseline Scenario

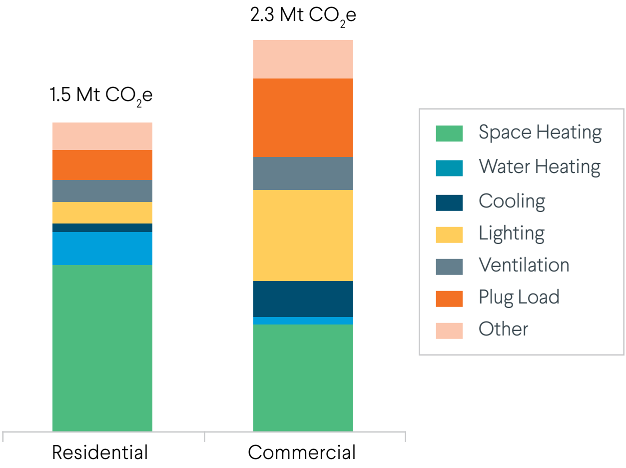
We developed a model to simulate building energy use across Boston and to test the impact of energy conservation and emissions reduction measures. This model employs representations of 15 typical building types across five age classes. Each individual building type energy model captures (i) the physical aspects of a building (insulation, infiltration); (ii) the demand for energy (heating, cooling, plug-load, lighting, etc.); (iii) how and when the building is used by its occupants; and (iv) the impact of weather on energy use. Figure 12 illustrates our estimates of GHG emissions by age and type of building.

By 2050, Boston's estimated population will be more than 800,000 people, and economic growth is expected to remain strong. This growth is projected to add approximately 77,500 new housing units and 40 million square feet of non-residential space by 2050. That increase in floorspace will increase energy use and GHG emissions. However, we assume the increase will be mitigated by a number of existing policies. Boston's green building zoning requirement and its Building Energy Reporting and Disclosure Ordinance (BERDO), along with the Massachusetts stretch energy code, is expected to produce energy efficiency improvements in both new and existing buildings. We also assume that the state building code steadily improves over the next 30 years and reaches net-zero energy performance in 2045. This means net emissions associated with new buildings are expected to be modest, especially in comparison to the current stock, but the opportunity remains for the City to accelerate the transition to net-zero performance.

The net result of these assumptions is reflected in the baseline scenario, in which GHG emissions from buildings remain relatively constant through 2050. The baseline includes the assumption that there is no change in the carbon intensity of the electricity purchased from the ISO New England electric grid ("the grid"). In this scenario, buildings built before 2018 contribute 93 percent of building GHG emissions in 2050.

Figure 11. Comparison of the Proportion of GHG Emissions from Residential and Commercial Buildings by End Use in 2015

Each bar represents 100% of the GHG emissions from the labeled building type. Source: Institute for Sustainable Energy model calculations.



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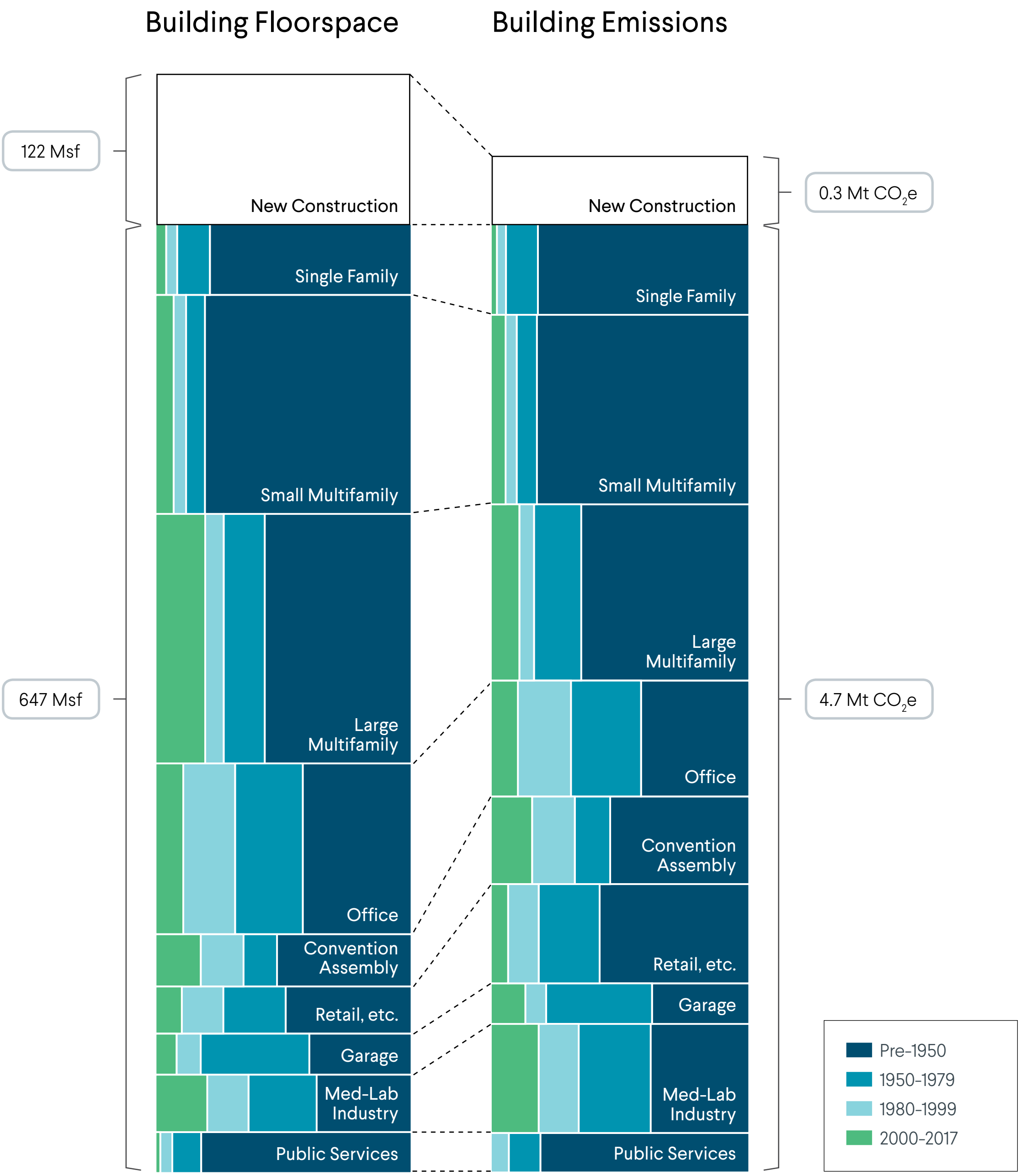
[11] The use of fuel oil declined by nearly one-half from 2005 to 2016 due to a shift to natural gas.

Figure 12. 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 (left bar) and emissions (right bar) by building use class (rows) and age class (colored blocks). The area of a block relative to the total area is proportional to the floorspace 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 now and 2050. Note that new buildings are significantly less GHG intensive than the existing stock, while Medical, Laboratory, Industrial Buildings are much more GHG intensive than the average building. Retail etc. includes retail stores, hotels, and restaurants. Public services include K-12 schools, fire, and police stations. Garage includes parking garages and warehouses. Sources: Boston Assessors Database and Institute for Sustainable Energy model calculations.



Strategies to Reduce GHG Emissions

Boston can make meaningful headway toward a carbon-neutral building stock with intentional and simultaneous action across three areas: (i) wide deployment of energy efficiency measures, especially deep energy retrofits; (ii) the replacement of natural gas and heating oil with electricity to the fullest extent practicable; and (iii) the establishment of strong performance standards for all buildings. While not commercially available today, renewable natural gas and hydrogen manufactured from renewable electricity may also have a future role to play in Boston's zero-GHG building energy supply.

Energy Efficiency

Energy efficiency is the cornerstone of any plan to produce carbon-neutral buildings. Energy conservation measures (ECMs) are actions that reduce the quantity of energy needed to deliver thermal comfort, illumination, and other building services. These actions include switching to efficient lighting and appliances, reducing air leaks, adding insulation, and optimizing performance of heating, ventilation, and air conditioning (HVAC) systems.

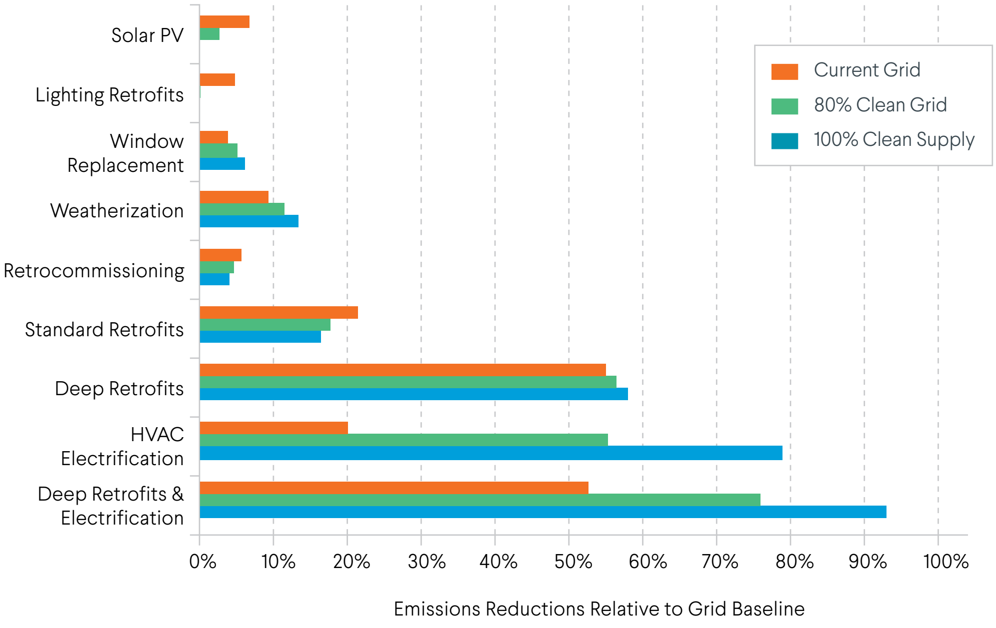
Many single-action ECMs have a short payback period, and if implemented citywide could reduce emissions by 2 to 6 percent (Figure 13). But alone they do not result in the reductions necessary to achieve carbon neutrality. Instead, building retrofits will need to include a larger, integrated combination of ECMs, which is most cost-effective through a whole-building, deep retrofit approach.

Deep Energy Retrofits

A building retrofit refers to the upgrading of the building envelope, heating and cooling systems, and other equipment and appliances. Retrofits can significantly decrease the GHG emissions from today's older, energy-inefficient buildings. A deep

Figure 13. GHG Reduction Potential of Energy Efficiency and Electrification

Potential citywide emission reductions associated with the application of energy conservation measures (ECMs) and electrification retrofit strategies across all existing buildings. Retrocommissioning, retrofits, and electrification involve multiple actions taken together. Emission savings are shown as a percentage of total building sector emissions in 2050 under three assumptions about the GHG intensity of electricity purchased from the regional grid: the intensity in 2016, the intensity associated with 80% zero-GHG sources, and the intensity associated with 100% zero-GHG sources. The longer the bar, the greater the emission savings potential. The impact of some measures diminishes as the grid becomes cleaner. Conversely, the impact of electrification increases as the grid becomes cleaner. Source: Institute for Sustainable Energy model calculations.



Residential Energy Efficiency. Insulation added to walls reduces heat loss and lowers energy bills. Photo credit: National Renewable Energy Laboratory

energy retrofit goes further and seeks to improve the building as a whole, and typically combines measures such as replacing equipment to more energy-efficient models, properly sizing equipment to building loads, air sealing, moisture management, controlled ventilation, insulation, and other measures that reduce energy use while producing optimal building performance. Typically, deep energy retrofits aim to achieve at least 50 percent reduction in energy use per square foot.

Our analysis indicates that by 2050, deep energy retrofits in typical buildings in Boston have the potential to reduce citywide energy use by 30 to 40 percent using existing technologies. Less aggressive, or standard, retrofit packages yield emission reductions in energy use of at least 20 percent (Figure 13).[12] Deep energy retrofits create greater energy and monetary savings; however, they have historically been regarded as expensive and disruptive. New design solutions and technologies are reducing both the upfront cost and the impact on building inhabitants. Costs will likely continue decline as the market for deep energy retrofits and their associated technologies mature. The City can help accelerate this market transformation through citywide retrofit programs, supported by a large mobilization of trained labor, local manufacturing of retrofit materials, and access to capital.

Electrification

Energy-efficient buildings reduce emissions and improve quality of life. But if those buildings use heating oil and natural gas, efficiency alone will not get Boston's building stock to carbon neutrality. A second strategy must be combined with efficiency: the clean and efficient electrification of building energy services.

There are two forms of building thermal electrification. The conventional approach uses electricity to directly generate heat in a boiler or a radiant heater. Alternatively, building electrification can rely on heat pumps that use electricity to move heat from one location (e.g., outdoor air or ground) to another (the indoor building space). Unlike the conventional approach, heat pumps are very efficient and can reduce GHG emissions by more than 50 percent under a low-carbon grid compared with a natural gas system. But heat pumps have several constraints. First, they require space outdoors for heat exchangers, limiting their potential where outdoor space (e.g., rooftops) is constrained. Second, as temperatures drop, they become less efficient, and at very low temperatures (-5°F) they can cease to operate. As a result, the full electrification of some non-residential buildings will require a mix of heat pumps and electric boilers, which increases the demand for electricity.

The potential of electrification via heat pumps as a GHG reduction measure depends on several forces. First, like ECMs, the GHG benefits from electrification are highly dependent on the carbon intensity of the grid. 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 GHG benefits grow as the grid becomes cleaner. Second, as noted above, heat pump efficiency can drop considerably in very cold weather, which raises energy use (and possibly emissions, depending on the energy source). In addition, during very cold periods the current grid is forced to rely on oil-based peak generation plants, which further increases the carbon intensity of electricity used for heating. Finally, 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.

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[12] Energy storage technologies save generated energy and use it when demand is high. Energy storage includes electric systems such as batteries as well as thermal systems such as hot- and cold-water storage tanks. Energy storage can enhance the technical and economic viability of generation from renewable sources, and it can operate critical systems during grid outages.

Figure 14. Equity Scorecard: Retrofit and Electrify Existing Buildings

Components	Evaluation
Is it green?	
Is it GHG-free?	**Depends:** Delivers net-zero emission buildings over time when paired with 100% clean energy policies
Is it environmentally sustainable?	**Yes:** Enhances energy efficiency of buildings every year; reduces emissions associated with fuel combustion and harmful co-pollutants caused by fuel combustion
Does it promote smart behavior?	**Depends:** With intentional design, energy efficiency measures and electrification can facilitate integration with grid and shave peak demand; smart thermostats, appliances, and building design, together with behavioral changes, can reduce and improve building energy use, and give owners and occupants more control over their space
Is it fair?	
Is it accessible?	**Depends:** Deep reductions in energy use and electrification of thermal services may not be accessible to all; pairing this policy with subsidies, tax credits or rebates as well as strategic communications a broad and accessible strategic communications strategy to address cultural and language differences offer a partial solution
Is it affordable?	**Depends:** While electrification of thermal services and deep reductions in energy use lower energy costs and customer bills, associated capital costs may not be affordable to all, even with financing mechanisms; pairing this policy with exemption options, public funding, and additional renter protections offers a partial solution
Are workforce opportunities just?	**Depends:** Opportunities for substantial local, diverse workforce development depend on policy design; careful planning will be necessary to identify training opportunities that expand this workforce beyond those with existing technical qualifications
Who gets to decide?	
Is it inclusive?	**Depends:** Opportunities for inclusive decision making with intentional planning and prioritization; decision-making processes need to include renters as well as property owners
Are values considered?	**Depends:** Opportunities for values-based decision making with intentional planning and prioritization
Is it measurable?	**Depends:** Easy measurement for energy usage, dollars, number of furnaces and boilers replaced, number of buildings addressed; more difficult for community and workforce impacts

Carbon Free Boston's strategy to retrofit and electrify buildings addresses the City's largest source of GHG emissions and will, over time, guarantee a GHG-free building stock if electricity is produced from 100% GHG-free sources. Retrofits of Boston's existing buildings can alleviate existing sources of inequity by giving owners and occupants more control over their space and comfort, and by improving building energy use, which will lower energy costs and customer bills. Most importantly, deep retrofits can improve health outcomes for at-risk populations. Building upgrades present an opportunity to facilitate a fair and just workforce by ensuring that diverse local workers and contractors are trained and hired. Careful planning will be necessary to identify training opportunities that expand this workforce beyond those with existing technical qualifications. Building retrofits may exacerbate existing inequities if these programs are designed without adequate financing mechanisms, public funding, exemptions, renter protections, and any other necessary protections to ensure that benefits and costs are justly distributed among City residents.

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. This will moderate the costs and impacts of electrifying heating. We return to this point in the Energy chapter.

High-Performance New Buildings

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 standards, including net-zero or net-positive,[13] will result in fewer emissions and prevent the need for future retrofits in these buildings. While the Commonwealth sets building code standards, Boston can work with state agencies to advance the energy code at triennial revisions and introduce net-zero stretch energy code options. The City could also enact carbon emission performance standards through the zoning code, including phasing in net-zero emissions requirements starting with residential multifamily low-rise buildings.

Either way, timing is a key driver of the magnitude of emission reductions in new buildings. For example, the implementation of a net-zero policy for all new buildings in 2030 reduces cumulative emissions by 17 percent (Figure 15). 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 the carbon-neutral target.

Renewable Fuels

Renewable natural gas, also known as biomethane, is methane gas manufactured from biological sources that is fully interchangeable with conventional natural gas. Renewable natural gas can be distributed to buildings via the existing gas pipeline network and used with existing equipment (gas

Boston Skyline from Malone Park. Photo credit: Riptor3000/English Wikimedia Commons

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[13] A net-zero emission building uses energy ultra-efficiently and meets any remaining energy needs from renewable sources. A net-zero energy building differs only in that the renewable generation must occur on-site. Going even further, a net-positive building generates more renewable energy than needed for its operations.

stoves, furnaces, and hot water heaters). But biological feedstocks have low energy densities and are highly dispersed, which currently restricts biomethane production primarily to anaerobic digesters at wastewater treatment plants and the capture of methane from landfills. The potential to expand the sources and conversion pathways for biomethane is an area of active research.

Hydrogen has zero-GHG emissions at the point of combustion and can be manufactured with extremely low lifecycle GHGs with wind or solar electricity to drive electrolysis (splitting water into hydrogen and oxygen). There is little utility-scale hydrogen delivery infrastructure anywhere in the world, but like biomethane, this is an area of active research.

Should renewable natural gas or hydrogen become commercially available at a utility scale, the City will have another option in addition to electrification to power its buildings. In the interim, the limited supply of renewable natural gas and the costs of hydrogen technologies may constrain their expansion to district energy co-generation systems that have the capacity to maximize fuel-use efficiency and economies of scale. We return to these topics in the Energy chapter.

Figure 15. Reducing GHG Emissions in New Buildings

Early action to reduce GHG emissions yields a large reduction in 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%. A net-zero buildings policy instituted in 2023 will reduce cumulative emissions through 2050 by 42%. Source: Institute for Sustainable Energy model calculations.

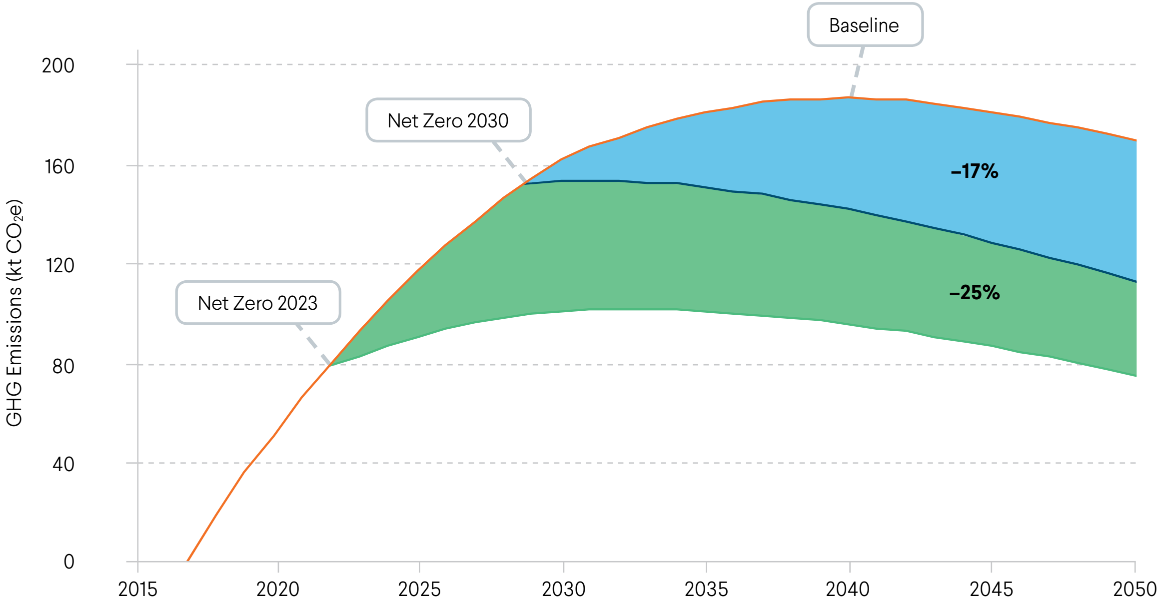


Figure 16. Equity Scorecard: Zero GHG New Construction

Components	Evaluation
Is it green?	
Is it GHG-free?	**Yes:** Delivers net-zero emission buildings
Is it environmentally sustainable?	**Yes:** Net-zero buildings use energy more efficiently while avoiding emissions associated with fuel combustion and electric generation
Does it promote smart behavior?	**Yes:** While not an explicit goal, net-zero building design facilitates "smart" buildings technology and better integration with grid
Is it fair?	
Is it accessible?	**Depends:** Net-zero buildings may not be accessible to all; pairing this policy with subsidies, tax credits or rebates as well as strategic communications designed to address cultural and language differences offer a partial solution; careful planning will be necessary to avoid displacement of each neighborhood's existing residents
Is it affordable?	**Depends:** Net-zero buildings entail lower energy costs but depending on building type and timing, may not be always be affordable to purchase, rent, or build; intentional planning and financial support may be required to ensure affordability
Are workforce opportunities just?	**Depends:** Opportunities for substantial local, diverse workforce development depend on policy design; careful planning will be necessary to identify training opportunities that expand this workforce beyond those with existing technical qualifications
Who gets to decide?	
Is it inclusive?	**Depends:** Opportunities for inclusive decision making with intentional planning and prioritization
Are values considered?	**Depends:** Opportunities for values-based decision making with intentional planning and prioritization
Is it measurable?	**Depends:** Easy measurement for number of net-zero buildings and building energy use; more difficult for community and workforce impacts

As Boston continues to grow, ensuring all Bostonians have access to affordable housing is an ongoing challenge. The construction of new residential buildings has the potential to improve access and affordability, reduce the need for GHG-intensive commutes, and if designed to be GHG-free, can limit the emissions associated with growth. Lower energy use by new buildings lowers long-term costs for residents, and better designed buildings improve health outcomes for at-risk populations. New building construction is an opportunity to expand the workforce in a manner that benefits socially vulnerable populations. Careful planning will be necessary to identify training opportunities that expand this workforce beyond those with existing technical qualifications.

New growth tends to be less accessible to low-income communities. Zero-GHG buildings may unintentionally exacerbate this challenge. Incorporating inclusionary policies in new construction can limit these impacts. To ensure that implementation is fair and just policy choices must be made with input from those most affected and deliberate action taken for inclusive decision making at each step in the process.

The Path to Carbon-Neutral Buildings

The elimination of GHGs from Boston's buildings sector requires the deployment of actions that support a suite of synergistic strategies: net-zero emission new buildings, deep energy retrofits, the electrification of building energy systems, and the procurement of GHG-free electricity (Figures 17 and 18) along with the complementary programs to address upfront costs, workforce development, and related market and equity considerations.

Maximum energy efficiency is the foundation of a carbon-neutral building stock. In addition to ensuring all new construction is designed to meet high performance standards, carbon neutrality will require, on average, deep energy retrofits to between 2,000 and 3,000 buildings each year. In tandem with the deep energy retrofits, the path to carbon neutrality includes the electrification of space heating, cooking and hot water production. To ensure that building electrification does not lead to increases in GHG emissions, it should be pursued with efficient heat pump technologies for space heating and hot water, not electric boilers and electric resistance heating.

If GHG intensity of the grid declines 80 percent by 2050 as required by the Massachusetts Clean Energy Standard, electrification of heating will result in a 30 percent reduction in GHG emissions from buildings when combined with deep energy retrofits. The integration of battery and thermal storage into deep efficiency and electrification strategies further improves performance by reducing the need to turn on inefficient peak generator plants that use fossil fuels. Going one step further, if the City procures enough renewable electricity to yield a

Figure 17. 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 GHG-free 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. Requirements for deep efficiency performance (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 are defined by their goal of 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: Institute for Sustainable Energy model calculations.

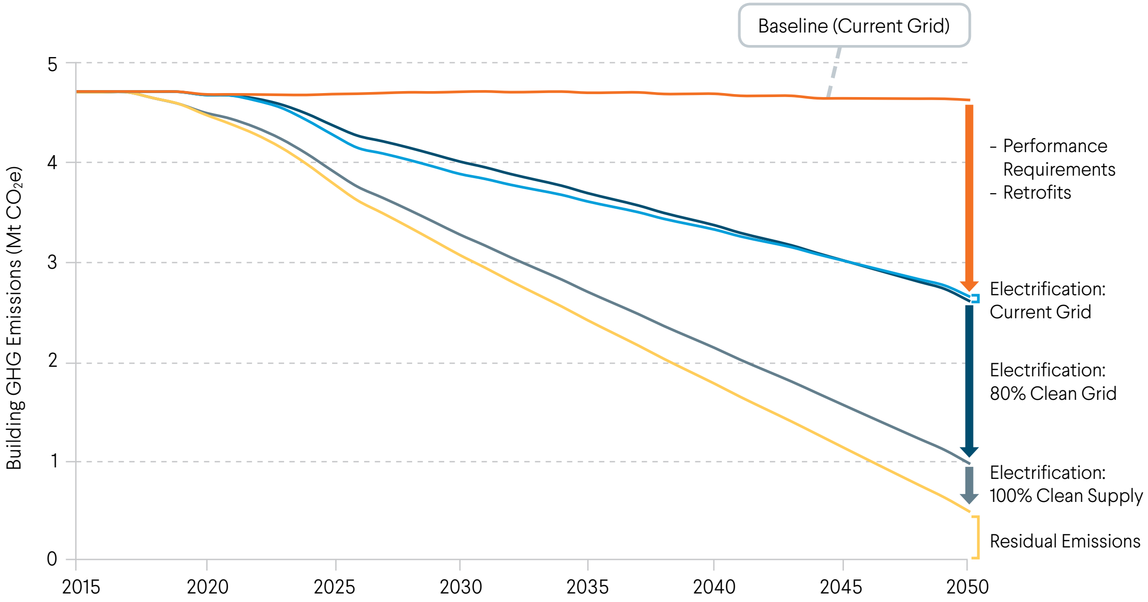
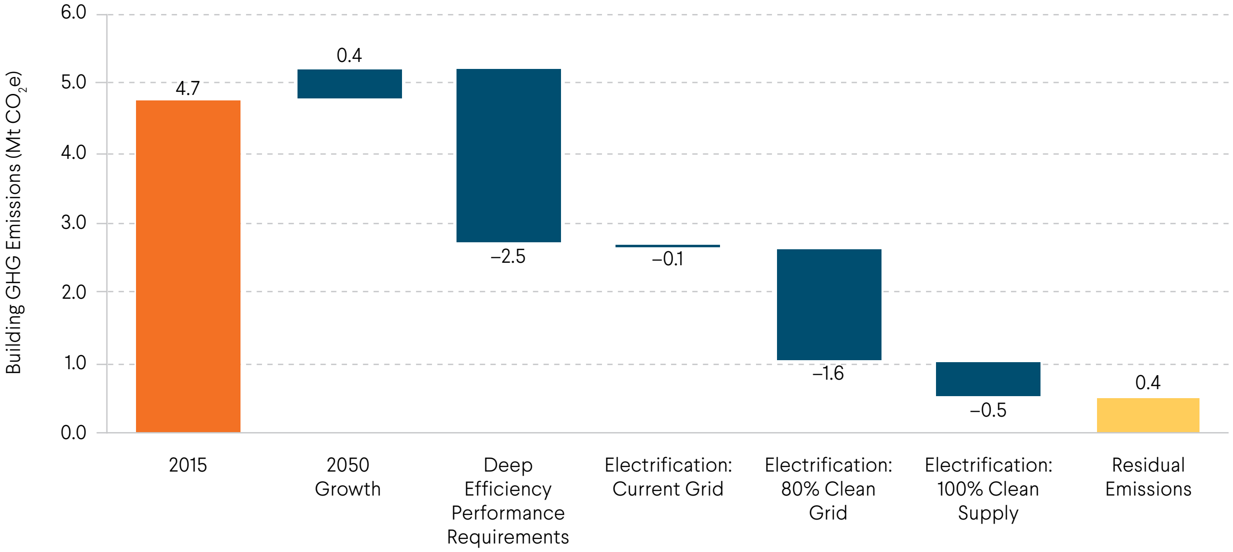


Figure 18. The Steps to Carbon Neutrality in Boston's Buildings

The steps reflect the GHG reduction potential of specific consecutive actions starting from today's conditions. Source: Institute for Sustainable Energy model calculations.



100 percent GHG-free supply of electricity, GHG emissions are reduced by an additional 9 percent in 2050, and fully electrified buildings become carbon neutral.

Residual emissions will likely remain in the building sector in part due to heating systems that use fossil fuels and are currently too costly or impossible to electrify. These include back-up energy systems in hospitals, district heating systems, some cooking, and large hot water heating systems. In some cases, historical preservation goals may preclude efficiency and electrification measures. Such activities could be fueled by renewable natural gas or hydrogen if they become available. Residual emissions ultimately may require the purchase of carbon offsets. We explore offset options in the Offsets chapter.

Boston skyline. Photo credit: City of Boston

The Cost of GHG Reduction in Buildings

In Figure 19, the cost-effectiveness of measures to reduce GHG emissions is represented by a marginal abatement cost (MAC) curve. A MAC curve is a convenient tool that measures the impact of a measure in emissions abatement potential and economic terms (\$/t CO_2e), 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 19 assume current industry best practice for replacement of equipment at the end of its normal life span or in conjunction with a major renovation project.

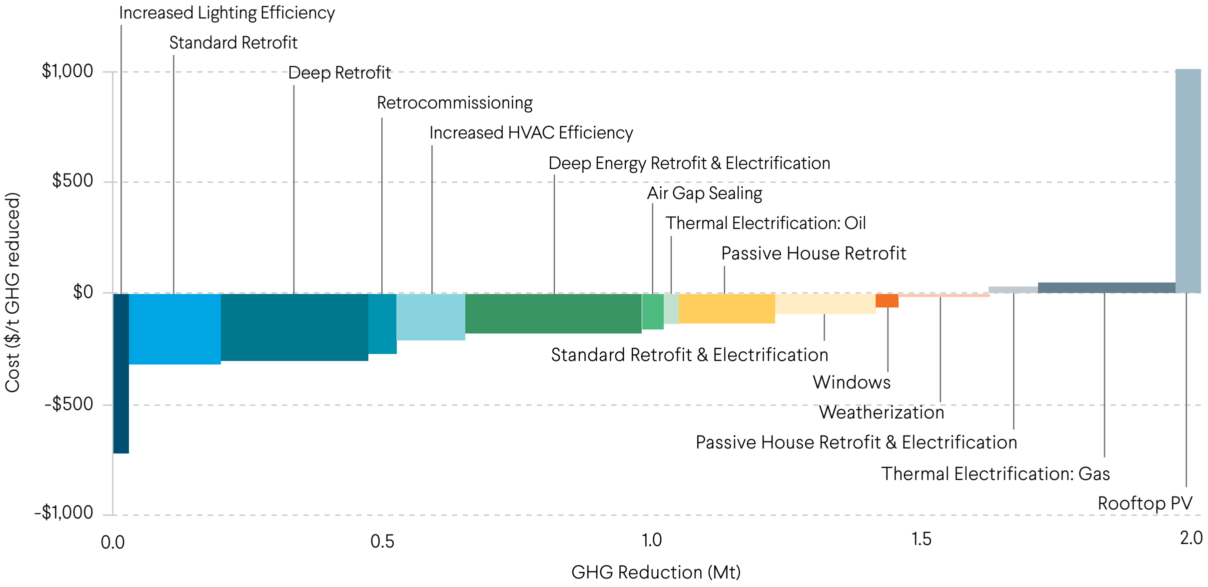
Retrofits yield large reductions in GHG emissions over the lifetime of the equipment installed. Cumulatively over this period, most decarbonization building strategies have negative costs—this means that the dollar value of energy saved is greater than the cost of implementation. In effect, most energy conservation measures pay for themselves. But they do not all achieve the same level of emission reductions. For example, individual measures that are readily available to households and businesses such as the installation of energy efficient lighting and weatherization unequivocally save energy and reduce utility bills and emissions, but they yield small GHG reductions. Conversely, over the lifetime of the equipment (about 20 years), a deep retrofit project is 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 further increases the GHG reduction compared with a retrofit alone. These results demonstrate that energy efficiency and electrification are complementary strategies when they are implemented in tandem.

Benefits and Opportunities of Carbon-Neutral Buildings

In addition to the GHG benefit, energy-efficient buildings powered by clean fuels and electricity do far more than reduce emissions (Table 1). Improving energy efficiency in buildings creates conditions that support improved health and well-being for occupants. The reduction in use of heating

Figure 19. Marginal Abatement Cost 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 CO_2e). 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: Institute for Sustainable Energy model calculations, ASHRE & DOE Advanced Energy Design Guides, One City: Built to Last (NYC).



oil and natural gas reduce local air pollution that translates to improved public health. Energy-efficient buildings also have better thermal quality and less mold caused by dampness. Positive health outcomes from better air quality and thermal comfort are consistently strongest among vulnerable groups, including children, the elderly, and those with pre-existing illnesses.

Energy-efficient buildings have lower energy costs. The city-wide cost of energy in 2050 could decline by an estimated $600 million, providing a particularly important benefit to low-income households for whom energy costs comprise a larger fraction of their budget. Lower energy costs increase disposable income that in turn stimulates the regional economy. The thousands of retrofits required for Boston to achieve carbon neutrality will also result in job creation and will increase the asset value of both renter- and owner-occupied buildings.

Deep energy retrofits make living and workspaces more resilient. Boston's older building stock was not designed for the warmer temperatures that the city will likely experience in the coming years. Ensuring that buildings stay cool will save lives. In areas prone to flooding, existing homes can simultaneously be made more resilient by moving critical equipment out of risk-prone basements.

Table 1. Benefits of Carbon-Neutral Buildings in 2050

Benefit Category	Magnitude/ Nature of Benefit
Cost of energy to consumer	$600 million in savings in 2050*
Atmospheric emissions of particulate matter and nitrogen oxides from energy combustion	75% reduction in 2050*
Thermal comfort	Increase in average winter-time indoor temperature; improved relative humidity
Indoor air quality	Lower infiltration of allergens, pest, and moisture; less mold caused by dampness
Impact on regional economy	Increase in disposable income, jobs, and building asset value
Climate resiliency	Retrofits can be coupled with design to reduce risks of flooding and thermal stress

* Results from Institute for Sustainable Energy model calculations in buildings sector

Solar roofs can leverage unused building space to generate renewable electricity. Photo credit: City of Boston

Actions to Support This Pathway

Energy retrofits and clean electrification can generate numerous benefits, but action is needed to realize those benefits. Policies are needed to address a number of market, financial, and social equity-related challenges. These include limited knowledge by building owners, managers, occupants, and contractors about the benefits of energy efficiency; the need to grow the workforce of trained and experienced energy efficiency professionals; and improvements to the supply chain to improve access to these technologies. Other challenges include the real and perceived disruptions to households and businesses during implementation, and the upfront financial costs and—for many building owners—access to capital to pay for the retrofits. Specific policy actions to address these considerations will need to prioritize the needs of socially vulnerable populations, ensuring they have access to the benefits of these measures (e.g., lower utility costs and job opportunities) and are not displaced by increased housing costs.

Performance Standards and Mandates

The results of our analysis and the experience of other cities indicate that energy and emissions-based performance standards for all buildings are the most effective measures for achieving the scale of change required. Voluntary programs alone will not result in sufficient uptake. Performance standards can target energy use or GHG emissions; the latter is more consistent with achieving a carbon-neutral building stock in 2050. We evaluated two variants of performance mandates. One type of mandates sets a timetable for a

The Roxbury E+ project consists of four three-story wood-frame homes built as part of the City of Boston's Energy Plus (E+) Green Building Program. The housing development at 226-232 Highland Street consists of four three-bedroom townhomes in Boston's Roxbury neighborhood. Photo credit: City of Boston performance target. Such mandates can be highly effective in larger and lower-performing buildings, which often have the greatest potential for emissions reduction. Alternatively, a performance target can be triggered when a building undergoes a major renovation, property sale, or lease. This approach connects emissions reduction with an action that already triggers regulatory review (e.g., permitting). Such actions typically coincide with financing cycles, and limit the potential disruption to occupants. In our pathway to 2050 for buildings (Figure 17), we modeled this approach by assuming that three percent of Boston's buildings undergo a deep energy retrofit with electrification each year.

In some cases, limited prescriptive mandates may be required to eliminate the use of fossil fuels where clean fuels or systems that use electricity are available. For example, banning the use of heating oil reduces GHG emissions in the building sector by 8 percent in 2050, and delivers air quality benefits.

The City has a history of leadership in implementing high performance building requirements. Boston was the first city in the nation to deploy a green building standard through municipal zoning requirements. The Building Energy Reporting and Disclosure Ordinance (BERDO) provides a strong foundation for expanded building performance standards. Every five years, buildings that do not meet performance levels necessary to be certified as highly efficient must demonstrate a 15 percent reduction in building energy use or GHGs, or undergo an audit. BERDO currently covers approximately 2,000 large commercial and large multifamily residential buildings, nearly half of the built environment in the city. Performance standards ensure that buildings make steady progress on emissions reductions and give flexibility to building owners to develop solutions that are cost effective and specific to the occupational needs of the buildings. The design of any mandate will need to consider, and ideally prioritize, the needs of socially vulnerable populations.

Enabling Actions

Performance mandates will need to be paired with programs that support their compliance, specifically for buildings with low- and moderate- income owners and tenants. This includes financial mechanisms that mitigate the burden of upfront and financing costs, targeted communication strategies that clarify the objectives and details of the mandate, and educational programs to build the necessary workforce.

A residential air source heat pump. Photo credit: user Kristoferb/Wikipedia

Incentive-based energy efficiency programs have an important supporting role in the path to carbon-neutral buildings by 2050. Programs such as *Mass Save* and *Renew Boston* offer incentives to implement energy conservation measures such as lighting replacement, efficient appliance upgrades and weatherization. Our analysis of these prescriptive incentives found that while they can reduce emissions and save money, their limited impact and program penetration is insufficient to attain the deep carbon reductions necessary for the City to achieve its goal of carbon neutrality. Despite this limitation, these, and similar programs do provide solid benefits and can be used to support the implementation of performance standards and as vehicles to educate building owners and occupants about energy savings.

The deep retrofit of 2,000 to 3,000 buildings a year will require a large and experienced workforce trained in expanded vocational and technical programs. New forms of project financing will be needed to provide the upfront capital necessary for deep retrofits and enable building owners to realize future energy cost savings, health improvements, and better comfort. Education is essential to overcome a formidable knowledge barrier. Many owners, managers, and occupants are unaware of the availability and benefits of energy efficiency programs.

New tools, approaches, partnerships, and institutional capacity will be necessary to implement the scope of work required and ensure all Bostonians have access to the informational, technical, and financial resources that are required to realize the potential of energy efficiency.

The City also has a role to play in fostering market development to support implementation. Besides leading by example with its own municipal buildings, 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.

Across Boston, building owners are stepping forward. 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. At this site, Boston Properties, the building's owner, aims for a 45 percent reduction in emissions by 2025. Boston University recently committed to achieving carbon neutrality by 2040 with an anticipated one-third of emission reductions coming from building energy-efficiency measures. Boston's top 75 property owners account for one-fifth of the city's total GHG emissions. Leadership and early commitments to carbon neutrality by a few major property owners can demonstrate that decarbonization is feasible. First-movers can help mature the market, pave the way and reduce costs for others to act, and otherwise accelerate progress.

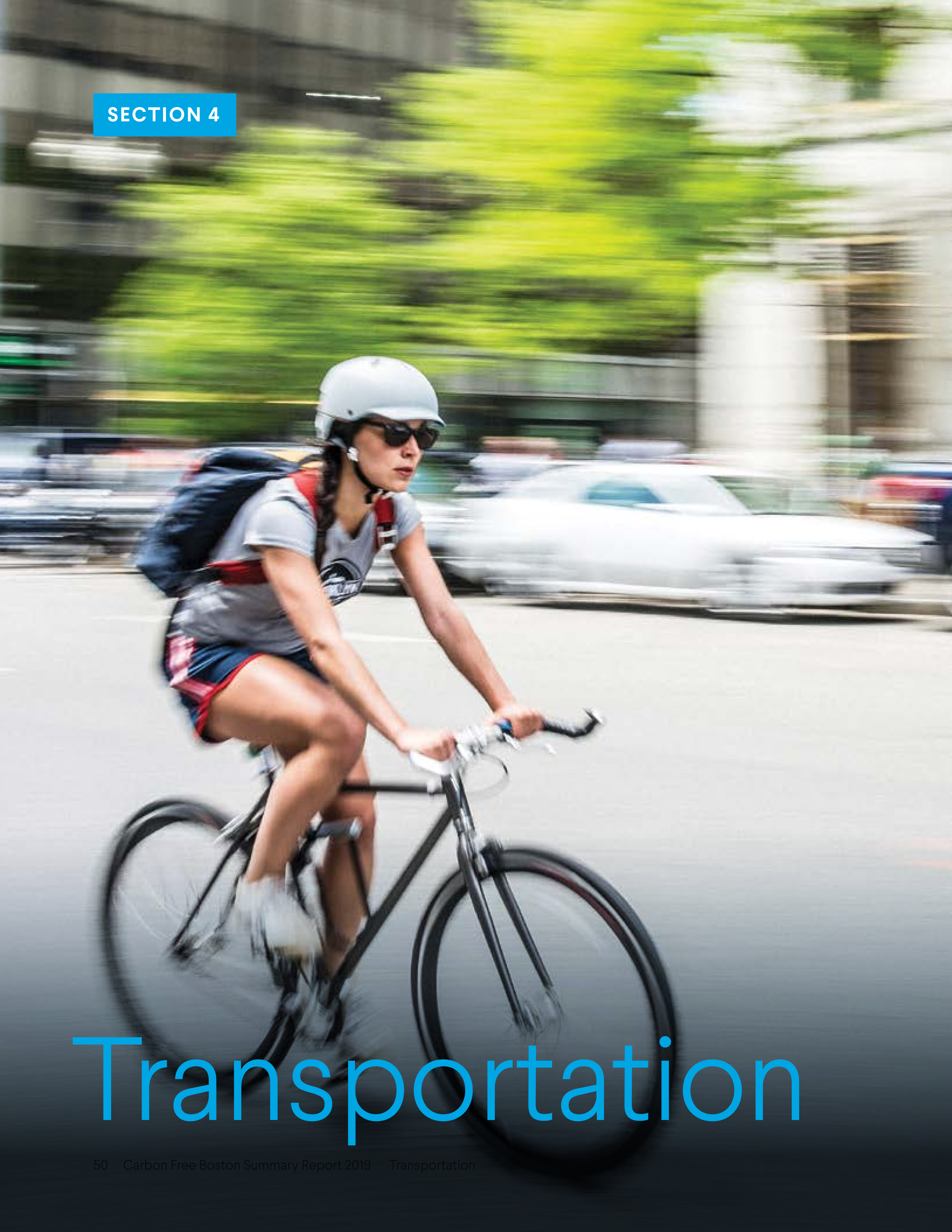
The Williams Building in Downtown Boston houses the General Services Administration Building. Photo credit: City of Boston

Shaping the Future of Boston's Buildings

To reach carbon neutrality by 2050, nearly every building in Boston will need to undergo retrofits that holistically and dramatically reduce energy consumption. The use of efficient and zero-GHG electric technologies, and possibly zero-GHG renewable fuels if they become widely available, will need to replace the use of natural gas and fuel oil for heating and hot water. To implement these changes, building owners, managers, operators, occupants, and contractors will require educational, technical, and financial assistance to make informed decisions. This includes data on energy use, financial assistance programs, easy-to-understand regulatory processes, community support, regional collaboration, and training. Support for vulnerable populations will need to be prioritized to ensure access to the benefits of deep energy retrofits and building electrification, and minimization of financial risks.

The transformation of Boston's buildings will fuel change across every aspect of life in the city. A citywide, comprehensive approach to deep energy retrofits and building electrification will save money for households, businesses, and institutions, while making Boston a global hub of the sustainable building industry with a massive opportunity for entrepreneurship and workforce development.

A thermal image of a home shows the intensity of heat released from the surface of the home. The yellow and orange areas indicate areas of greater heat loss. Energy auditors and inspectors use these images to detect areas of a building that are not well insulated. Photo credit: Avalon/Construction Photography/Alamy Stock Photo



SECTION 4

Transportation

Background

Transportation connects Boston's workers, residents and tourists to their livelihoods, health care, education, recreation, culture, and other aspects of life quality. In cities, transit access is a critical factor determining upward mobility. Yet many urban transportation systems, including Boston's, underserve some populations along one or more of those dimensions. Boston has the opportunity and means to expand mobility access to all residents, and at the same time reduce GHG emissions from transportation. This requires the transformation of the automobile-centric system that is fueled predominantly by gasoline and diesel fuel. The near elimination of fossil fuels—combined with more transit, walking, and biking—will curtail air pollution and crashes, thus dramatically reducing the public health impact of transportation. The City embarks on this transition from a position of strength. Boston is consistently ranked as one of the most walkable and bikeable cities in the nation, and one in three commuters already take public transportation.

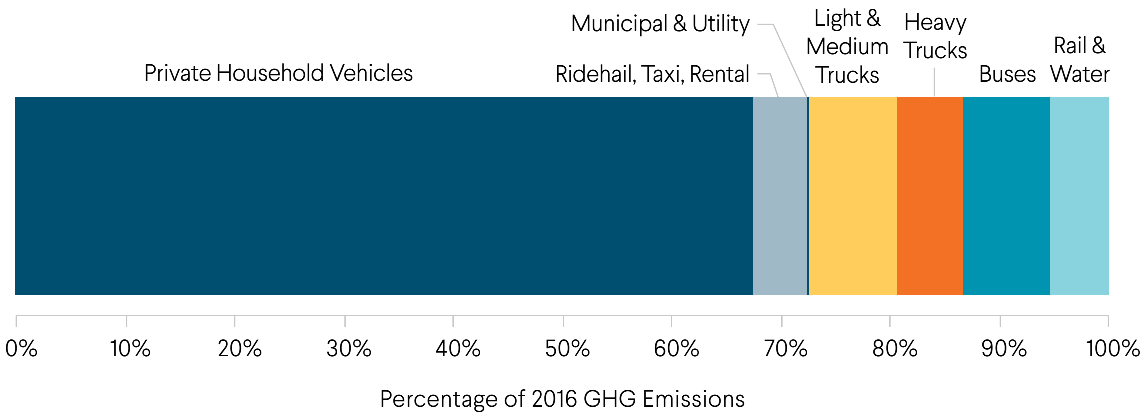
There are three general strategies to reaching a carbon-neutral transportation system:

- Shift trips out of automobiles to transit, biking, and walking;
- Reduce automobile trips via land use planning that encourages denser development and affordable housing in transit-rich neighborhoods;
- Shift most automobiles, trucks, buses, and trains to zero-GHG electricity.

Even with Boston's strong transit foundation, a carbon-neutral transportation system requires a wholesale change in Boston's transportation culture. Success depends on the intelligent adoption of new technologies, influencing behavior with strong, equitable, and clearly articulated planning and investment, and effective collaboration with state and regional partners.

Figure 20. Transportation Emissions by Mode of Travel in 2016

Rail refers to the MBTA commuter and subway lines. Water refers to MBTA water ferries. Source: Institute for Sustainable Energy model calculations.



Drivers of GHG Emissions

During the peak hour of a typical morning commute, about 400,000 people head to destinations across Boston. The GHG emissions associated with commuting, and trips made for other purposes, are determined by several factors: total vehicle activity (vehicle-miles traveled, or VMT), the mode of travel (cars, public transportation, bikes, walking), the fuel efficiency of vehicles (miles per gallon equivalent), and the GHG intensity of fuels used.

Vehicles traveling in and out of Boston currently emit about 2 Mt CO_2e emissions annually, representing 29 percent of the total city emissions. Three-quarters of transportation-related emissions come from private passenger vehicles, with 15 percent from trucks and 10 percent from transit buses (Figure 20). The dominance of passenger vehicles suggests two obvious routes to carbon neutrality: reduce trips in passenger vehicles by converting those trips to other modes of transport, and convert vehicles to zero-GHG electricity.

The geography of travel is an important element of this challenge. Most of Boston's transportation GHG emissions are from trips that start or end outside the city. In fact, less than one-quarter of transportation GHGs are generated by trips that start *and* end in Boston. An additional quarter comes from within the I-95 beltway, with most of the remaining emissions from trips to or from communities between I-95 and I-495 (Figure 21).

The geography of the GHG emissions from the region's transportation system is important for several reasons. Households in outlying communities generate significantly more transportation GHG emissions than households in Boston due to longer trip distances and few non-driving options (Figure 22). Longer trips are predominantly made in private vehicles powered by internal combustion engines that burn gasoline or diesel fuel. Closer to the city center, trip distance shrinks and more trips are made by walking, biking, or public transit, modes that release far smaller quantities of GHGs per trip, if any.

Heavy rush hour traffic on the Zakim Bridge into Boston. Photo credit: Michael Dwyer/Alamy Stock Photo

Figure 21. Transportation GHG Emissions by Region in 2016

Sources: Institute for Sustainable Energy model calculations and Central Transportation Planning Service.

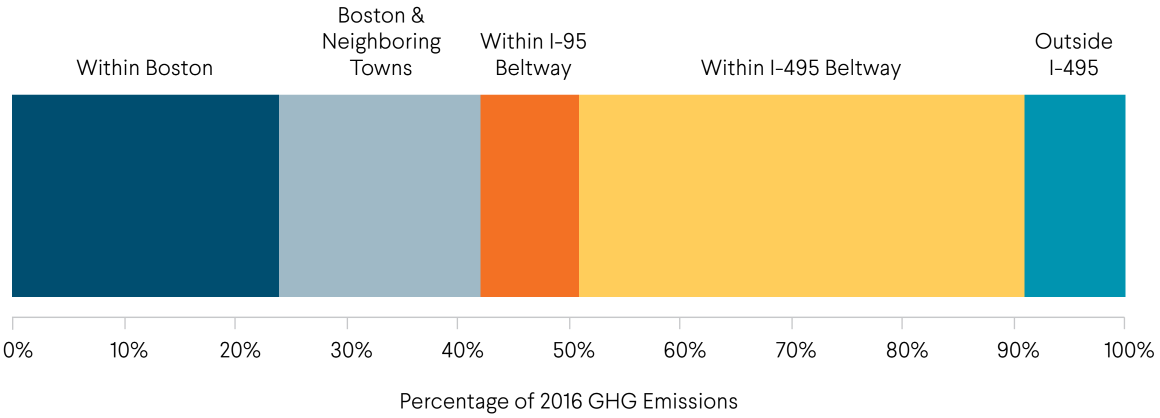
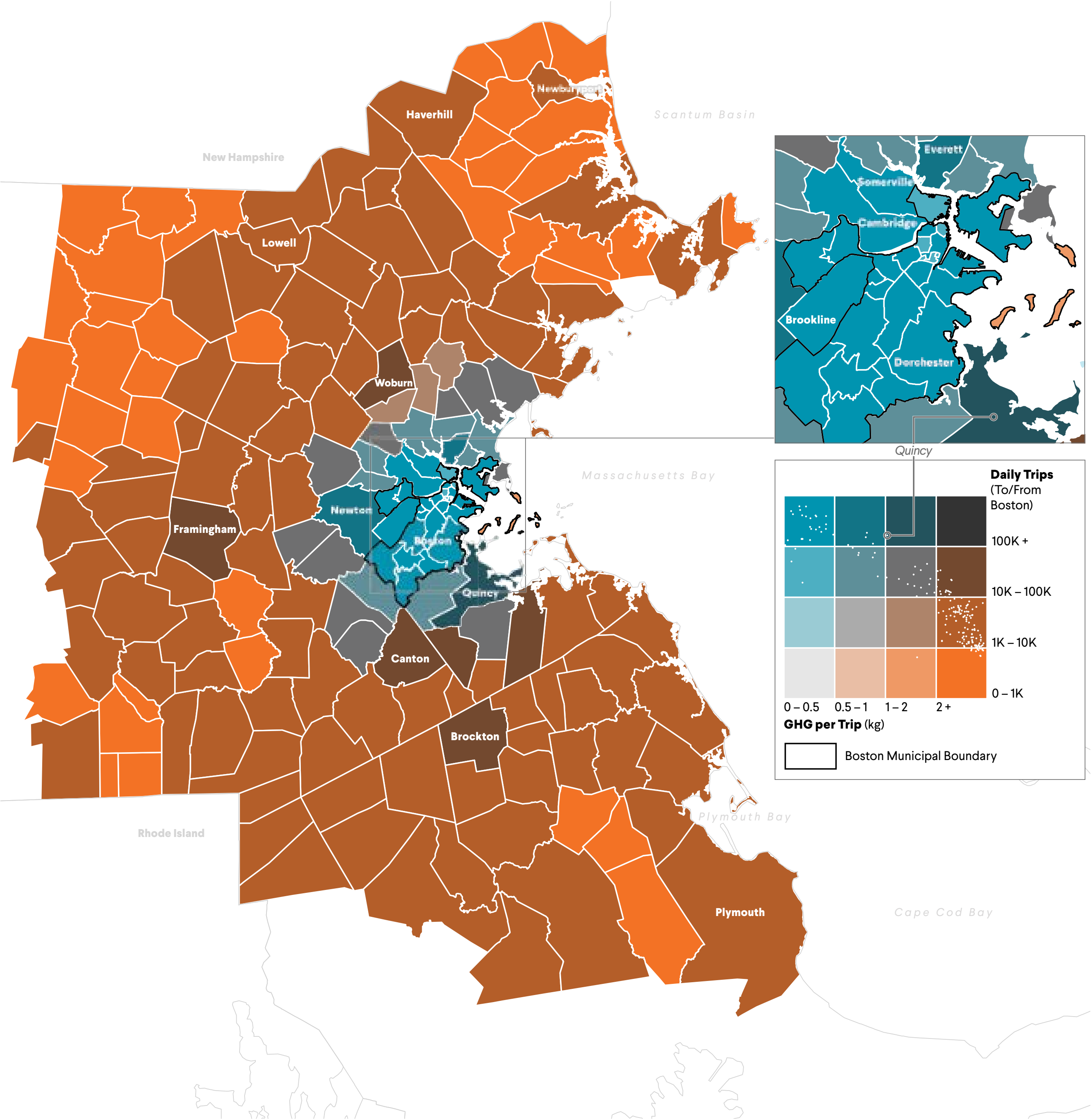


Figure 22. Trips and GHG Emissions in 2016

Map: This map depicts the relationship among three factors: the number trips made to/from Boston, the GHG released per trip, and the distance from Boston. A color represents two dimensions: the number of trips that start or end in Boston, and the quantity of GHG released per trip. The blue inner core has a greater number of trips, but much lower GHGs per trip compared with outer regions. **Inset Graph:** The vertical axis is the average number of daily trips to/from Boston; the horizontal axis is the GHG released per trip. Source: Institute for Sustainable Energy model calculations and Central Transportation Planning Service.



Baseline Scenario

To understand what it takes to have a carbon-neutral transportation system, we developed a model to assess strategies and actions that encourage mode shifts and reduce energy use and emissions. Our model accounts for projected growth in population, employment, and transportation activity in the city, changes in government regulations regarding emissions, and assumptions about the adoption of EVs. As described in the previous chapter, Boston's population and economy are expected to continue to grow in the coming decades. Vehicle-miles of travel (VMT) are expected to hold steady, despite increasing jobs and population, as growth is projected to occur mainly in centrally located, transit-rich neighborhoods. On its own, the VMT trend would hold emissions at current levels. But there are additional positive trends: the fuel efficiency of internal combustion engine vehicles is projected to increase due to federal fuel efficiency standards, there will be a modest shift toward active modes of transport (biking and walking), and the GHG intensity of electricity from the ISO-New England grid is expected to decline. The emissions intensity of the grid becomes more important as EVs gain a foothold in the vehicle fleet.

Our analysis indicates that the net effect of these forces is a 40 percent decline in transportation GHG emissions from 2016 to 2050, largely due to more fuel-efficient internal combustion engine vehicles. This reduction is insufficient to meet Boston's carbon-neutrality goal. The baseline scenario indicates that in 2050, private, on-road vehicles powered by gasoline and diesel fuel accounts for 68 percent of GHGs. Decisive action is needed to shift people out of automobiles, and power the remaining vehicles with zero-GHG electricity.

The MBTA Green Line at Park Street station. Photo credit: MBTA

Strategies to Reduce GHG Emissions

Shift Trips to Transit and Active Transport

An essential element of a carbon-neutral transportation strategy is the shift of people out of private, single-occupant automobiles because public transit, walking, and biking release far smaller quantities of GHGs compared with automobiles (Figure 23), if any. Boston is the hub of one of the most traffic-congested regions in the U.S., so moving people out of automobiles will waste less fuel, reduce air pollution, and make streets less crowded, less stressful, cleaner, quieter, and safer. We identified a combination of actions that together would shift 20 to 30 percent of trips out of single-occupant vehicles into less GHG-intensive modes of transportation.

Expand and Improve Biking

We evaluated the impact of a fourfold expansion of Boston's bike network. This expansion will attract more riders with protected lanes and improved connectivity that make riding safer, less stressful, and more efficient. This includes expansion of the bike network targeting the wide swaths of Dorchester, Mattapan, and other areas that lack protected bike lanes to connect residents to adjoining neighborhoods and to facilitate commutes into Downtown.

Expand and Improve Walking

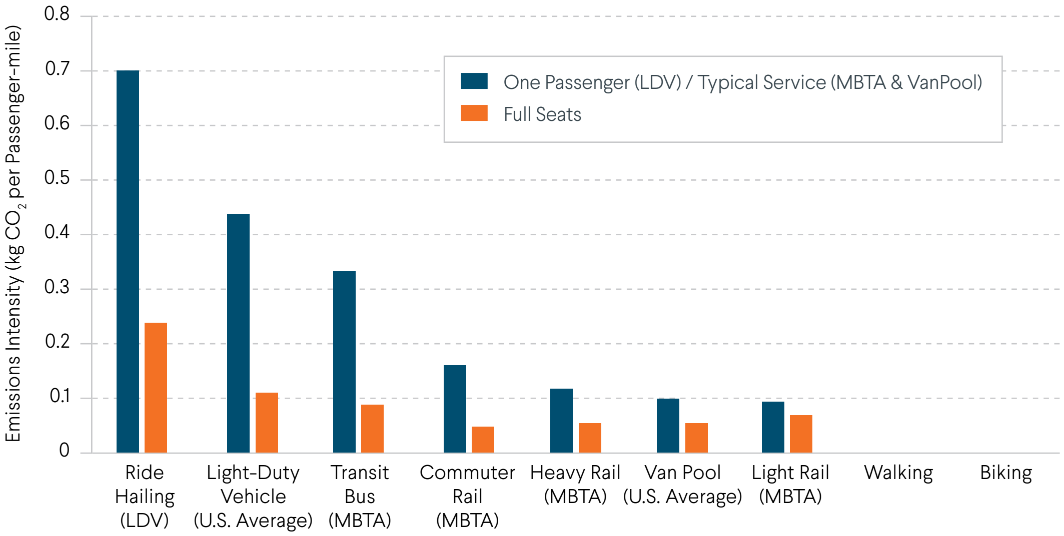
Go Boston 2030 calls for a 50 percent increase in walking as a commuting mode for Bostonians. Walking increases as connectivity improves and sidewalks are repaved and repaired quickly and responsively. Pedestrians are also more likely to walk when they feel safe walking on sidewalks and crossing streets, which is particularly an issue during and after snow events, at rush hour, and in places where vehicle traffic dominates the speed and design of intersections and roadways.

Expand and Improve Public Transportation

Go Boston 2030 proposes a fivefold increase in rapid bus miles and a 25 percent increase in new urban rail. This expansion will improve ridership and reduce inequities if it connects the growing, transit-dependent neighborhoods of Dorchester,

Figure 23. GHG Intensity of Transportation Modes

Transportation modes have very different impacts on emissions of GHGs. Emissions from light-duty vehicles (LDV) are based on the national average fuel economy for the in-use fleet of all light-duty vehicles (cars, SUVs, and pick-up trucks). Ride hailing assumes a deadhead factor of 1.6. "Full seats" = 3 passengers for ride hailing, four passengers for typical LDV use, and full capacity for other modes. In Boston, heavy rail refers the Red, Orange and Blue lines, and light rail refers to the Green line. Sources: Data from U.S. Department of Transportation, Federal Transit Administration, *Public Transportation's Role in Responding to Climate Change (2010)*, with updated 2017 ISO-New England grid GHG emissions factor.



Mattapan, and Hyde Park, to the Seaport, and the Longwood medical areas, where job growth is strong. Careful planning based on inclusive decision making combined with iterative evaluation and adjustment is needed to make a meaningful, long-lasting effect on the distribution of transit resources in Boston.

Free and Reduced-Cost Public Transportation

We evaluated the effect of providing free public transit for those that walk or bike to a bus, subway, or commuter rail station, and a 50 percent reduced fare for those that drive to a commuter rail or ferry station. This strategy not only encourages the overall use of public transportation, it particularly benefits low-income households and encourages the combination of active transport with bus and rail.

Private Vehicle Pricing

We evaluated the impacts on travel, mode choice, and GHG emissions of the following pricing strategies:

- **Congestion (Cordon) Fee:** A $5 charge for every trip made in a private vehicle that starts or ends within a zone that rings Downtown, Back Bay, the Seaport, and the Longwood medical areas (Figure 24). This amounts to $10 to $15 per day to drive within the congestion area, depending on the number of trips made. This fee is at the high end of the range of congestion fees in other major cities in the world.[14]
- **Parking Fee:** A $5 parking fee placed on every trip made into Boston that ends at a location other than a personal residence. This fee could be collected by a public or private entity.
- **VMT Fee:** A $0.20 fee charge for every mile traveled in the city in a private vehicle. We assume that this is a statewide policy and that the charge would be levied and collected by the Commonwealth.
    - Ride-hailing Cross-Subsidy: A $1 per mile fee imposed on ride-alone trips using ride hailing or an autonomous vehicle, and a $1 per mile subsidy for shared-ride trips.

Road pricing strategies such as congestion and VMT fees serve multiple purposes: they reduce congestion at peak travel periods; they reduce fuel use, air pollution, and crashes; they open space for biking and walking; they shorten travel times and improve the delivery of emergency services; they improve workforce productivity; they generate revenue that can be used in a variety of ways for public works projects, such as bus, rail and bicycle travel; they can finance transport for low-income households; and they help cities meet their GHG reduction targets.

Smart mobility options such as ride-hailing services are rapidly transforming transportation, and emerging technologies such as autonomous vehicles and electric scooters will also have dramatic impacts that are not fully understood. Currently, about 1 out of 25 trips ending in Boston uses ride hailing; this share is expected to increase steadily. Evidence from major cities in the U.S. indicates that, in an unregulated environment, ride hailing increases VMT and GHG emissions.

Figure 24. Modeled Congestion Zone

Congestion pricing refers to charging a fee to enter or drive within a congested area. We evaluated the effects of a $5 fee placed on every trip made in a private vehicle within the zone depicted here. The area of the assessed cordon covers 4.4 square miles and approximately 100,000 residents. For comparison, London's congestion fee covers 8 square miles and 136,000 residents. Source: Institute for Sustainable Energy.

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[14] The average driver in the proposed congestion zone in Boston currently makes an estimated 2.3 trips per day. The congestion charge in London is $14.50 each day for each non-exempt vehicle that travels within the cordon zone. The charge in Stockholm is between $1.70 and $3.90 per entry to or exit from the cordon zone. The charge in Milan is between $2.26 and $5.65 per entry into the cordon zone. The charge in Singapore is between $1.45 and $11.00 per entry into the cordon zone.

Street markings and signs with the white-on-red C alert drivers in London that they are entering the congestion charge zone. Photo credit: Mariordo/ Wikimedia Commons

The impact of autonomous vehicles is speculative at this point. They could reduce energy use and GHG emissions by improving the efficiency of traffic flow, reducing the time spent hunting for parking, and by decreasing the importance of vehicle performance. Countervailing effects include the increased demand for travel, more “empty miles” traveled (no passengers), and shifts away from walking, biking, and transit. Many transportation planners expect that shared autonomous vehicles will reduce vehicle ownership but increase travel per vehicle. Total VMTs increase under this scenario in an unregulated environment. Thus, these new mobility options will reduce GHG emissions only if they are used mainly by multiple occupants and if they rely on clean vehicle technology. It will also help to have single-occupancy ride-hailing and autonomous vehicle trips subsidize shared-ride trips, which we assessed through a cross subsidy of shared-ride trips.

Figure 25. Equity Scorecard: Invest and Improve Public Transit

Components	Evaluation
Is it green?	
Is it GHG-free?	**Yes:** Operational improvements and free/reduced-price transit lowers emissions, even more so when transit electrification is done with GHG-free electricity
Is it environmentally sustainable?	**Yes:** Public transit is more energy efficient than travel by private vehicle
Does it promote smart behavior?	**Yes:** Encourages a large-scale transition to mass transit, reducing the length of commutes and road congestion
Is it fair?	
Is it accessible?	**Depends:** New, free, and reduced-price transit reduce obstacles to accessibility; operational and infrastructure improvements have the potential to greatly increase transit accessibility depending on decisions made regarding type and location of investments
Is it affordable?	**Depends:** New, free, and reduced-price transit are more affordable for low-income communities; New investment in public transit may impact public budgets. Pairing with policies that generate revenue (e.g., private travel pricing) can limit this impact
Are workforce opportunities just?	**Depends:** Opportunities for diverse new workforce and contractors depend on policy design
Who gets to decide?	
Is it inclusive?	**Depends:** Opportunities for inclusive decision making with intentional planning and prioritization
Are values considered?	**Depends:** Opportunities for values-based decision making with intentional planning and prioritization
Is it measurable?	**Depends:** Easy measurement for trips, dollars; more difficult for community and workforce impacts

Carbon Free Boston's strategy to build new transit infrastructure, improve existing transit infrastructure, and offer free and reduced-price access to public transit will lower GHG emissions, especially if electricity is produced from GHG-free sources. Higher-quality and lower-cost transit will profoundly enhance equity if widely accessible. Transit upgrades should prioritize the "transit poor" areas that now exist in parts of several SVP communities. The construction of new infrastructure presents an opportunity to facilitate a fair and just workforce by ensuring that diverse local workers and contractors are trained and hired. This strategy has the potential to exacerbate existing inequalities if decisions regarding the type and location of investments are made without specific attention to accessibility, affordability, and inclusive decision making.

Compact Land Use and Reducing the Demand for Travel

The future demand for travel in Boston will be determined in part by the proximity of population growth to public transit and walking. The City can increase transit mode share by directing future population growth into areas that are centrally located, walkable, and transit-rich. This includes all or parts of Downtown, Mission Hill, South Boston, Roxbury, Back Bay, Allston, the South End, the Seaport, and the Longwood medical areas. Our analysis integrated this opportunity by assuming that three-quarters of population growth through 2050 will occur in these areas compared with the anticipated 30 percent of citywide population growth expected in these neighborhoods.

Employers can reduce the number of trips their employees take by offering them more opportunities and economic incentives for teleworking and compressed work schedules. These are two of the most popular transportation demand management strategies for reducing motor vehicle travel and fuel consumption. In our model, we assumed that transportation demand management strategies increase their market penetration by 20 percent compared with the Baseline.

In our analysis, the combined effects of the increased investment in transit, walking and biking; economic incentives to use transit, drive less, and share private vehicles; and compact land use and stronger travel demand management result in large changes in mode shares by 2050 (Table 2). Many trips now taken by private automobiles would be made by bus, rail, bike, and walking. Private vehicle trips would be far more likely to be shared with others. The streets of Boston would be less crowded with expected total vehicle travel dropping by one-third.

Bicycle commuting. Photo credit: City of Boston

Table 2. Daily Person Trips Made in Boston in 2050

Mode	Baseline	Pathway to 2050 Scenario	Percentage Change
Private Vehicles	2,010,145	853,748	-58%
Shared Mobility	79,899	884,065	+1,006%
Transit	470,680	672,406	+43%
Walking & Biking	973,448	1,079,763	+11%
Total Person Trips	**3,534,172**	**3,489,983**	**-1%**
Cumulative VMT to/from Boston			**-33%**
Auto Ownership in Boston			**-45%**
Auto Ownership Outside Boston			**-30%**

GHG-Free Electric Vehicles

Carbon-neutrality requires that all vehicles making trips in Boston release no GHGs. One plausible strategy to accomplish this is to use EVs powered by zero-GHG electricity. We reflect this by assuming that (i) advances in EV technology enable 100 percent of light- and medium-duty vehicles to be powered by electricity in 2050, including all autonomous vehicles and shared mobility services, and (ii) that 100 percent of trips beginning or ending in Boston in light- and medium-duty vehicles in 2050 are made in EVs.

While we assume that the economic and technical viability of EVs will rapidly improve, we do not explicitly represent how full electrification happens in Boston. The Carbon Free Boston Technical Report includes a more detailed discussion of the options available to the City to encourage the use of zero-GHG electric vehicles. The deployment of one of these options alone will not be sufficient to accelerate market transformation toward EVs in an equitable and cost-effective way. Instead, a comprehensive suite of actions to address each of its market barriers will result in faster, broader EV adoption. For example, Oslo, Norway deployed policies to make EVs relatively less expensive to purchase compared with internal combustion engine vehicles, less expensive to operate, easier to drive to and around the city, and easier to park. To address equity concerns, Oslo is subsidizing EV charging readiness in affordable, multifamily residential buildings, among other programs. While the design of Oslo's specific policies may not be appropriate for Boston, the market results they have achieved demonstrate the benefits of comprehensive approach.

One specific policy option to consider as part of a comprehensive package follows the leads of London, Los Angeles, Paris, Mexico City, Seattle, Copenhagen, Barcelona, Vancouver, Milan, Quito, Cape Town, Auckland, and other cities who proposed, or are considering, a complete ban on all or some types of internal combustion engine vehicles that burn gasoline or diesel fuel. From a GHG perspective, a ban on internal combustion engine vehicles has the desirable effect of eliminating vehicle emissions by the date the ban goes into effect, and it is a relatively low cost to the City. A ban requires lead time sufficient to allow vehicle turnover that does not impose unreasonable costs on owners, and to enable the installation of sufficient charging infrastructure. Social equity concerns could be addressed via rebates to low-income car owners or by providing improved alternative transit options.

Electric Vehicle Charging. Photo credit: Dennis Schroder, National Renewable Energy Laboratory

Boston already has an EV policy that requires 5 percent of parking be equipped with EV charges and an additional 10 percent be EV-ready in new construction projects and all projects in certain areas of South Boston and Downtown. However, roughly half of the car owners in the city do not control their parking space (e.g., renters and street parkers). Therefore, public EV infrastructure is a critical, albeit challenging, component of the city's EV charging network. Street parking spaces, sidewalks, and electrical infrastructure will need to be reallocated to dedicated EV spaces and chargers. Support infrastructure may be difficult to install in historic neighborhoods with narrow streets and sidewalks. Installation of EV infrastructure could "lock-in" parking and make it difficult to reallocate that space in the future to bike lanes, bus lanes, shared mobility services, expanded sidewalks or greenways. Early experimental piloting of EV support infrastructure can help provide insights on the best allocation of public resources and methods of implementation to ensure the widest possible public acceptance, while maintaining other community priorities for this space.

The transition to EVs raises equity concerns. In the absence of subsidies, early adopters of EVs are likely to be wealthier due to the current high cost of EVs relative to conventional vehicles. The City could implement a targeted subsidy for EV adoption—together with zero- and low-interest financing—and intentional investment in public infrastructure in low-income neighborhoods and near business districts with minority-owned businesses. The City could also accelerate investment in transit infrastructure and facilitate equitable shared mobility services to compensate for residents who may be priced out of the early EV transition.

Figure 26. Equity Scorecard: Electric Vehicles

Components	Evaluation
Is it green?	
Is it GHG-free?	**Depends:** EVs reduce GHG emissions; when paired with 100% GHG-free energy they reach zero emissions
Is it environmentally sustainable?	**Yes:** Electric vehicles use energy more efficiently than internal combustion-engine vehicles and reduce tailpipe emissions and other harmful pollutants
Does it promote smart behavior?	**Depends:** Smart timing of EV charging can store energy and stabilize the grid. Dedication of public space to charging stations needs intentional design to ensure access and must balance competing demands for space
Is it fair?	
Is it accessible?	**Depends:** Banning fossil-fuel based transport limits access for anyone relying on these vehicles; careful policy design is needed to ensure that socially vulnerable communities are not left out of this transition. Public charging must be available to all communities
Is it affordable?	**Depends:** Purchase price of EVs is higher than conventional vehicles, but operating costs are lower. Electrification of transit and fleet vehicles may impact their affordability. Intentional planning and financial support may be required to ensure affordability
Are workforce opportunities just?	**Depends:** Opportunities for diverse workforce development depend on policy design
Who gets to decide?	
Is it inclusive?	**Depends:** Opportunities for inclusive decision making with intentional planning and prioritization. Decisions regarding public charging infrastructure need to include people beyond drivers and car owners as EVs will impact the urban landscape and may come at the cost of other curb-use options
Are values considered?	**Depends:** Opportunities for values-based decision making with intentional planning and prioritization
Is it measurable?	**Depends:** Easy measurement for infrastructure changes, EV adoption, dollars spent; more difficult for community and workforce impacts

Carbon Free Boston's strategy to electrify most vehicles is major step toward carbon neutrality. EVs have the potential to alleviate existing inequity by making vehicles with lower operating costs more available. However, EVs currently are more expensive than internal combustion engine vehicles, so action is required to make them affordable for low-income households. Charging infrastructure should be available to all Bostonians, but it should not lock out the reallocation of curb space to non-automotive uses in order to better serve communities. Action should include equitable access to shared mobility services that use EVs. To ensure that implementation is fair and just policy choices must be made with input from those most affected and deliberate action taken for inclusive decision making at each step in the process.

Table 3. Strategies to Reduce GHG Emissions in Transportation

STRATEGY	MODEL SCENARIO ASSUMPTIONS
SHIFT MODES	
Citywide bike lane network	250 new miles of protected bike facilities, covering entire City with routes spaced a half-mile apart
Go Boston walking improvements	Walk and bike friendly main streets; *Vision Zero* priority corridors and safe crossings
Go Boston transit operational improvements	Improve speed and reliability
Go Boston transit infrastructure	42 new miles rapid bus & 35 new miles urban rail
Free/reduced cost transit	Free for walk-access transit, including rapid transit and local bus 50% fee reduction for drive-access commuter rail and ferry
Private vehicle pricing	
Smart mobility	$1 per mile increase for ride-alone $1 per mile decrease for shared-ride
Parking fee	$5 /trip ending in non-home location in Boston
Cordon fee	$5 per modeled trip ($10 to $15 per day) within cordon
VMT fee	$0.20 per mile for all vehicle trips
REDUCE DEMAND FOR TRIPS	
Compact land use	75% of future population growth in transit-rich, walkable, and centrally located neighborhoods
Travel demand management (TDM)	20% increase in TDM market penetration
ELECTRIFY VEHICLES	
Electrify transit and fleet vehicles	Early action on buses and fleet vehicles Upgrade commuter rail when feasible
Expand charging infrastructure	Strategically install infrastructure that avoids prioritizing EVs over other uses of the urban landscape
Prohibit fossil-fuel based transport	100% of trips in light-/medium-duty vehicles

Path to Carbon Neutrality in Transportation

Transportation GHG emissions rise relative to the baseline if ride-alone smart mobility and autonomous vehicles are not discouraged ("Unmanaged Smart Mobility") because their lower cost in time and money encourages people to travel more. In the baseline scenario with current policies, GHG emissions decline by 44 percent, largely due to improvements in vehicle fuel efficiency (Figures 27 and 28). Implementation of all mode shift strategies (pricing and investments in transit and active transport), TDM, and denser development combine to reduce emissions by 22 percent compared with the baseline.

With the current GHG intensity of the ISO-NE grid, the electrification of all light- and medium-duty vehicles, rail, and bus transport reduce emissions by 29 percent by 2050 relative to the baseline. The large impact of electrification is due to the fact that an EV is three times more efficient than an internal combustion engine vehicle in the conversion of energy into motion.

The GHG intensity of electricity exerts very strong influence on the effectiveness of electrification as a strategy to reduce GHG emissions. The Massachusetts Clean Energy Standard requires clean energy sources to provide 80 percent of electricity in 2050. That change alone would reduce transportation emissions by 32 percent by 2050, roughly equal to the combined effects of demand reduction plus vehicle electrification. With City procurement of 100 percent clean electricity, GHG emissions by 2050 are reduced by an additional 9 percent.

After the implementation of all of these strategies, about 102 kt CO_2e in 2050 remain as "residual emissions." This results from our assumption that the heavy-duty truck, intercity bus, and ferry sectors will be electrified at a much slower rate than light- and medium-duty vehicles, and thus continue to use fuels that release GHGs. A carbon-neutral transportation sector in 2050 would require some combination of two strategies to address residual emissions: the consumption of new types of zero-carbon fuels, or the purchase of carbon offsets equal to these residual emissions. These are discussed later in the report.

Figure 27. The Path to Carbon Neutrality in Transportation

Vehicle miles traveled (VMT), and hence GHG emissions, increase due to the (presumed) lower cost in time and money to travel by an autonomous vehicle. Transit-focused Growth refers to the combined impacts of investment in transit, walking, and biking, plus the effect of future growth in the City being concentrated near transit. Pricing refers to the combined impacts of a VMT fee, a congestion (cordon) fee, a parking fee, a subsidy to shared smart mobility, and free/reduced cost public transit. Clean Vehicles (Current Grid) represent 100% EV use with the current GHG intensity of the regional grid. Clean Vehicles (80% Clean Grid) reflects a grid that is 80% GHG-free by 2050. The Clean Vehicles (100% Clean Supply) scenario assumes that the City procures a quantity of zero-carbon electricity that "offsets" all the GHGs in the electricity it purchases from the grid. Residual emissions are the GHGs that remain after all the strategies are implemented. Source: Institute for Sustainable Energy model calculations.

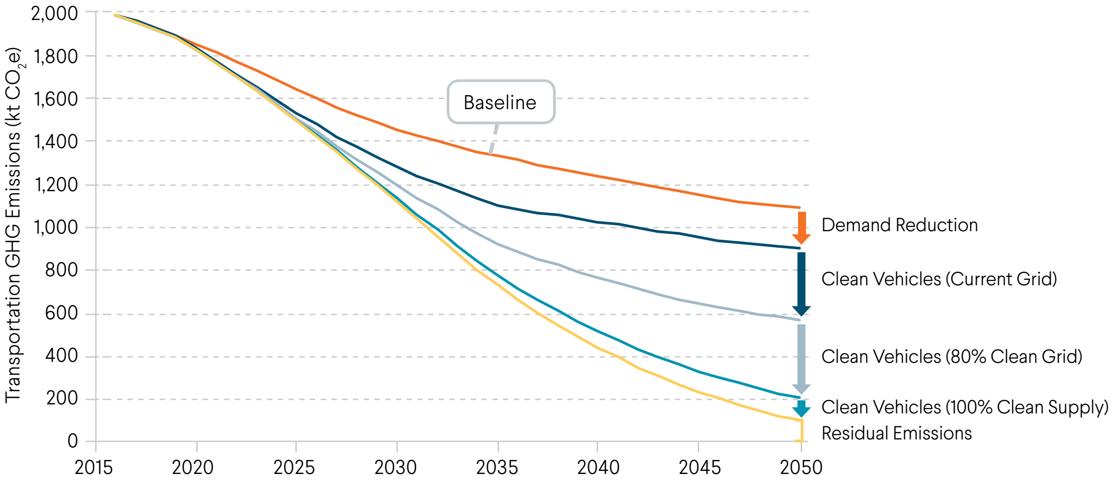
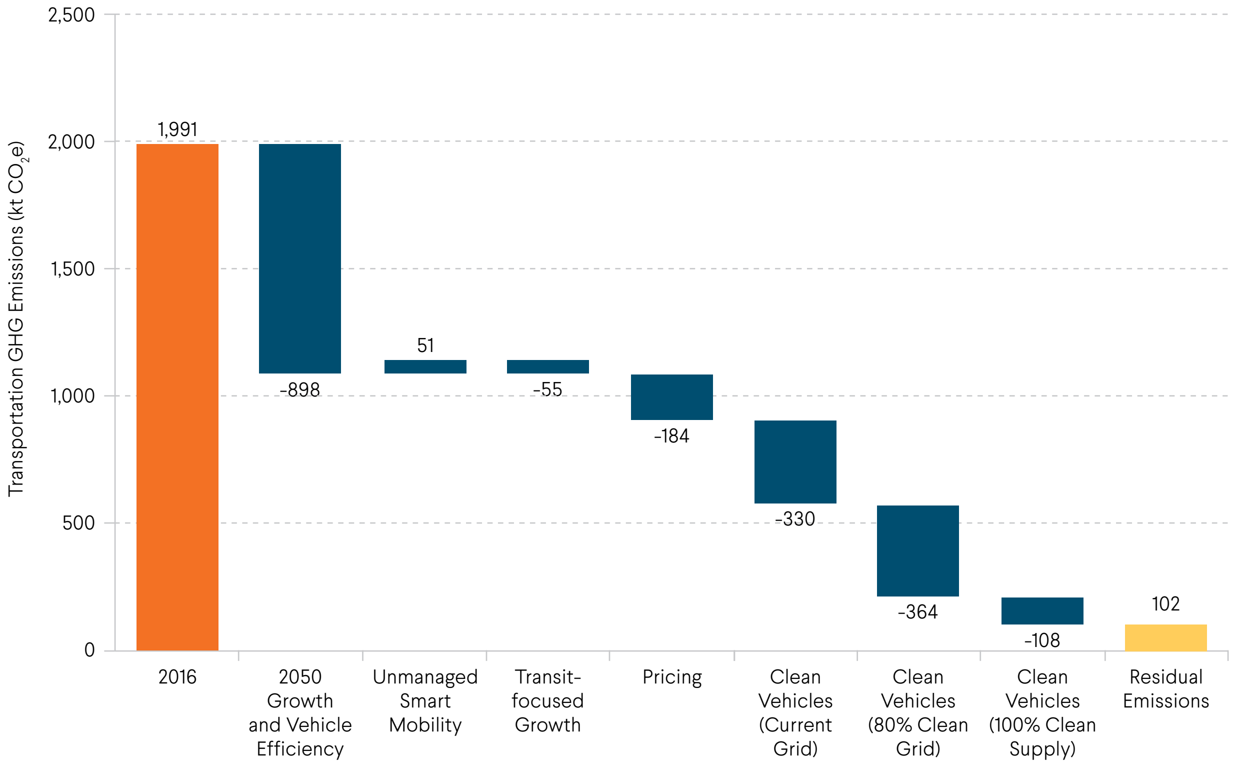


Figure 28. Steps to Carbon Neutrality in Transportation

In 2016, GHG emissions from transportation in Boston were about 2.0 Mt CO_2e. Each subsequent column indicates reductions caused by specific actions that are possible by 2050. “80% Clean Grid” reflects the reduction in emissions caused by the expected contribution of the Massachusetts Clean Energy Standard (80% clean electricity by 2050). “100% Clean Supply” assumes that the City procures a quantity of zero-carbon electricity that “offsets” all the GHGs in the electricity it purchases from the grid. Residual emissions remain due to our assumption that the heavy-duty truck, intercity bus, and ferry sectors will be electrified at a much slower rate than light- and medium-duty vehicles, and thus continue to use fuels that release GHGs. Residual emissions are generated by sectors that are difficult to fully decarbonize and will likely require the use of low-carbon fuels or offsets. Source: Institute for Sustainable Energy model calculations.



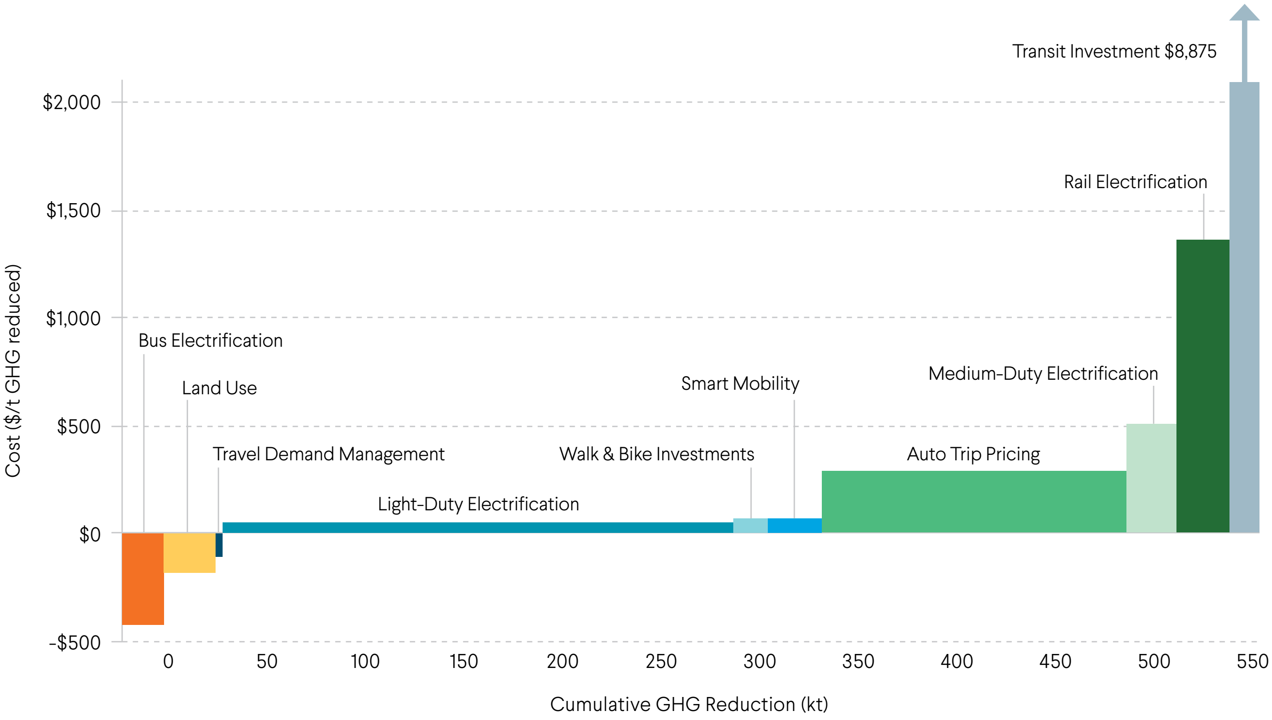
Cost-Effectiveness and Timing

Strategies to reduce GHG emissions in transportation exhibit wide ranges in cost (Figure 29). Note that some strategies have a "negative cost," meaning that the strategy saves money. Thus, the electrification of buses, land use, and travel demand management are money-savers *and* they reduce GHG emissions, albeit modestly. Investments in walking and biking have a slightly larger GHG impact and come at a very modest cost. The electrification of light-duty vehicles has the single largest impact on emissions and also has a low abatement cost. Investment in new transit has the highest cost and a relatively small potential to reduce GHG emissions.

Public transit illustrates the limits of using a single criterion such as abatement cost. Except for bus electrification, transit is a very expensive way to reduce GHG emissions. However, that cost per unit of GHG emissions is just one of many that factor into transportation planning. A city's transit system is the center of economic opportunity, and the extent to which it is planned and invested in equitably is a major determinant of life quality. Investment in transit and active modes produces modest reductions in GHGs, but they also reduce vehicle traffic. If those investments are not made, vehicle traffic in Boston will increase as the lower cost of operating EVs and the convenience of ride-hailing apps result in growing the demand for vehicle travel. In addition, equity is not captured in a MAC curve, and socially vulnerable populations rely more on transit than the general population.

Figure 29. Marginal Abatement Cost Curve for Transportation

The vertical axis is the cost associated with reducing GHG emissions by one metric ton for a particular strategy ($/t CO_2e). The horizontal axis is the total reduction in GHG emissions caused by that strategy; the wider the bar, the greater reduction. Marginal abatement cost curves should not be viewed as recommendations for a rank ordering of policy implementation because important dimensions of decision making are excluded, and because they measure costs under a narrow set of fixed conditions. The transit investment represents 42 new miles of rapid bus lanes and 35 new miles of urban rail. Source: Institute for Sustainable Energy model calculations.



Benefits and Opportunities of a Clean Transportation System

A reduction in VMT is one of the many potential benefits of transportation climate planning that addresses both the supply and demand for transportation services. A transportation system characterized by clean energy, greater transit use, and more active transportation will benefit the people of Boston in very tangible ways (Table 4).

A carbon-neutral transportation system has the potential to improve people's health and safety. The physical activity resulting from the big increase in the number of miles people travel by biking and walking are projected to lower health care costs by $52 million in 2050. Vehicle electrification at scale reduces air pollution from fuel combustion, which is projected to reduce health care costs by another $8 million. In Massachusetts urban regions, air pollution disproportionality burdens non-Hispanic blacks, individuals with lower educational attainment, and households with an annual income of less than $20,000. These communities in particular will benefit from a cleaner transportation energy system in Boston.

The expansion of public transit and walking will increase access to and affordability of transportation, if it is properly implemented, because (i) many socially vulnerable populations heavily rely on these modes, and (ii) low income households spend a larger fraction of their income on transportation services compared with their higher income counterparts. Free or lower cost transit, improved service on existing routes, and better walking infrastructure will produce immediate benefits. The benefits of new investment hinge on where it is made and how it is implemented. Channeling new development into transit-rich, walkable, and centrally located

Table 4. Benefits of a Carbon-Neutral Transportation System in 2030 and 2050

Benefit Category	2030	2050
Motor vehicle crash cost change ($M)*	-$86	-$259
$PM_{2.5}$ change (kg)	-2,000	-3,700
NO_x change (kg)	-100,000	-226,000
$PM_{2.5}$ change	-13%	-29%
NO_x change	-19%	-55%
Air pollution cost change ($M)	-$8	-$15
Physical activity health care cost change ($M)	-$17	-$52
Vehicle operation cost change ($M)	-$138	-$414

*Combination of VMT reduction and improvements from autonomous vehicles. Numbers in parentheses indicate a negative cost, i.e., a monetary savings.

Commuter rail. Photo credit: City of Boston neighborhoods will reduce GHG emissions, but it will improve equity only if coupled with action to improve affordable housing in neighborhoods such as Back Bay, Downtown, and the Longwood medical areas.

The expansion of Boston's bike infrastructure will also improve transportation equity if it targets underserved neighborhoods. Recent efforts to expand bike lanes and Blue Bikes stations outside Boston's urban core will increase accessibility, but many of the Boston's neighborhoods are still underserved. Continued engagement with neighborhood communities to experiment with and provide micro-mobility and last-mile transit options can identify opportunities to better serve Boston's diverse communities and neighborhoods.

Unlike the expansion of transit, walking, and biking infrastructure, the pricing strategies to reduce VMT have the potential to both benefit or burden different populations in Boston. The key is how the fees are levied and how the revenues are spent. Levying a fee can create a cost burden to low-income households. However, the revenues collected from VMT, parking, and congestion fees can subsidize shared-ride smart mobility and transit fares as well as expand investment and access to mobility in currently underserved neighborhoods.

Figure 30. Equity Scorecard: Active Transportation

Components	Evaluation
Is it green?	
Is it GHG-free?	**Yes:** Biking and walking are GHG-free modes of transport
Is it environmentally sustainable?	**Yes:** Transition to active modes of transportation saves energy per mile traveled and reduces pollution from vehicles and electric generation
Does it promote smart behavior?	**Yes:** Encourages a large-scale transition to active transportation, reducing the length of commutes, and reducing road congestion
Is it fair?	
Is it accessible?	**Depends:** Intentional planning and investment are need to ensure equitable access to walking and biking infrastructure
Is it affordable?	**Depends:** Opportunities to preserve and enhance affordability with intentional planning during the transition to active modes of transportation
Are workforce opportunities just?	**Depends:** Opportunities for diverse new workforce and contractors depend on policy design
Who gets to decide?	
Is it inclusive?	**Depends:** Opportunities for inclusive decision making with intentional planning and prioritization
Are values considered?	**Depends:** Opportunities for values-based decision making with intentional planning and prioritization
Is it measurable?	**Depends:** Easy measurement for dollars, miles of lanes installed, operational improvements, health benefits; more difficult for community and workforce impacts

Carbon Free Boston's strategy to improve and expand walking and biking infrastructure will lower GHG emissions. This strategy also has the potential to alleviate existing inequity by facilitating greater access to free, active modes of transport and by enabling healthier lifestyles. Biking infrastructure upgrades should prioritize the lack of protected bike lanes and docking stations that now exists in parts of several SVP communities. The construction of new infrastructure presents an opportunity to facilitate a fair and just workforce by ensuring that diverse local workers and contractors are trained and hired. This strategy has the potential to exacerbate existing inequalities if decisions regarding the type and location of investments are made without specific attention to accessibility, affordability, and inclusive decision making.

Figure 31. Equity Scorecard: Private Travel Pricing

Components	Evaluation
Is it green?	
Is it GHG-free?	**Depends:** Has the potential to reduce private vehicle GHG emissions to the extent that: EVs are widely adopted, electrification is powered by clean energy, and fees shift commuters from private to public transit
Is it environmentally sustainable?	**Depends:** Has the potential to reduce VMTs and reduce energy use per VMT to the extent that fees shift commuters from private to public transit
Does it promote smart behavior?	**Yes:** Reduces peak road congestion, encourages more efficient modes of transportation
Is it fair?	
Is it accessible?	**Depends:** Private vehicle travel would not be accessible to all; pairing this policy with more accessible public transit along with policies addressing ride hailing and autonomous vehicle developments may be a partial solution
Is it affordable?	**Depends:** Private vehicle travel would not be affordable to all but these fees generate revenue for the public sector; individual affordability depends on revenue recycling choices
Are workforce opportunities just?	**Depends:** Opportunities for diverse new workforce and contractors depend on policy design
Who gets to decide?	
Is it inclusive?	**Depends:** Opportunities for inclusive decision making with intentional planning and prioritization
Are values considered?	**Depends:** Opportunities for values-based decision making with intentional planning and prioritization
Is it measurable?	**Depends:** Easy measurement for trips, VMT, dollars, pollution emissions; more difficult for community and workforce impacts

Carbon Free Boston's strategy to enact private travel pricing strategies—shared ride-hailing incentives, parking fees, congestion fees, and VMT fees—will simultaneously reduce GHG emissions and shift travel from private, single occupancy vehicles to public transit and other low-carbon and shared modes. This mode shift will make transport to more accessible, safer, less polluting, and healthier. Fees on private vehicles raise costs for drivers, but at the same time they provide substantial revenue to the sector, which can be used to improve affordability. Reasonable alternative modes must be available that are equitable in terms of time and distance. Travel pricing should not divert traffic through SVP communities, and it should be phased in gradually with ample advance notice and education. Any travel pricing system will generate new employment opportunities that can increase workforce diversity.

Shaping the Future of Boston's Transportation

A carbon-neutral transportation system requires fundamental changes to how people and goods move around Boston and its environs. The foundation for change has three pillars. The first is to shift people out of automobiles to low- and zero-carbon modes such as public transit, biking, and walking. The second is to reduce the total number of automobile trips via land use planning that encourages denser development. The third is to shift most automobiles, trucks, buses, and trains to zero-carbon electricity.

The enhancement of transit, biking, and walking infrastructure produce benefits that extend far beyond GHG reduction: improved public health, greater social connectivity, a more equitable distribution of transportation services, and a city that is more attractive for economic development. Boston's streets will be safer, quieter, and more accessible. Support for transit and active transport are consistent with a fundamental tenet of development: bringing people and economic activity closer together reduces the climate footprint of transportation. At the same time, rapid development of low-income or otherwise investment-poor neighborhoods is not without its risk and long-term impacts. To avoid gentrification and the displacement of socially vulnerable populations it is critical to plan intentionally and practice inclusive decision making.

The electrification of vehicles coupled with zero-GHG electricity will produce a large GHG reduction at moderate cost. Accelerated clean electrification can be achieved through a comprehensive approach to market transformation above combined with the energy supply strategies discussed later in this report.

A fee placed on private vehicles traveling in Boston will generate revenue that can fund a multitude of actions to reach carbon neutrality and make the city more resilient in the face of climate change. Like Stockholm and London, Boston can direct revenue to expand, public transit, walking, and biking. It could pay for deep energy building retrofits, the installation of rooftop solar energy, and the procurement zero-carbon electricity. The revenue could also expand the resiliency efforts of *Resilient Boston Harbor.* Cordon and VMT fees that are properly designed and implemented can avoid burdens on socially vulnerable populations, and their revenues can expand access to mobility in currently underserved neighborhoods.

MBTA Commuter Rail. Photo credit: MBTafan2011/Wikipedia

New mobility services such as ride hailing are transforming personal transportation in Boston. The enticing vision of smart mobility as clean, green, efficient, and flexible transport runs up against the unfolding reality in U.S. cities: to date, smart mobility has benefited higher income households disproportionately and is expected to increase both VMTs and emissions. Autonomous vehicles have the potential to worsen or improve GHG emissions, congestion, and the equity of access to mobility. Through regulation and economic incentives, the City has the means to steer all forms of smart mobility toward its climate and social goals. The actions needed to reduce GHG emissions in transportation move in lockstep with the actions proposed in *Go Boston 2030, Imagine Boston 2030, Resilient Boston, Climate Ready Boston,* and *Resilient Boston Harbor.*

SECTION 5

Waste

Zero-Waste Planning in Boston

As a part of its 2014 *Climate Action Plan* update, Boston committed to become a "waste- and litter-free city." A major step toward this goal was launched in 2018 in the form of *Zero Waste Boston*, an initiative that aims to "...transform Boston into a zero-waste city through planning, policy, and community engagement." A commonly adopted benchmark for achieving zero-waste is to divert at least 90 percent of waste from landfills and municipal solid waste (MSW) combustors. Diversion refers to waste source reduction, reuse, repair, recycling, and biological treatment of organics. Zero-waste diversion activities conserve resources, reduce wastes and GHG emissions, and minimize the environmental and health impacts of the materials we use.

In early 2019, the Zero Waste Advisory Committee presented 30 recommendations to help Boston achieve its zero-waste goals. These strategies are divided into four core categories: reduce and reuse, recycle more, increase composting, and inspire innovation. Not only do these strategies aim to encourage Boston's residents and businesses to increase their waste diversion, they also establish the framework and infrastructure that is necessary to do so.

Each of these strategies require new rules to incentivize diversion activities, new services to handle the capacity for increased diversion, and education and outreach initiatives to help residents and businesses move toward zero-waste. New rules include requirements, fees, and bans that incentivize residents and businesses to reduce, reuse, recycle, and compost their waste. New services include food waste collection services, neighborhood drop-off centers, and City-owned transfer and processing facilities. Education and outreach initiatives include technical assistance, behavior-change marketing campaigns, and community waste prevention and recycling grants. The *Zero Waste Boston* analysis projected that implementation of these strategies would increase the overall diversion rate from 25 percent to 80 percent or more.

Waste diversion can be designed to reduce the burdens on, and realize the potential benefits for Boston's socially vulnerable populations. In general, incentives and bans place a smaller burden on low-income households compared with fees. When fees are used, robust education, outreach, and warning systems—paired with a prohibition of building owners passing surcharges onto renters in the instance of failed audits—can mitigate the burden to these households.

Employment and entrepreneurship opportunities abound in a zero-waste city. Opportunities span the range from large industrial recycling centers to local community projects focused on reuse. Examples include donations of leftover food to shelters, fertilizer to schools in community gardens in low-income neighborhoods, furniture to refugees, and business clothing to people entering the job market.

A zero-waste Boston would enhance social equity outside the city's geographic boundaries, as well, because it would reduce the demand for landfills and waste combustion facilities, which are disproportionately sited in or adjacent to environmental justice populations. This includes the communities around the waste combustion facilities in Saugus and Haverhill, which receive residential waste from Boston.

Zero Waste Boston meeting. Photo credit: City of Boston

Municipal Solid Waste in Boston

Boston's residents and businesses produced about 1.2 million tons of solid waste in 2017 with nearly 80 percent generated by the commercial sector and the remaining 20 percent by households. While the collection and transport of solid waste generates some emissions, its treatment and final disposition generate significantly more. The magnitude and type of direct emissions associated with solid waste treatment varies based on the treatment process and material type. The use of waste materials as a resource, such as for energy production or for recycling can potentially avoid emissions. This complexity makes the waste sector challenging to assess, but within this complexity there are significant avenues to reduce emissions.

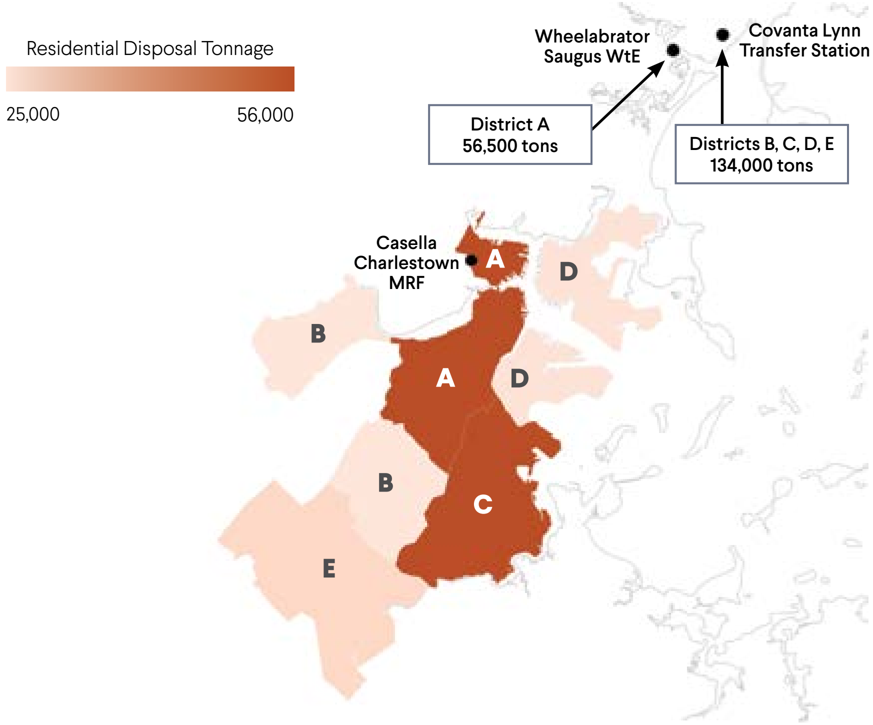
Discarded materials follow one of two routes: *diversion* (reuse, recycling, or biological treatment of organics), and *disposal* (landfill or combustion).

Diversion (25 percent): Boston currently diverts about 25 percent of its waste, which has increased from approximately 10 percent since Boston's adoption of single-stream recycling in 2009. Most of this is material for recycling, which is processed at Casella's material recovery facility in Charlestown. The remaining diverted material is predominantly organic, and comprised mostly of yard waste with some food waste collected by the private sector. Most of this organic material is composted, although a small amount is anaerobically digested, a process that converts organic waste to methane and a nutrient rich soil amendment.

Disposal (75 percent): All of the residential disposal waste stream is collected and transported to waste-to-energy combustion facilities outside of the city boundary (Figure 32). While a portion of the waste is passed through a transfer station in Lynn, MA, the waste is ultimately delivered to the Wheelabrator Saugus, Covanta Haverhill, and Covanta SEMASS Rochester waste-to-energy facilities. At these facilities, the waste is burned to generate electricity that is used by the New England grid.

Figure 32. Residential Disposal Tonnages and Destination Pathways in 2017.

MSW collection districts: (A) Charlestown, Chinatown, Downtown, Bay Village, Back Bay, Beacon Hill, South End, North End, Roxbury, Fenway, Mission Hill, Financial District; (B) Jamaica Plain, Allston/Brighton; (C) North & South Dorchester, Mattapan; (D) East & South Boston; and (E) West Roxbury, Hyde Park, Roslindale. Data from Boston Department of Public Works.



Drivers of GHG Emissions

Municipal solid waste generates GHG emissions in all stages of its management: from collection to final treatment. These emissions are divided among three categories:

Direct Emissions: Emissions from waste decomposition and combustion, plus emissions from fuel combustion by transportation vehicles and other onsite equipment.

Indirect Emissions: Emissions caused by the generation of purchased electricity that is used throughout the MSW management system.

Avoided Emissions: Emission "savings" or "benefits" that *potentially* could be realized via energy recovery, material recovery, nutrient recovery, and carbon storage. An example is the reduced energy (and, hence, GHG emissions) associated with the manufacture of an aluminum can from recycled metal rather than metal extracted and refined from virgin ore.

Avoided emissions are difficult to account for with certainty, and therefore their contribution to the reduction of GHGs is not currently reliable under a robust carbon-neutral strategy. GHG accounting protocols, such as the *Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories* discussed in the Approach chapter, stipulate that avoided emissions should be reported separately. Although, estimates of avoided emissions are highly uncertain and variable, understanding the general potential for avoided emissions allows for a broader evaluation of the potential impacts of alternative waste treatment options.

Covanta Haverhill waste-to-energy facility. Photo credit: Google Earth

Material composition is a major factor in determining the GHG impact of a waste stream. Depending on its composition, the waste stream may emit carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), or biogenic CO_2. MSW materials are divided into six main categories: paper, plastics, metals, glass, organics (food waste, yard waste, etc.), and other (textiles, leather, rubber, electronics, etc.).

Once MSW enters the waste stream, discarded materials follow a either a diversion pathway and are recycled or biologically treated, or a disposal pathway via landfilling or combustion (Figure 33). Each practice has different GHG implications for each material type. For instance, the combustion of plastic waste releases CO_2 and N_2O, but if recycled or landfilled it will not release any emissions. On the other hand, organic waste releases biogenic CO_2 and N_2O if combusted, and releases CH_4, N_2O, and biogenic CO_2 if landfilled or biologically treated. Any efforts to reduce or divert waste need to consider these material-treatment dynamics that drive emissions.

Figure 33. Municipal Solid Waste Flows and Treatment Options

In Boston, approximately 20% of recycling is contaminated and is redirected to the waste disposal stream.

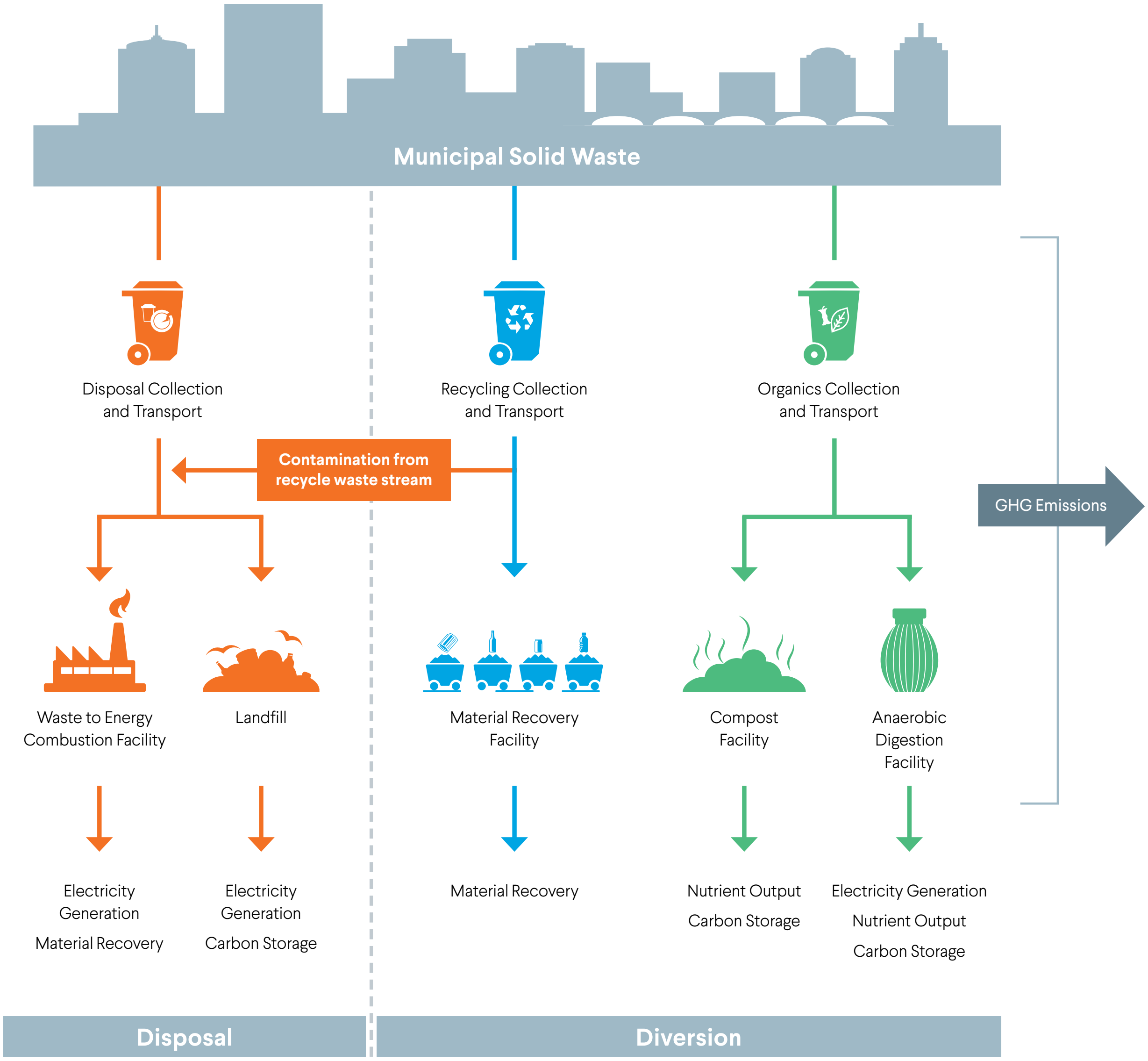


Figure 34. Equity Scorecard: Increasing Waste Diversion and Source Reduction

Components	Evaluation
Is it green?	
Is it GHG-free?	**Depends:** Source reduction and recycling avoid emissions associated with waste treatment and disposal, and emissions from new product manufacturing; but they produce emissions when treated. Composting can increase emissions compared with waste combustion under certain conditions
Is it environmentally sustainable?	**Yes:** Avoids harmful pollutants associated with combustion, reduces demand for virgin materials, ensures a more sustainable use of organic waste, and delivers energy savings in the form of avoided energy
Does it promote smart behavior?	**Depends:** While not an explicit goal, wide adoption of source reduction, composting and recycling can encourage more responsible consumption and use of materials and avoid the creation of waste
Is it fair?	
Is it accessible?	**Depends:** Intentional planning and information campaigns are necessary to ensure equal access to GHG-free waste infrastructure
Is it affordable?	**Depends:** New investment in waste management may impact public budgets; opportunity for realized cost-savings to be passed onto households; fines must be structured to accommodate low-income households
Are workforce opportunities just?	**Depends:** Opportunities for diverse new workforce and contractors depend on policy design
Who gets to decide?	
Is it inclusive?	**Depends:** Opportunities for inclusive decision making with intentional planning and prioritization
Are values considered?	**Depends:** Opportunities for values-based decision making with intentional planning and prioritization
Is it measurable?	**Depends:** Easy measurement for waste streams and costs; more difficult for community and workforce impacts

Carbon Free Boston's strategy to reduce solid waste generation, increase recycling and reuse, and to capture renewable energy from waste water is essential for a carbon-neutral waste system. Intentional design of source reduction action has the potential to alleviate inequity by encouraging "smarter" consumption and lowering the cost of living. Programs focused on behavioral change must communicate in a manner that addresses disparate incomes, language, and customs. Reuse programs can improve equity by the redistribution of useful goods—food, clothing, furniture—to those in need. Accessible recycling and composting programs can reduce the potential burden associated with pay-as-you-throw systems. Zero-waste action should intentionally aim to build social capital, such as tool sharing and skills sharing for reuse and repair activities.

Baseline Scenario

To estimate the GHG impact of increased diversion, we begin with a baseline scenario that establishes the magnitude of Boston's waste-related emissions between 2017 and 2050 in the absence of action. In 2017, the processing (i.e., waste combustion, composting, etc.) of the Boston's MSW generated about 6 percent of the total emissions reported in the 2015 emissions inventory.[15]

The baseline scenario assumes that the overall diversion rate remains constant at its current level of about 25 percent, while total waste generation grows due to increases in population and employment. This results in a 14 percent increase in waste generation and 14 percent increase in direct emissions from the 2017 baseline.

The avoided emission benefit from the combustion of the city's waste stream shrinks as the regional electricity grid substantially decarbonizes through 2050. Currently, the combustion of biogenic carbon-rich MSW generates less GHG emissions per MWh than the combustion of fossil fuels. As natural gas electric generation is replaced with clean energy sources, MSW combustion becomes one of the most carbon-intensive energy sources on the grid. Thus, annual avoided emissions from energy recovery would decline 74 percent by 2050 under the Massachusetts Clean Energy Standard.

For the illustrative purposes of this analysis we assumed that Boston's non-diverted waste will continue to be combusted at waste-to-energy facilities. This assumption does not reflect the potential of these facilities to retire due to a changing regulatory and economic landscape prior to 2050, which is beyond the expected operating lifetime of these facilities.

Project Oscar is Boston's community compost pilot program. Photo credit: City of Boston

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[15] As described in the Approach chapter, the City's *Community Greenhouse Gas Inventory* follows the *Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories* guidance on emissions from waste-to-energy plants and attributes them to regional electricity generation. We take a different approach by assessing emissions associated with alternative waste management strategies. These include direct emissions from collection, combustion, composting, and landfilling, as well as avoided emissions with energy recovery, material recovery, and carbon storage.

Zero-Waste Pathway

In 2017, approximately 75 percent of Boston's MSW stream was sent to combustion facilities for final treatment, while the remaining 25 percent entered diversion pathways (Figure 35, top). This suggests a huge potential for Boston to enhance its waste diversion efforts. For instance, food waste accounted for 23 percent of Boston's total generated MSW in 2017, but only 8 percent of that was diverted from the disposal stream. Similar potential for greater diversion exists for paper, plastic, metal, and glass; only a fraction of what could be recycled was. Of the materials that made it into the recycling stream, 20 percent was contaminated and therefore was ultimately unable to be recycled.

A zero-waste pathway achieves a 90 percent diversion of its waste stream from disposal, sending only 10 percent of its waste to disposal (Figure 35, bottom). We assessed the impacts of zero-waste policies by assuming that diversion increases from 2020 to 2030 to achieve the 80 percent diversion target, continues to rise to 90 percent diversion by 2040, and then remains constant through 2050.

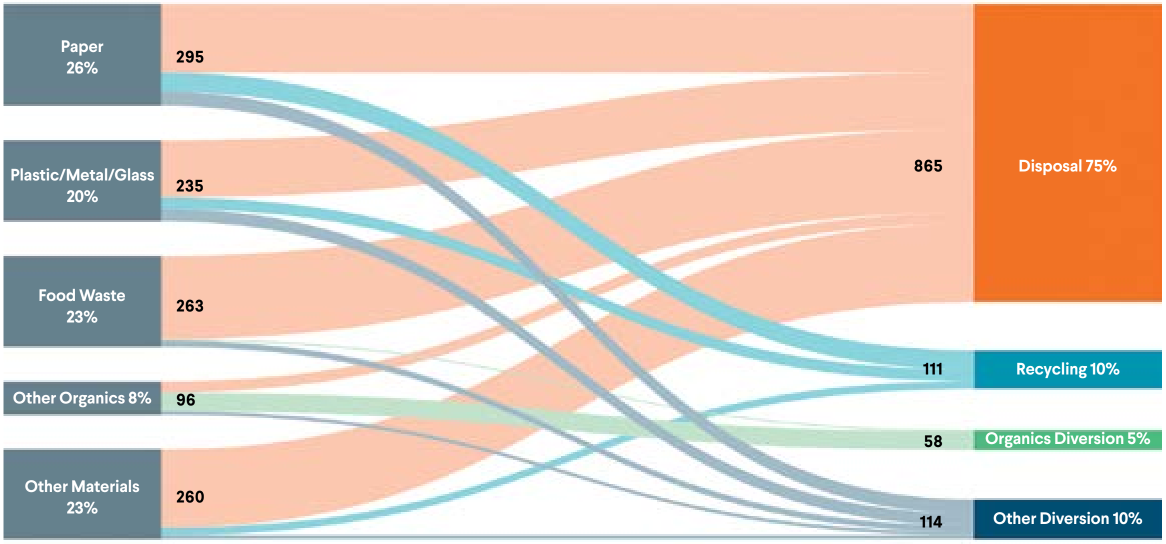
The strategies to achieve zero-waste that also support carbon neutrality include source reduction, paper recycling, plastic recycling, and other diversion strategies (Figure 36). The largest emissions reductions are expected to come from the implementation of source reduction policies that reduce waste generation. These include plastic bag bans, packaging requirements, and conservation efforts. Diverting plastics from combustion also produces a significant reduction in direct emissions as fossil carbon embodied in the plastic is recycled rather than emitted. The diversion of a number of other materials such as electronics, tires, and textiles, and

Group of workers sorting papers at recycling plant. Photo credit: vm/iStockphoto

Figure 35. Boston's Current and Future Waste Flows

Top: Municipal solid waste (MSW) in 2017. **Bottom:** MSW under 90% diversion conditions in 2050. Units are in 1,000 tons and percentage of total material waste generated or diverted. Along the left are the categories of MSW. Along the right are waste disposal and waste diversion strategies. In the bottom graph, 10% of the MSW stream is disposed, 29% is recycled, 32% is organics diversion, 17% is other diversion, and 13% is source reduction. Sources: Calculations based on data from Boston Department of Public Works, Zero Waste Boston, and Massachusetts Department of Environmental Protection.

Boston 2017—Waste Generation (thousand tons)



Boston 2050—Waste Generation (thousand tons)

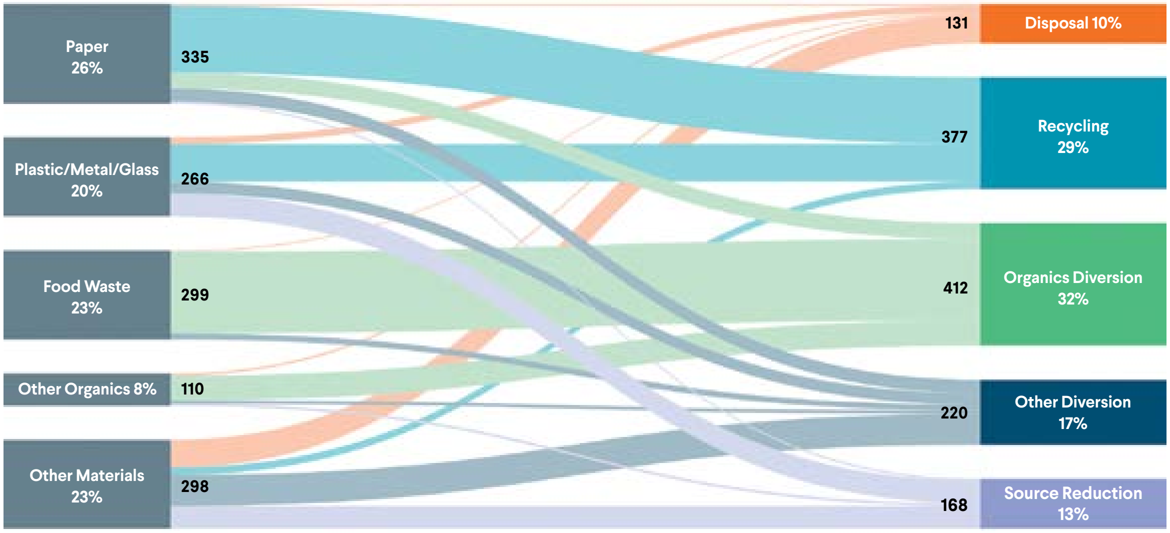
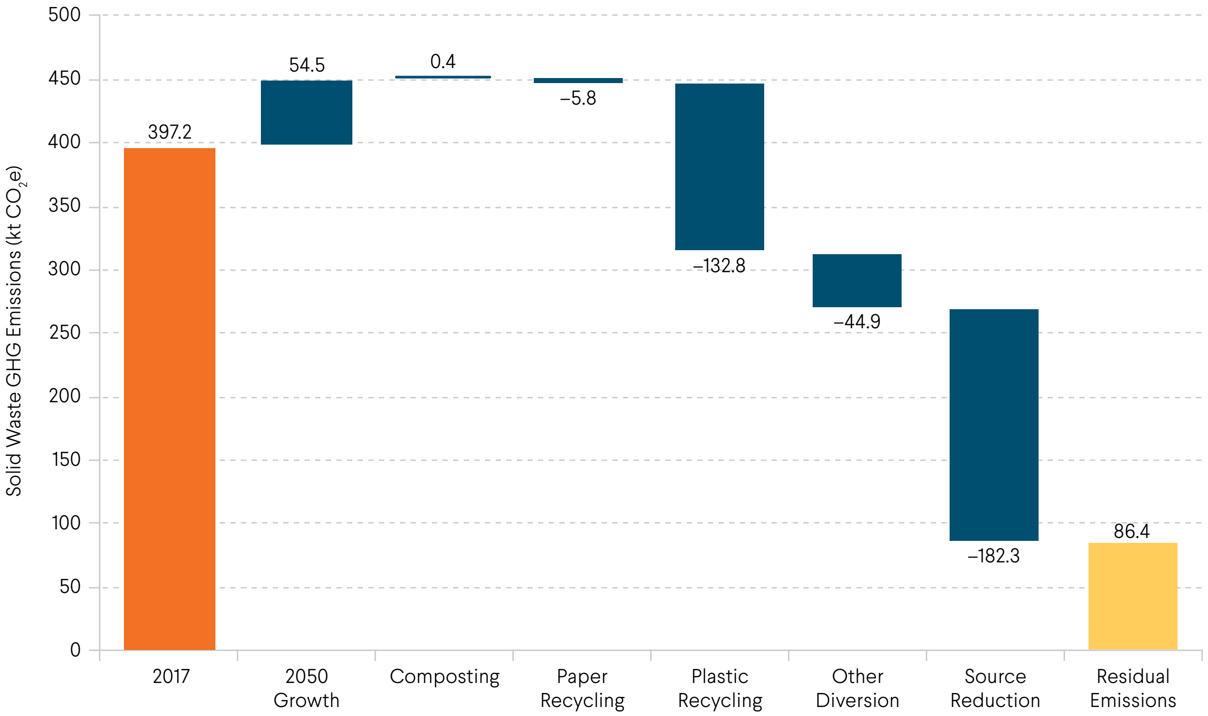


Figure 36: Pathway to 2050 in Municipal Solid Waste

The steps reflect the GHG reduction potential of specific consecutive actions starting from today's conditions. "Other" refers to textiles, mattresses, tires, electronic waste, and other miscellaneous materials. Source: Institute for Sustainable Energy model calculations.



the recycling of paper also contribute to the 78 percent GHG emission reduction that can be achieved relative to the 2017 baseline with a 90 percent diversion rate. The residual emissions mostly stem from the combustion of the last 10 percent of solid waste, but also include some direct emissions from composting and collection services.

Composting organic waste instead of sending it to an MSW combustion facility is consistent with efforts to achieve a 90 percent diversion rate, but it increases direct process emissions compared with MSW combustion. This is due to the fact that depending on the implementation or environmental conditions, composting can generate higher levels of CH_4 and N_2O than the combustion of organic MSW. The magnitude of this increase in direct emissions is relatively small compared with the combustion of the fossil-carbon fraction of MSW (e.g., plastics).

Final Waste Treatment Options

Zero-waste implies a future with no burning or burying of waste material. Technical or economic limitations may make 100 percent diversion impractical, and therefore the zero-waste framework sets a 90 percent diversion target that while ambitious and would leave Boston with 133,000 tons of waste earmarked for disposal. The diversion of organics and recoverable materials will leave a waste stream mostly comprised of materials that are not recyclable or compostable under current technology.

Under Boston's current waste stream, combustion is less GHG intensive compared with state-of-the-art methane capture landfills. Combustion of the low-organic residual waste stream is more GHG intensive than landfilling since the primary driver of landfill methane emissions has been diverted to biological treatment. Further, the diversion of organics and plastics reduces the energy generating potential of combustion because those materials have a high energy content, which would make waste-to-energy a less favorable option.

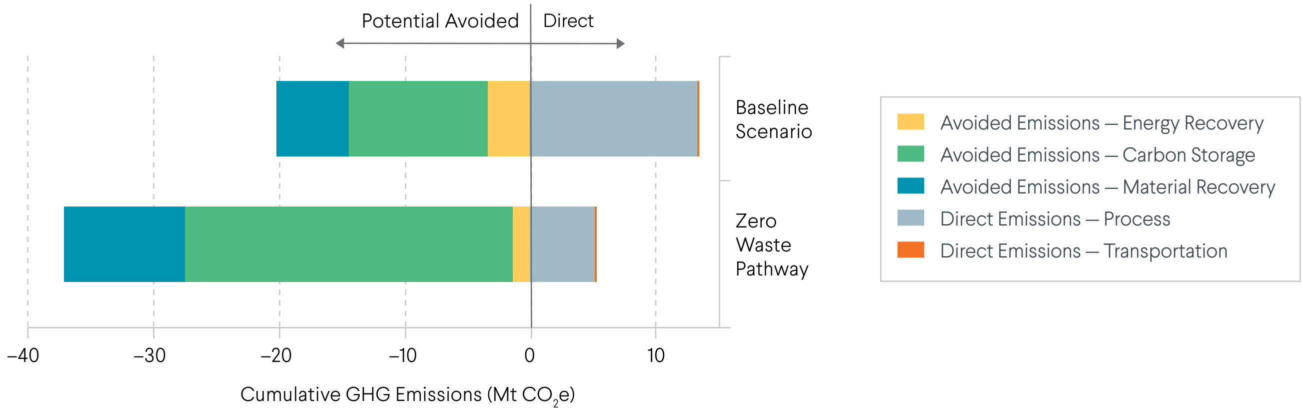
Additional Reduction Potential Through Avoided Emissions

Focusing only on the direct emissions can obscure other potential benefits of zero-waste. For example, under a zero-waste future, avoided emissions from waste-to-energy electricity generation decline with diversion and source reduction due to the combustion of material with lower energy content. Although composting can lead to an increase in direct emissions, the diversion of material to composting and material recovery can avoid emissions through carbon storage[16] and material recovery.[17] Figure 37 shows the impact of a zero-waste pathway based on the cumulative GHG emissions from 2020 to 2050. Under this alternative pathway, cumulative direct emissions would decline by 60 percent, while realizing an 84 percent increase in additional avoided emissions.

The Mattapan Ecovation Center uses composted materials to generate heat for a 2,800 square foot greenhouse in Boston's Mattapan neighborhood. Photo credit: City of Boston

Figure 37: Cumulative Solid Waste GHG Emissions from 2020 to 2050

We present our results here as cumulative emissions to capture the time dynamics associated with the evolving carbon intensity of the avoided emissions from energy recovery. The benefits of energy recovery will decline as the New England grid decarbonizes. We anticipate that the emissions intensity of the avoided emissions from material recovery will also decline as the national economy decarbonizes, but we cannot reasonably estimate that change. Additional avoided emissions from carbon storage can vary significantly by location. Source: Institute for Sustainable Energy model calculations.



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16 When organic materials derived from biomass sources are landfilled, their biodegradation is prevented. The carbon in those materials that does not fully decompose in landfills (anaerobically) is removed from the global carbon cycle, is said to be "stored," and is counted as an "avoided emission."

17 Recycling paper, metal, and plastic reduces the quantity of timber, metal ores, and petroleum that is extracted and processed. The reduction in the extraction of virgin materials reduces the energy (and, hence, GHG emissions) associated with the manufacture of a consumer good (paper, aluminum cans, plastic bottles).

Deer Island facility. Photo credit: City of Boston

Water and Wastewater Services

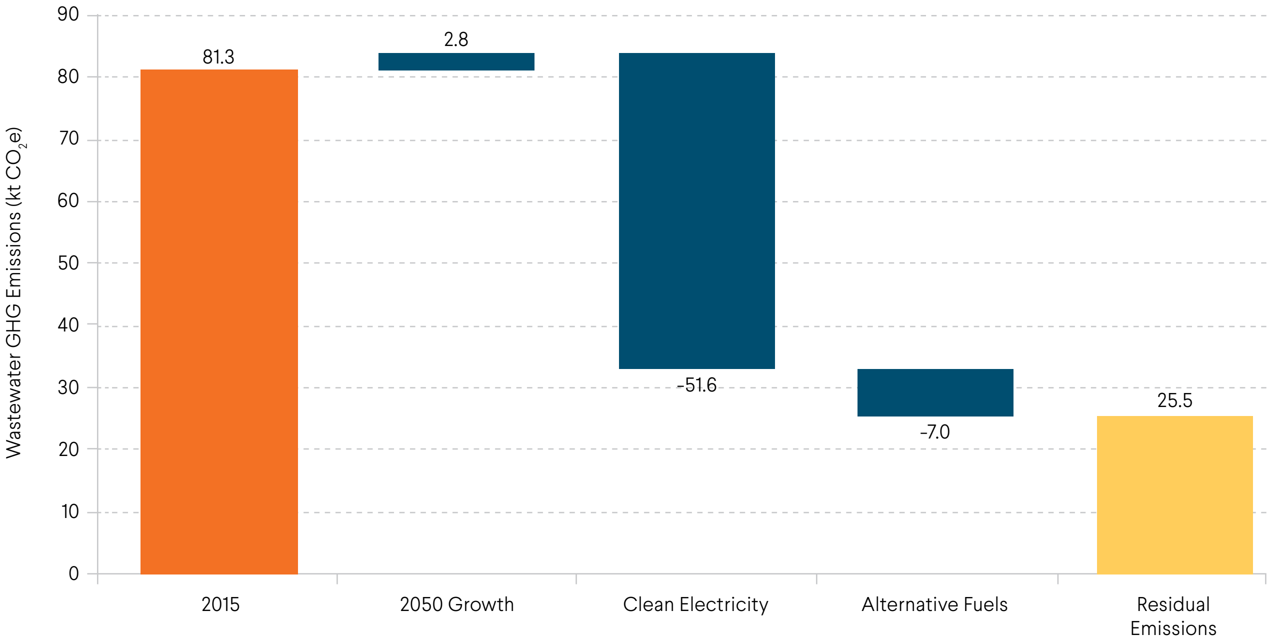
The systems that deliver clean water to Boston and treat the associated wastewater form a critical part of the city's infrastructure. The Boston Water and Sewer Commission (BWSC) oversees in-city water distribution and sewage collection. The Massachusetts Water Resources Authority (MWRA) provides the BWSC with freshwater and ultimately receives sewage for collection and treatment at the Deer Island Wastewater Treatment Plant, which is physically located in Boston. GHG emissions from water delivery and treatment are approximately 1 percent of the city's total emissions, but these systems are important to assess because the BWSC and the MWRA are among the largest energy consuming entities in the city, and they have been at the leading edge of sustainable water delivery and wastewater treatment services. Such services are critical to public health and protecting freshwater and marine resources.

We assessed the emissions in the water and wastewater treatment systems in three distinct categories: consumption of electricity, onsite combustion of digester biogas and fossil fuels, and wastewater. Figure 37 shows the estimated emissions from these categories in 2015, and their pathway to carbon neutrality.

Replacing diesel fuel used by site vehicles with clean fuels yields a modest GHG reduction. A much larger reduction is achieved if the grid follows the Massachusetts Clean Energy Standard. Unavoidable emissions refer to small amounts of CH_4 and N_2O that are released from the incomplete combustion of the biogenic digester gas at the Deer Island facility. Uncertain emissions include potential N_2O generation from wastewater effluent that is released into Massachusetts Bay, but is difficult to accurately quantify.

Figure 38: Pathway to 2050 for Water and Wastewater Services

The steps reflect the GHG reduction potential of specific consecutive actions starting from today's conditions. Clean electricity includes both renewable onsite generation and procurement. Alternative fuels replace on-site fossil combustion that generates process heat. Residual emissions include N_2O and CH_4 emissions from biological breakdown that are difficult to mitigate. Source: Institute for Sustainable Energy model calculations.



Shaping the Future of Boston's Zero-Waste System

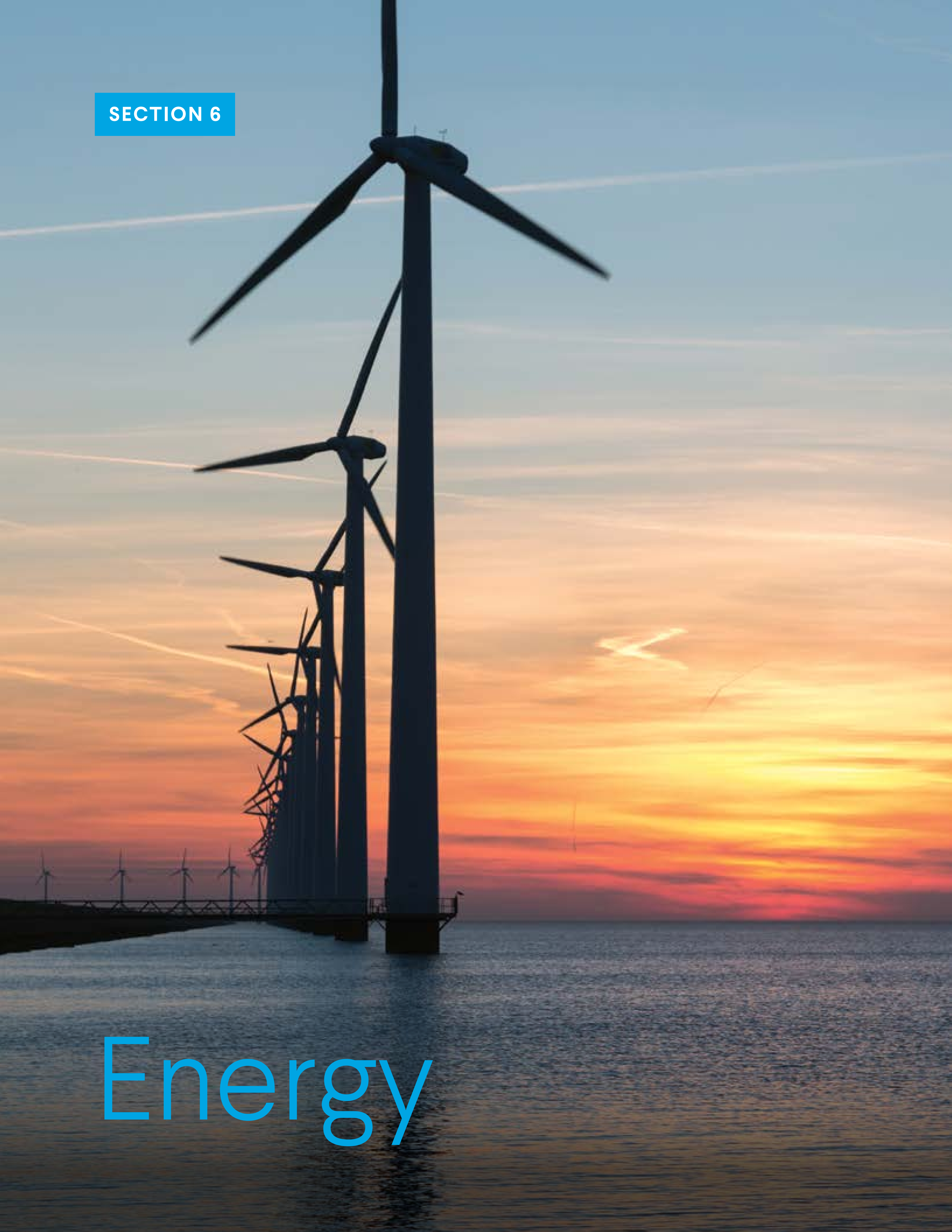
The emergence of modern municipal solid waste management and wastewater treatment systems has greatly improved sanitation and the quality of life in the urban environment. It has also enabled Boston's residents and businesses to dispose of their waste elsewhere, out of sight in environmental justice communities. This approach is unsustainable. It was unsustainable in the 1960s and 1970s when Boston's aging wastewater treatment plants failed to keep Boston Harbor clean, prompting the construction of the most advanced wastewater treatment plant of its time. It is unsustainable now as Boston's waste is combusted elsewhere and generates pollutants that affect vulnerable neighboring communities and GHG emissions that have a global impact.

Rethinking consumption to reduce waste generation can lead to significant reductions in GHG emissions at low cost. The Boston plastic bag ban is a first step in this direction but the opportunity exists to go much further. Boston's innovation ecosystem can spur the design of new packaging materials that are zero-waste compatible. New services and incentives can prompt Boston's households and commercial entities to recycle and reuse valuable material. The collection of organic waste can serve as a feedstock for the generation of renewable natural gas (more on this in the next chapter).

Despite the above efforts, it may be impossible to eliminate 100 percent of emissions from the waste sector due to problem materials and hard-to-mitigate emissions. Should that be the case, offsets (also discussed in a later chapter) will likely be needed to complement zero-waste efforts to achieve carbon neutrality.

Pursuing the goal of net-zero emissions through zero-waste will require participation from all of Boston's constituents. The City can lead by example by implementing zero-waste strategies for its own operations, as it implements new rules and services for its constituents. The commercial sector will need to track and more actively manage its waste streams. Residents will need to participate in diversion efforts and programs. Notably, zero-waste initiatives are relatively inexpensive from a carbon mitigation standpoint and are not as reliant on emerging technologies as the other sectors. Additionally, trash management at the personal and household level—or in the workplace—is something that everyone can participate in. Emissions mitigation though waste reduction can thus be an early point of action.

Boston Public Works waste collection. Credit: City of Boston



SECTION 6

Energy

Energy for a Carbon-Neutral City

Reducing energy consumption, electrifying services once dependent on fossil fuels, and procuring zero-GHG fuels and electricity will cause sweeping changes in the quantity, composition, and timing (daily and seasonal) of the demand for energy in Boston (Table 5). The combination of our pathways to carbon neutrality in buildings, transportation and waste management reveals that total energy use in 2050 could be less than half of what is today, the demand for electricity could remain about the same, and that demand for gasoline, diesel fuel, and natural gas will likely plummet. Some residual fossil fuel consumption will remain in heavy-duty transportation and building systems that are difficult to electrify.

The Combined Effects of Energy Efficiency and Zero GHG Electricity

The peak demand for total energy in Boston occurs on very cold days in the winter when demand for heating energy is highest. That heat is currently supplied predominantly by natural gas, and to a lesser extent by heating oil and electricity (Figure 39). Peak demand for electricity occurs in the summer, often during the afternoon and early evening on very hot days when air conditioning consumes a lot of electricity.

The Buildings and Transportation chapters described the strategies to replace fossil fuels with low- to zero-GHG electricity, and to improve the energy efficiency of transportation and buildings. Our analysis indicates that this will dramatically alter the magnitude and timing of total energy use in two major ways. First, total electricity demand will be about 12 percent higher in 2050 compared with 2015. This is a remarkable result in light of the fact the city will have over a hundred thousand more residents, nearly 100 million more square feet of building space, and a much larger economy in 2050; and most activity will be electrified. This is a testament to the power of deep energy retrofits and electric vehicles to radically improve energy efficiency. The combination of a modest increase in electricity use plus much lower use of natural gas means that the total cost of energy to Boston's businesses and residents could be much lower than today. This will create enormous social and economic benefits, especially for low-income households who spend a large fraction of their budget on energy.

The second big change is the timing of electricity demand. Figure 40 shows the winter and summer peak days when energy use is the greatest for heating and cooling. In 2050, large scale deep energy retrofits reduce the use of air conditioning. Electric vehicles add to electricity demand, but in the summer, that is more than offset by a more-efficient building stock.

Electrification will shift peak demand from summer to winter, predominantly due to the electrification of heating despite the deployment of deep energy retrofits. Notably, dawn and dusk peaks will also grow during the winter, when residential and commercial heating demand is the highest. This will have significant consequences for how the grid is managed and for the use of renewable resources. The intermittency of solar and wind is a big challenge. Solar is available only during the

Table 5. Citywide Energy Use Summarizing Scenarios of Building and Transportation Electrification and Demand Reduction

Scenario	Electricity (TWh)	Fuels (TWh)	Total (TWh)
2015	6.6	19.7	26.3
2050 Baseline	7.7	16.1	23.8
2050 Electrification Only	10.4	4.3	14.7
2050 Electrification plus Efficiency and Demand Reduction Measures	7.4	3.6	11.0

day, but the offshore wind profile more closely tracks peak heating demands (dawn and dusk, and winter). Offshore wind is more costly than onshore wind and solar, but its costs are falling quickly, the resource potential is enormous, and there are several large new projects in the pipeline. While not currently available, using off-peak wind energy to manufacture hydrogen for storage is an area of active research and could to some extent ameliorate the intermittency challenge.

There are other energy options that we did not assess that could be important in the future. New nuclear capacity could provide large quantities of zero-carbon electricity, but there currently are no expansion plans in the region. Carbon capture and storage could make electricity generation from natural gas a low- to zero-carbon option if it can be affordably and rapidly scaled. Energy storage, particularly thermal storage, could provide additional capacity inside the city. Energy storage and distributed generation (discussed below) would require new systems and capacity to control how and when power flows. ISO-New England, the local utilities, and the City would have to work together to manage that change.

Figure 39. The Impacts of Energy Efficiency and Electrification

Daily citywide energy demand for natural gas and electricity in 2015 (left) and 2050 (middle and right). The values represent the *maximum hourly quantity* of electricity or gas consumed in a given day. The Electrification Only scenario reflects deep electrification of the buildings and transportation sectors, with no additional action by the City to improve energy efficiency in buildings, or to dampen the demand for travel in personal EVs. In the third scenario (far right), deep electrification is coupled with deep efficiency gains and demand reduction in the buildings and transportation sectors. Source: Institute for Sustainable Energy model calculations.

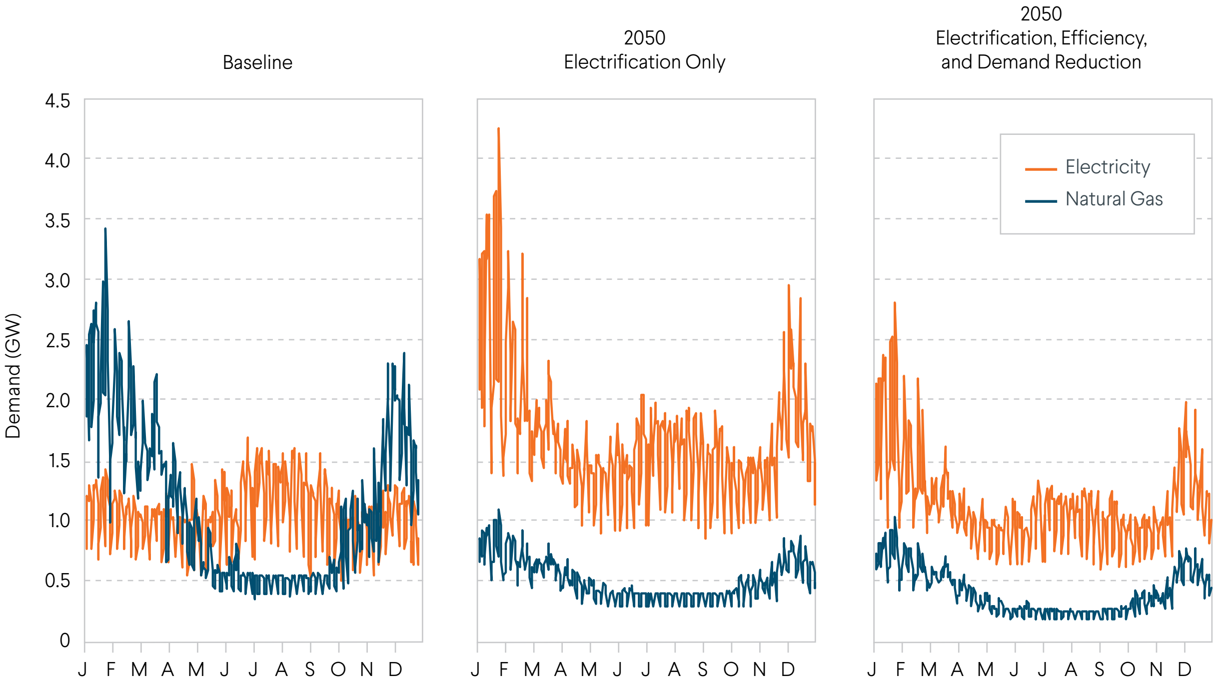
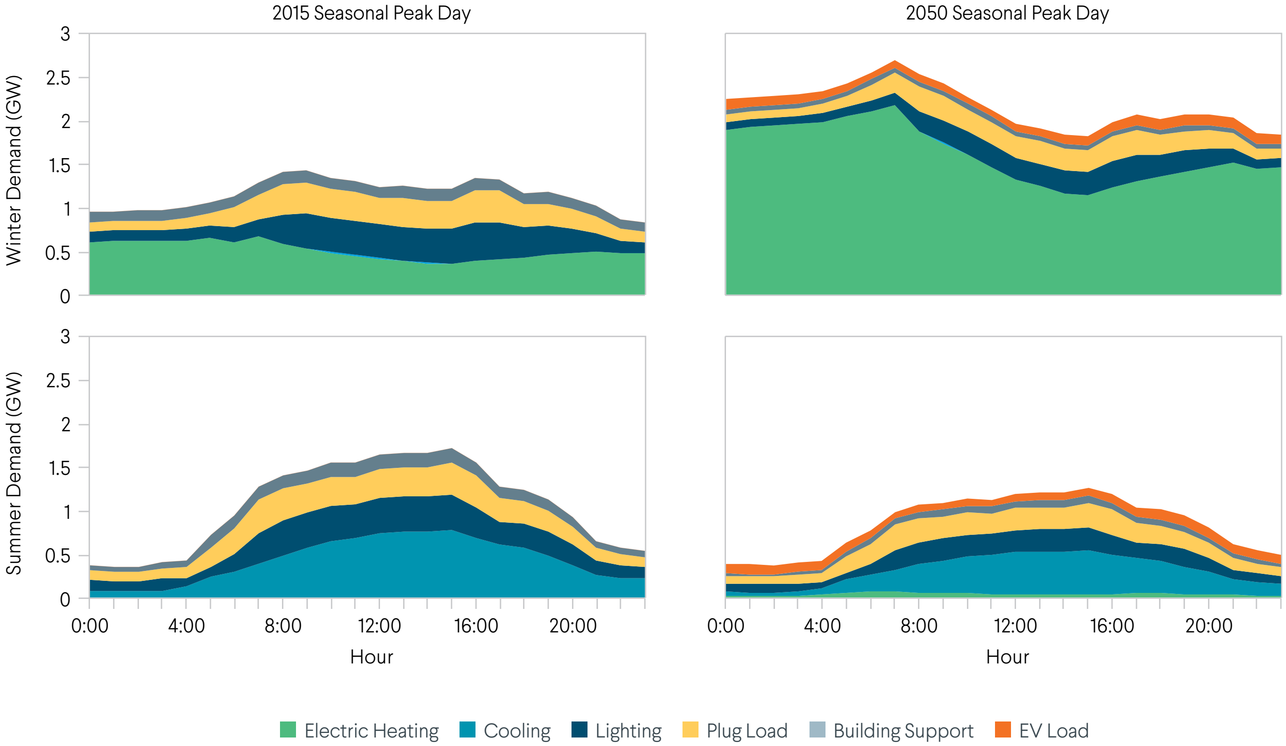


Figure 40. Profile of Electricity Demand

Citywide hourly electricity demand for 2015 (left) and 2050 (right) for winter (top) and summer (bottom) peak days. 2050 data represents a scenario with deep efficiency gains and demand reduction in the buildings and transportation sectors. Colored areas show demand of end uses. Source: Institute for Sustainable Energy model calculations.



Meeting the Demand for Clean Electricity

Rooftop Solar PV

Community-scale or in-city "distributed" renewable energy can be deployed to reduce GHG emissions. The largest potential source is solar photovoltaic (PV) installed on building rooftops ("rooftop solar"). Rooftop solar is gaining a strong foothold in Boston, spurred by falling prices and financial incentives. Through mid-2018, about 2,450 solar systems have been installed in the City of Boston. Eighty-six percent of these are residential solar installations, and most installations occur on owner-occupied units subsidized by Solar Renewable Energy Credits (Figure 41).

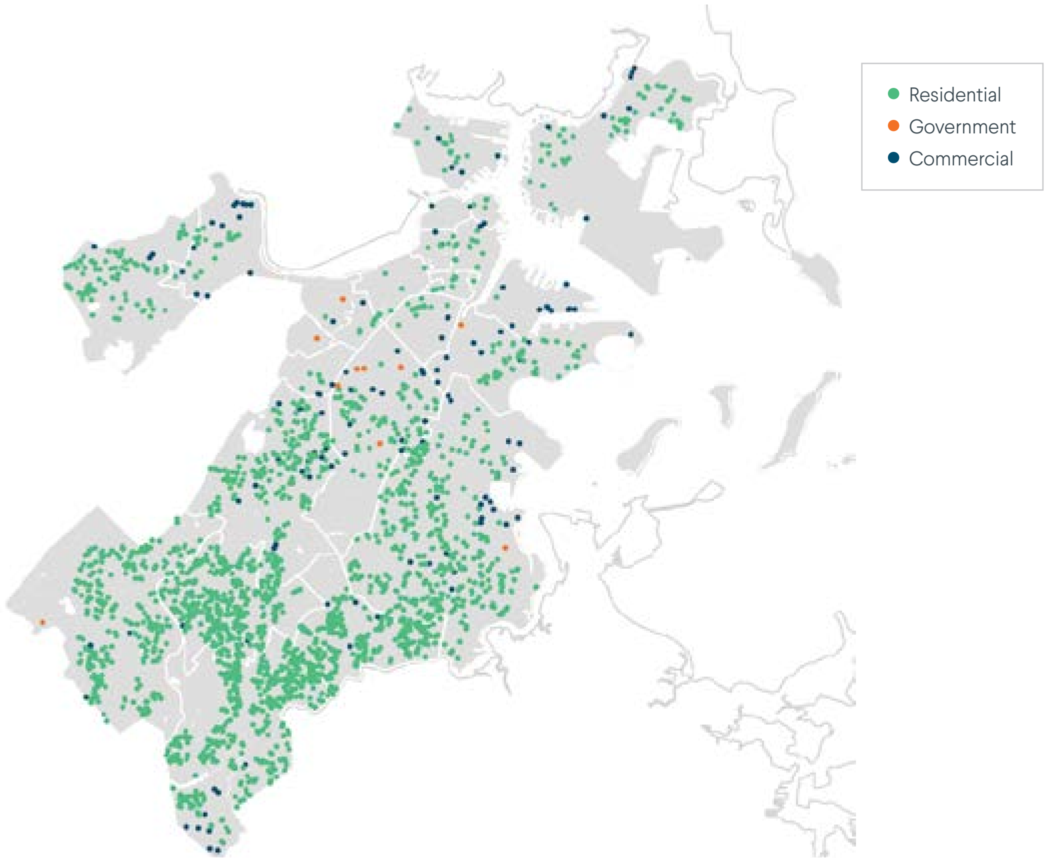
Recent residential rates of installation hover at around 300 per year. This is a large increase from just a few years ago, but is well below the installation rate needed to realize the full rooftop PV potential in Boston of about 1 TWh, equivalent to about 15 percent of current electricity demand (Figure 43). The work required to achieve this scale of rooftop PV deployment provides an excellent opportunity to implement in-city workforce development.

District Energy

District energy systems have been a part of Boston's energy infrastructure for over a century and currently provide heating to 10 percent of floorspace in the city. Four district energy systems are operated by Boston College, Northeastern University, Boston University, and Harvard University. Two additional steam run systems are operated by Veolia and provide service

Figure 41. Rooftop Solar in Boston

Solar installations in the City of Boston that were funded through 2018 via programs of the Massachusetts Clean Energy Center. Green = residential, blue = commercial, orange = government. Source: Massachusetts Clean Energy Center.



to the Longwood medical area (Medical Area Total Energy Plant – MATEP), and the Downtown and Back Bay neighborhoods (Veolia main loop). (Figure 44).

These systems rely on the combustion of natural gas or oil at a central plant to generate heat that is transferred via steam or hot water into nearby buildings. By providing energy from a central plant, district energy systems can take advantage of higher operational efficiencies and greater economies of scale to reduce emissions and costs. This is especially the case for combined heat and power plants that simultaneously generate electricity and heat.

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 store thermal energy at times of low demand, and then utilize it 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.

Figure 42. Equity Scorecard: Private Rooftop Solar

Components	Evaluation
Is it green?	
Is it GHG-free?	**Yes:** Creates GHG-free energy supply
Is it environmentally sustainable?	**Yes:** Reduces air pollution and resource depletion associated with fossil fuel generation
Does it promote smart behavior?	**Depends:** Enhances storm resiliency and energy island effects; as penetration of solar and wind generation increases pairing with energy storage may become necessary
Is it fair?	
Is it accessible?	**No:** Private clean energy procurement would not be accessible to all for technical reasons (e.g., roof siting or state of repair); pairing this policy with the purchase of clean energy is a partial solution
Is it affordable?	**No:** Private clean energy procurement would not be affordable to all; pairing this policy with public funding, lease options, and virtual net metering is a partial solution
Are workforce opportunities just?	**Depends:** Opportunity for diverse new workforce and contractors depends on program design
Who gets to decide?	
Is it inclusive?	**Depends:** Opportunity for inclusive decision making with intentional planning and prioritization
Are values considered?	**Depends:** Opportunity for values-based decision making with intentional planning and prioritization
Is it measurable?	**Depends:** Easy measurement for dollars, installed capacity; more difficult for generation, community and workforce impacts

Carbon Free Boston's strategy to catalyze rooftop solar will add a GHG-free source of electricity for the City, and reduce harmful pollution associated with fossil fuel generation. There is potential for private rooftop solar to alleviate existing inequity over time via lower energy costs and customer bills associated with the declining cost of solar energy. Information about technical and financial assistance must overcome income, cultural, and language barriers. Households that are unable to install rooftop solar for financial or technical reasons should nevertheless be able to participate in the local renewable energy market by way of clean energy procurement, public funding, lease options, or virtual net metering. A citywide solar energy initiative will require lots of new construction and maintenance that can expand the strength and diversity of the local workforce with intentional design.

The emissions reductions associated with new district energy systems will be short lived if fossil fuels are used (Figure 45). 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. One option that would require no significant change to existing infrastructure would be the substitution of fossil natural gas with sustainably sourced, GHG-free natural gas. Alternatively, sustainably sourced solid biomass could also be used as a source of energy but would require retrofits of existing systems as well as the construction of storage facilities and the transport of biomass. Hydrogen generated from renewable electricity has much higher costs and would require new pipeline infrastructure.

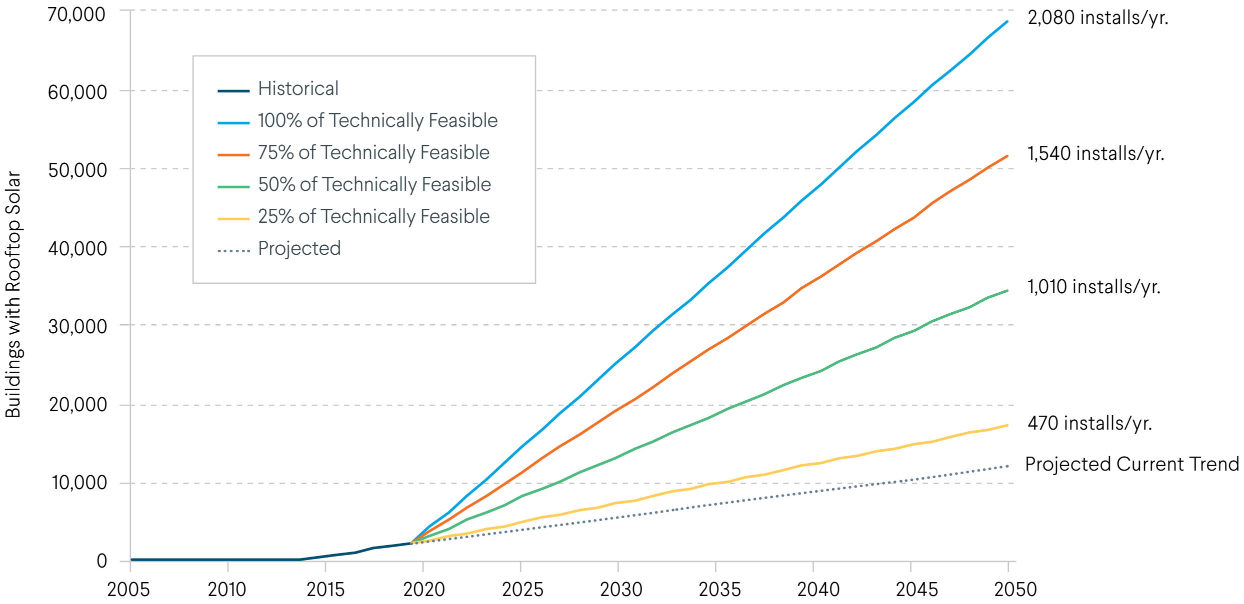
District energy systems can leverage heat sources other than fossil fuels, such as heat pumps that utilize waterbodies, sewage lines, subway systems, data centers, industrial processes, and the ground. While a full assessment of the potential of these systems was outside the scope of our analysis study, these potential resources merit deeper investigation.

Procurement Of Clean Electricity

One of the fundamental assumptions of our work is that 80 percent of electricity supplied to Massachusetts from the New England grid will be generated by renewable sources by 2050. That means that 20 percent of electricity would come from other sources, presumably natural gas. This means that there will be GHG emissions remaining in Boston's inventory even if it aggressively pursues the actions described in the Buildings, Transportation, and Waste chapters. Achieving carbon neutrality will require an additional important action: the procurement of 100 percent zero-carbon electricity and fuels.

Figure 43. Possible Future Installations of Rooftop Solar in Boston

Historical installs of rooftop PV 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 installations from Massachusetts Clean Energy Center; forecasts are Institute for Sustainable Energy model calculations.



There are three ways to procure 100 percent zero-carbon electric power: (i) buying MA Class I Renewable Energy Certificates (RECs), (ii) purchasing zero-carbon electricity directly from a producer via a local ISO-NE power purchase agreement (PPA), and (iii) entering into a virtual power purchase agreement (VPPA).

Renewable Energy Credits

A renewable energy credit (REC) certifies that electricity is actually produced from a renewable source. Specifically, a REC is a tradable certificate that represents the renewable attribute associated with one megawatt-hour (MWh) of electricity that was generated from a renewable energy source.

To convincingly achieve carbon reductions though REC procurement, the RECs should be “additional.” Additionality has three stringent tests. First, the project cannot be common practice or required by regulation. Second, the source of renewable energy must be “in addition to” current energy sources. Third, the financial incentive from the REC market should have enabled the project.

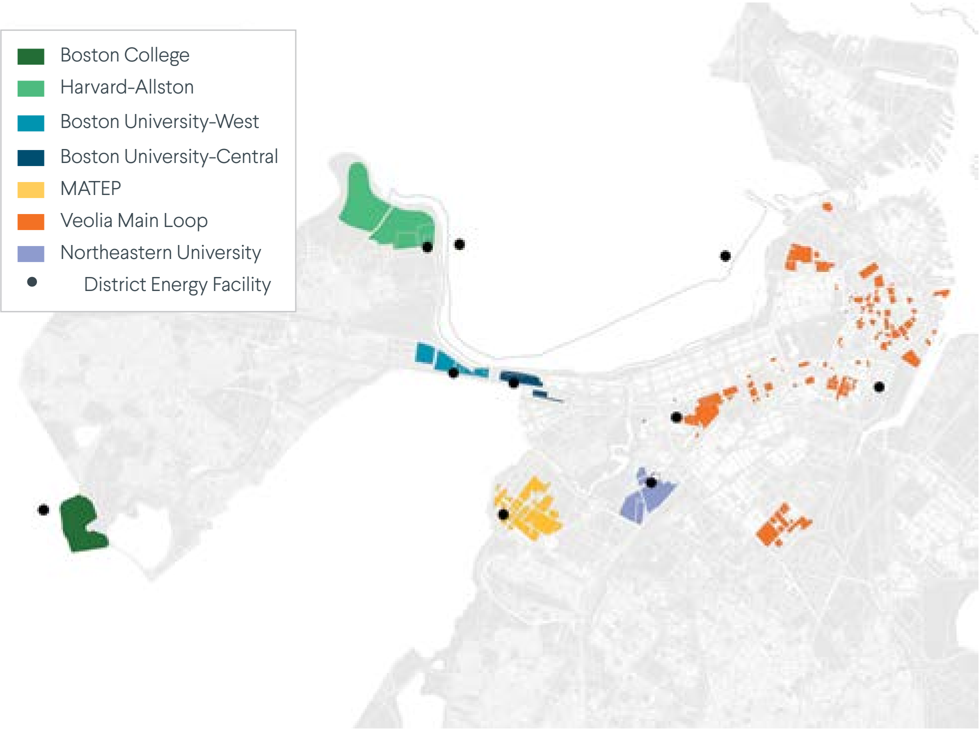
In Massachusetts, so-called “MA Class I RECs” may be generated from solar, wind, tidal, small hydropower (<30 MW), landfill methane and anaerobic digester gas, marine or hydrokinetic energy, geothermal energy and eligible biomass fuels. Our assessment of MA Class I RECs indicates that they are likely to satisfy the critical additionality criterion, and thus they may be a reasonable option for Boston to procure clean electricity.

Local Power Purchase Agreement

A second option to purchase clean electricity is to buy directly from a producer via a local ISO-NE power purchase agreement (PPA). A PPA is a contract between two parties, one of which generates electricity and the other being the customer, in this case Boston, looking to purchase electricity. In order for this electricity to be deemed zero-carbon and delivered to Boston, a PPA would need to specify that the electricity purchased comes from a clean generation unit connected to the ISO-NE grid, or delivered to ISO-NE by using firm, contracted transmission capacity.

Figure 44. Boston’s District Energy System

The colored areas are properties with buildings served by various district energy systems in the City and their central plants. Source: BERDO data and Boston Tax Assessors Database.



One particular form of a local PPA is for the City to purchase power on behalf of all residents and then decide for a utility to deliver it, much like current retail electric power suppliers. This is a municipal or community choice aggregation (CCA). Many of Boston's neighboring towns and cities have successfully implemented CCAs and increased the amount of zero-carbon electricity consumed in the Commonwealth. Boston has launched the development of a CCA program.

Virtual Power Purchase Agreement

The third procurement option is a Virtual Power Purchase Agreement (VPPA). A VPPA is the physical purchase of power from a carbon-neutral generation unit that is too far away to deliver the power to Boston. In this case, Boston would purchase the renewable power from a generation unit elsewhere in the country, and then resell the power in that distant market, since it cannot take physical delivery. By doing this, Boston could legitimately claim credit for the generation of 100 percent carbon-neutral power equal to its contracted electricity use.

VPPAs are an important tool for institutions that have strong climate action plans but are constrained by the carbon-intensity of their local grid, or by some of their own operations that are hard to decarbonize. In 2016, MIT, Boston Medical Center, and Post Office Square Redevelopment Corporation formed an alliance to buy electricity from a new, 60-megawatt solar farm in North Carolina. The project involves a 25-year VPPA between the three Boston-area institutions and Dominion, the Virginia-based energy company, which will own the facility and assume responsibility for the project's full development cost with financing made possible by the guaranteed power purchase. The City of Boston is currently evaluating the possibility of engaging in an inter-city VPPA to procure 100 percent clean energy for its municipal operations.

Figure 45. 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.

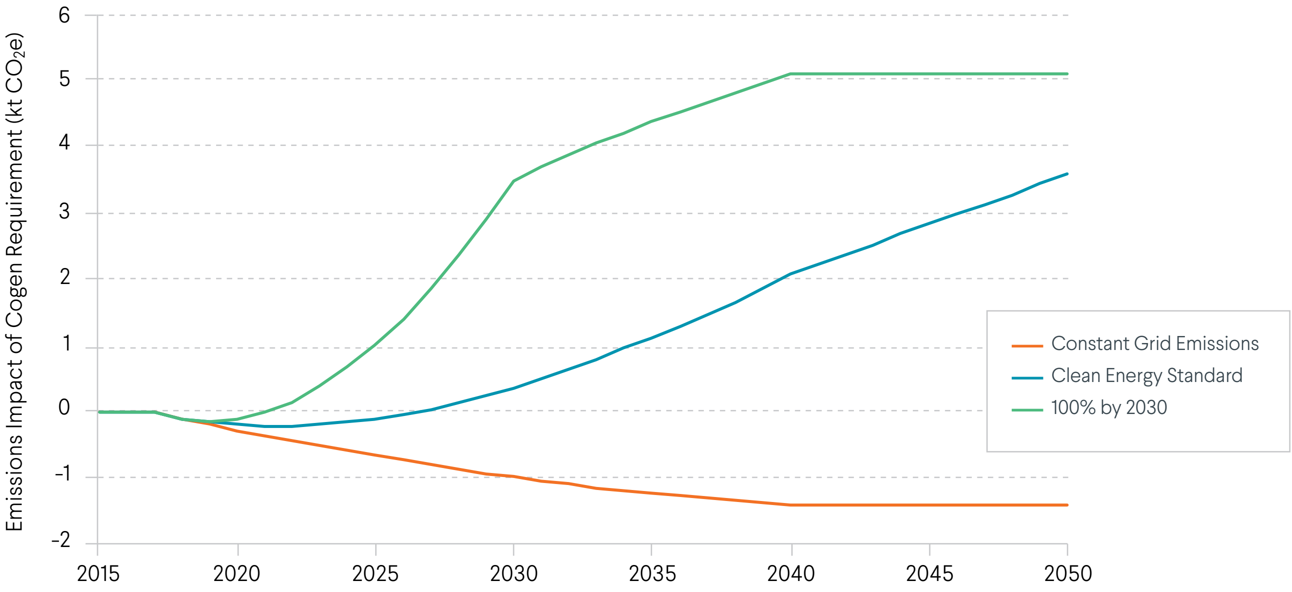


Figure 46. Equity Scorecard: Municipal Aggregation/Community Choice Energy

Components	Evaluation
Is it green?	
Is it GHG-free?	**Yes:** Will increase adoption of GHG-free energy supply
Is it environmentally sustainable?	**Yes:** Reduces air pollution and resource depletion associated with fossil fuel generation
Does it promote smart behavior?	**No:** Does not impact how private individuals or the public sector consume energy
Is it fair?	
Is it accessible?	**Yes:** Public clean energy procurement reduces obstacles to accessibility; intentional information campaigns need to ensure education regarding municipal aggregation programs and the option to opt out
Is it affordable?	**Depends:** Public clean energy procurement may impact the price of energy in either direction; opt-out option could improve affordability
Are workforce opportunities just?	**Depends:** Opportunity for diverse new workforce and contractors depends on adding specific policy choices
Who gets to decide?	
Is it inclusive?	**Needs to be addressed:** Opportunity for inclusive decision making with intentional planning and prioritization
Are values considered?	**Needs to be addressed:** Opportunity for values-based decision making with intentional planning and prioritization
Is it measurable?	**Needs to be addressed:** Easy measurement for dollars and generation; more difficult for community and workforce impacts

Carbon Free Boston's strategy to procure GHG-free electricity, possibly through municipal aggregation (also known as community choice energy), will increase the City's clean energy supply and reduce harmful pollution associated with fossil fuel generation. The procurement of GHG-free electricity by the City would significantly enhance equity by giving all Bostonians access to affordable, clean electricity. These positive outcomes require that socially vulnerable populations are represented in decision making, and that the City informs the public about the procurement programs and how to opt-out if needed or desired. Such programs have the potential to either increase or decrease energy costs for households.

The Future of Clean Electricity in Boston

The City has a number of options to meet a growing demand for clean electricity (Table 6). As the cost of building wind and solar generation declines (Figure 47) so too will the purchase price of 100 percent renewable power. Rooftop solar PV can supply up to one-sixth of the city's electricity demand, and expanding this type of energy supply system will boost the regional economy.

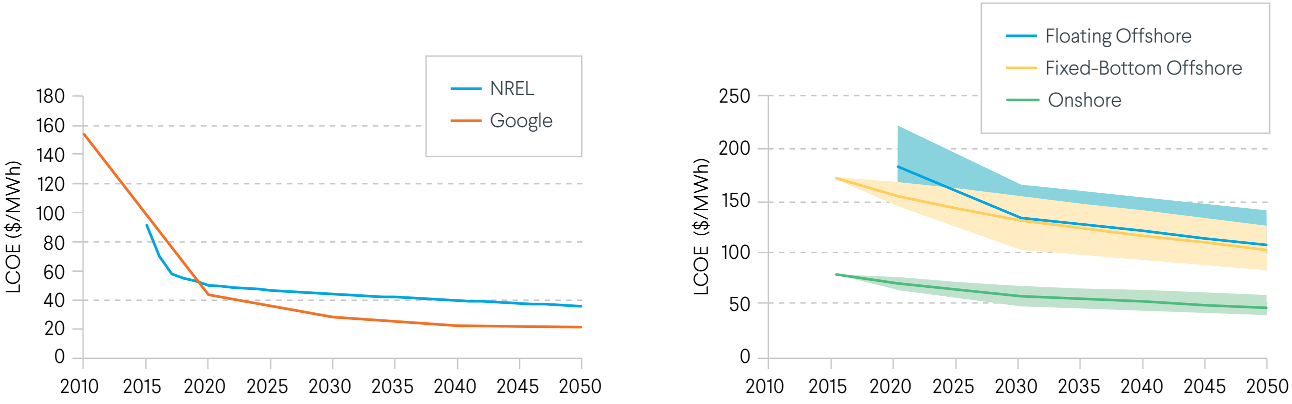
The three purchase approaches to obtaining clean electricity—PPAs, VPPAs, and the purchase and retirement of RECs with additionality—can be combined to yield the required amount of clean electricity. It is difficult to define a precise prescription for the combination and timing of procurement action due to uncertainty of future cost and market conditions. Our overall conclusion is that the City has good and improving opportunities to obtain clean electricity via all of the three procurement options. Reaching 100 percent GHG-free electricity by 2030 would enable the City to meet and exceed its interim target of a 50 percent reduction in emissions (2005 baseline) and meet the rate of decarbonization needed to align itself with the ambitious objectives of the Paris Climate Agreement.

Table 6. Summary of GHG-free Electricity Options

Mechanisms	Constraints	Benefits	Costs
Rooftop Solar	~15-20% of city demand	Local jobs, resiliency	High, but declining steadily
Carbon-Free District Cogen with Clean Fuels	Limited in-city application & supply of alternative fuels	Local jobs, resiliency	Moderate
Renewable Energy Credit Aggregation	New England market	Local jobs	Moderate
Local Power Purchase Agreement (e.g., Community Choice Aggregation)	New England market	Local jobs	Moderate
Non-local (Virtual) Power Purchase Agreement	Complexity of agreement	Cleans up fossil-intensive grids	Low

Figure 47. Declining Cost of Renewable Electricity

Levelized cost of energy (LCOE) of utility-scale electricity from solar PV (left) and wind (right) showing declining costs of renewable energy technologies. Data from National Renewable Energy Laboratory and Google.org



The Potential for Clean, Renewable Fuels

Electrification of building heating and transportation systems will significantly reduce fossil fuel consumption in Boston. However, not all energy services can be electrified and a residual amount of natural gas and diesel fuel will be necessary to provide certain key services (Table 7). Heavy transport such as trucking and ferry service may be difficult to electrify. In the buildings sector, the sheer number of building retrofits may be the biggest challenge to electrification. Fuels are essential for emergency services at a number of critical facilities including the Boston's hospitals, data centers, airport, and transit systems.

The residual GHG emissions shown in Table 7 amount to about 10 percent of Boston's current total GHG emissions. The fuels generating those emissions potentially could be replaced by low- or zero-GHG bioenergy or synthetic fuels, both of which can be produced with technologies that exhibit a wide range of technical viability, commercial availability, lifecycle GHG-intensity, and environmental sustainability.

Lifecycle analysis should be used in the evaluation of renewable fuels for two reasons. First, renewable fuels vary dramatically in their energy, GHG, and overall sustainability impacts. Second, in the complete overhaul of its energy system, the City has a diverse palette of choices, and it can actively and deliberately consider the impacts of its decisions beyond the narrow criterion of impact on its GHG inventory.

Liquid Biofuels

Ethanol and biodiesel produced from biomass are used on a large scale in many parts of the world. On the surface many biofuels may appear to be carbon neutral because the carbon a plant takes up during photosynthesis appears to be balanced by the carbon released when the biofuel is burned. In reality, most biofuels produce very modest GHG reductions relative to the petroleum fuel they replace.[18] Biofuel supply chains use large quantities of fossil fuels and agricultural chemicals, they often drive land use change that releases carbon dioxide into the atmosphere, they cause significant environmental damage, and in some nations, they dramatically exacerbate social inequality.

Table 7. Current and Projected Fuel Use by Sector and Associated GHG Emissions

Sector	Remaining Service	Current Demand (TWh)	Estimated 2050 Demand (TWh)	Current Emissions (kt CO_2e)	2050 Emissions (kt CO_2e)
Transportation	Heavy trucking, ferry	7.29	0.38	1,937	102
Buildings	Backup generation, legacy equipment, difficult/costly to electrify systems	12.05	2.90	2,239	528
MWRA	Backup generation	0.03	0.03	7	7
Massport	Backup, generation, snow melting, air support equipment	0.24	0.08	59.6	18.5
MBTA	Space heating, backup generation	0.07	0.02	18.9	5.1
Total		**19.7**	**3.4**	**4,262**	**661**

* Notes: Estimates of 2050 demand in buildings and transportation are taken from each sector's high electrification scenario. The estimates for other services reflect the continued use of fuels for critical services (backup generation, snow melting, etc.), and partial electrification of some services (e.g., Massport buildings and ground equipment). Source: Model calculations.

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[18] U.S. Environmental Protection Agency, Office of Transportation and Air Quality, July 2016, *Lifecycle Greenhouse Gas Emissions for Select Pathways* https://www.epa.gov/fuels-registration-reporting-and-compliance-help/summary-table-lifecycle-greenhouse-gas-emissions

Our assessment of biofuel supply chains indicates that sustainably-sourced biodiesel is a viable substitute for conventional diesel fuel in heavy-duty trucks, ferries, and emergency back-up energy systems. The best choice from a lifecycle GHG perspective is waste cooking oil and tallow but local supplies of these feedstocks are limited. Soy or canola-based biodiesel can provide a 50 to 60 percent reduction in GHG compared with petroleum diesel; however, these crop-based sources can have significant environmental and social impacts if not sustainably sourced. Thermal conversion of organic wastes is an emerging technology that could render a sustainable biodiesel. Because of the limited supply of low-carbon biofuels, all transport technology should be electrified as deeply as possible.

Renewable Natural Gas

Renewable natural gas (RNG), also known as biomethane, is methane gas manufactured from biological sources that is fully interchangeable with conventional natural gas. RNG can be distributed to buildings via the existing gas grid and used with existing equipment (gas stoves, furnaces, and hot water heaters). Biological feedstocks have low energy densities and are highly dispersed, which currently restricts biomethane production to anaerobic digesters at wastewater treatment plants and the capture of methane from landfills. The MWRA's Deer Island Wastewater Treatment Facility anaerobically digests the organic matter in wastewater to generate methane that is then combusted on site to generate almost all of the heat and one quarter of the electricity used at the facility. The potential to expand the sources and conversion pathways for biomethane is an area of active research and should be closely monitored by the City.

Biomass

Biomass combustion generates electricity or heat from the burning of solid organic matter such as wood pellets. Unlike renewable natural gas, biomass is not a “drop-in” solution for Boston. Switching existing energy plants to biomass would require new systems for boilers, emissions control, transport, and storage. Such a transition will likely have substantial costs and ultimately may not deliver the requisite carbon reductions in the absence of a sustainable source of biomass.

Our assessment of fuels from biomass lead to the following issues for the City to consider in its evaluation of any biologically-based energy source. First, currently there are no zero-carbon biomass supply chains, because they all use fossil fuels somewhere in the process of harvest, transport, conversion, and delivery. This may improve as other sectors decarbonize. Second, each biomass supply chain has a unique GHG and overall sustainability impact. Some provide significant GHG benefits, while others are worse than their fossil fuel counterparts and degrade environmental quality. Third, in many cases the use of land to provide bioenergy precludes its use for carbon storage, which is an essential climate-neutral action in addition to GHG reduction.

Hydrogen from Renewable Electricity

Hydrogen is a versatile fuel that is GHG-free at the point of combustion. The manufacture of most hydrogen today releases substantial GHGs because it relies on fossil fuel feedstocks (methane). But hydrogen can be produced with extremely low lifecycle GHGs with wind or solar electricity to drive electrolysis (splitting water into hydrogen and oxygen). This is known as a "power-to-gas" technology: the conversion of electrical power into gas that can be later distributed and combusted on an as-needed basis.

Hydrogen's versatility lies in the fact that it can directly generate electricity via a fuel cell or release heat through combustion. Its ability to be stored at high volumes makes it a suitable long-term storage medium for surplus electric power that can enhance the reliability of electricity delivery.

This versatility and storage potential could position hydrogen as an ideal fuel to deliver thermal and backup energy services. Renewable hydrogen can be blended into existing natural gas distribution systems to approximately 5 to 15 percent under current distribution and end use technologies. This would lower the GHG intensity of gas use but would not be sufficient to meet a carbon-neutrality goal. Higher levels would require significant infrastructure changes as hydrogen corrodes cast iron pipes that make up a considerable portion of the current gas infrastructure system.

"Energiepark Mainz" located in Mainz, Germany, is connected to an 8 MW wind farm. Three electrolysis units can produce 1000 Nm^3 hydrogen per hour (89.8 kg/h). Photo credit: Stadtwerke Mainz AG

The production cost of hydrogen is currently 15 to 25 times the cost of natural gas. The cost of developing a delivery infrastructure for hydrogen is large. Hydrogen can be transported under pressure via pipeline or truck, liquefied by refrigeration, or by using ammonia as a carrier. There are many large dedicated hydrogen pipelines already working around the world, generally associated with chemical plants or refineries, but these are mainly individual pipelines that span short distances. There is little utility-scale hydrogen delivery infrastructure anywhere in the world, but that may change quickly. Urban hydrogen distribution is currently in development in Leeds, UK, a city about the size of Boston. A growing number of power-to-gas projects using wind energy are being built that demonstrate technological viability. Conceivably a district scale hydrogen plant would lay the foundations of an infrastructure that could grow to support smaller applications. For these reasons, the City should monitor the rapidly evolving status of hydrogen as part of its overall energy and climate planning.

Massport free shuttle bus service between airline terminals at Logan Airport, Boston. Photo credit: Mark Waugh/Alamy Stock Photo

The Future of Clean Fuels in Boston

Low- or zero-carbon renewable fuels currently have a modest role to play in Boston, but technological advances could quickly change that picture. The feedstock for renewable natural gas exists in the form of organics in municipal solid waste and wastewater in Boston and surrounding communities. Much of the organic material in municipal solid waste is currently burned in waste-to-energy facilities at a much lower efficiency compared with anaerobic digestion that produces renewable natural gas. Boston's organic waste alone could provide 20 percent of residual gas demand in 2050 (Table 7, page 95). This technology is widely used around the world, and is currently being used to generate sustainable energy from Boston's wastewater. Boston can advance this option by collecting its organic wastes, attracting the capital to build a local digester, and cultivating potential consumers.

Boston's famous "Duck Boats" use biodiesel fuel that has lower greenhouse gas emissions compared with diesel fuel made from petroleum.
Photo credit: Lee Snider Photo Images/Shutterstock

Eliminating Methane Leaks

As natural gas moves through the pipeline system, emissions occur through intentional venting and unintentional leaks; together these are called "fugitive emissions." Eliminating these emissions is essential to reaching carbon neutrality because the global warming impact of methane is 28 to 100 times more potent than carbon dioxide. There is considerable uncertainty regarding the rate of fugitive emissions, but it appears that the Boston metro region is characterized by rates of fugitive emissions that are consistent with the most recent national estimates of 1 to 3 percent of gas supply. National Grid replaced about 550 miles of leak prone pipe from 2013 to 2017 in its Boston gas territory, and set a goal of 100 percent replacement of pipeline in less than 25 years. Cooperation among the City, the Commonwealth, National Grid, and other stakeholders will hasten the elimination of pipeline leaks as a critical ingredient of a carbon-neutral city.

Healthy Urban Trees Methane can damage the roots of trees, so repairing the gas leaks under Boston's streets promotes a healthy urban forest.
Photo credit: City of Boston

A Clean Energy Future for Boston

Over the next three decades, all of Boston must work to transform the city's energy system from one powered by fossil fuels to one powered by clean electricity and fuels. Our assessment indicates that the City and its partners have viable options to achieve this transformation, and at the same time provide safe, reliable, and clean energy for every person that lives, works, or visits Boston. Building a clean energy system will expand economic opportunities and improve quality of life.

Managing the transition to clean energy will require the City to take new action, such as leadership in the installation of rooftop solar, the procurement of clean electricity, and decisions regarding the choice of renewable fuels to replace petroleum. To do this, the City must work with its business and utility partners, energy and climate experts in academia and NGOs, community leaders, and state government. Collaborative decision making will ensure that every person in Boston has equal and affordable access to 100 percent GHG-free energy—a goal that is readily achievable by 2050, if not sooner.

Solar panels on the Epiphany School in the Dorchester neighborhood of Boston. Photo credit: Resonant Energy

SECTION 7

Offsets

Background

Overview

The strategies laid out thus far to decarbonize buildings, energy supply, transportation, and waste systems will put Boston on a path toward carbon neutrality. However, to address Boston's residual emissions—those the City is unable to reduce directly—the City will have to consider the potential role offset purchases may play.

Our illustrative scenario indicates that even with aggressive action on efficiency, electrification and clean electricity procurement, and zero-waste initiatives, approximately 500,000 tons, a little less than 10 percent of current emissions, will remain in 2050. The bulk of these emissions will likely be from fuel use. While some alternative fuels could substitute, their supply may be limited or they may deliver a partial reduction in emissions due to life cycle constraints. Other emissions may be nearly impossible or significantly costly to mitigate, such as process emissions from wastewater treatment and organic waste diversion. Thus, the City needs to plan for the use of offsets not only for the mitigation of hard to reduce emissions, but also potentially as a mechanism to achieve early ambitious emissions reductions goals.

What Is an Offset?

A carbon offset certificate, more often referred to simply as an offset or carbon credit, represents a metric ton of verified carbon dioxide or equivalent GHG emission that is permanently reduced, avoided, or removed ("sequestered") from the atmosphere through an action taken by the creator (i.e., project developer) of the offset. After the project and its GHG impact are verified by an independent third party, the creator is awarded a certificate showing the size of the reduction in tons of carbon-dioxide equivalent (CO_2e). The certificates can be traded or retired (that is, not re-sold); retiring emissions is an essential component of an overall voluntary emissions reduction strategy, alongside activities to lower an organization's direct and indirect emissions. In the *Global Protocol for Community-Scale Greenhouse Gas Emission Inventories* (GPC), the GHG accounting system used by the City of Boston, any carbon-offset certificates the City has created or purchased can be deducted from the City's GHG emissions.

One of the important steps to creating offsets is validation that the creator of the offset took an action that would not have otherwise occurred if that individual or organization was not pursuing offset certificates. As described earlier in this report, this aspect of offset validation is known as additionality, and it is a fundamental requirement that underpins the ability for offsets to drive change in net emissions. Emissions can only be "offset" if it is clear that those emissions reductions would only have occurred due to the specific project, status quo market trends and regulations would not have created those reductions, and the project did not move the emissions to somewhere else.

Offset Criteria

Historically, not all offset projects have realized their promised GHG emissions reductions, defeating the purpose of the investment and leading to mistrust of offsets as a mechanism to drive down global GHG emissions. To address these concerns, a number of best practice requirements have been established and upheld by third-party standards. The vast majority of projects on the voluntary market follows rules and procedures set out by five third-party carbon standards: the American Carbon Registry (ACR), the Climate Action Reserve, the Gold Standard, Plan Vivo, and Verra's Verified Carbon Standard (VCS). These standards seek to enforce the quality of offsets and increase transparency in the market. To be considered a verified emissions reduction, the offset must result from a project that meets a number of standard criteria:

- **Additional:** beyond business as usual (uneconomical, not policy driven);
- **Permanent:** non-reversible, lasts in perpetuity;
- **Real:** not subject to leakage (does not force emissions elsewhere), generates a true net reduction in GHG emissions;
- **Verifiable:** measurable, must be confirmed and monitored;
- **Enforceable:** clearly defined, exclusive ownership (to avoid double counting).

As the offset market matures, some procurers (end users) are looking for projects that meet other criteria. They may want to ensure the offsets are synchronous, only considering them valid if the GHG emission reductions, avoidance and removals occur during a distinct period of time that is reasonably close to the time it is used to balance, compensate, or offset their GHG emissions. More and more, end users seek projects that result in benefits beyond GHG emissions reduction and provide environmental, health, economic, and social benefits for local communities, either at home or abroad. They want project selection to consider all direct and indirect social and environmental impacts of the offset project, along with potential educational, economic development, and resiliency benefits. Similarly, they avoid projects with harmful impacts.

Offset Project Typologies

There are several common types of offset projects, and other typologies are emerging. The most common include

- **Energy Efficiency and Fuel Switching:** Improvements that reduce energy consumption and replace dirtier fuels with cleaner ones. Examples include the replacement of conventional light bulbs with LEDs; the provision of efficient and clean-energy cook stoves to replace open-fire combustion of wood, crop residues, and dung; and changes to water filtration and agricultural processes to reduce energy intensity.
- **Renewable Energy:** Projects range from the capture of methane at a landfill (see below) for use as a renewable fuel to large-scale wind turbine projects and sustainable biomass projects to replace wood burning in critical ecological places (e.g., the Amazon Rainforest).
- **Waste and Wastewater Management (Methane):** Projects that achieve emissions reductions by capturing and collecting methane, a GHG that is more than 20 times more potent than CO_2, from landfills or wastewater and then converting it to usable, renewable fuel for heating or transport.
- **Forestry and Land Use:** Biological sequestration projects that result in the removal of carbon from the atmosphere and storage of that carbon in living organisms, mostly plants. They include planting new trees where there were none originally, enhancing trees' carbon density through improved forest management, and avoiding deforestation.

There are other project types beyond the energy, waste, and land use ones listed above. They tend to be less common, either because they are hard to quantify, hard to enforce, hard to guarantee permanence, or they provide the risk of greater emissions. For some, this is due to the relative infancy of the technology, and, therefore, there is either a lack of information on the long-term consequences, a high cost to implement, or both.

Another offsetting strategy is the retirement of compliance credits. Compliance markets have developed in response to mandatory regional, national, or international programs.

Internationally, this has mostly focused on the requirements of the Kyoto Protocol;[19] however, related international standards and guidance are evolving due to the 2016 Paris Agreement. Voluntary buyers of carbon offsets, like Boston, can purchase the carbon credits from compliance markets and retire them, thus reducing the supply of compliance credits, increasing their price, and fostering the development of additional GHG emissions reduction projects.

Table 8. Transacted Volume, Value, and Average Price by Project Category

	Volume	**Average Price (per tCO_2e)**
Renewables	**18.3** $MtCO_2e$	**$1.4**
Forestry and Land Use	**13.1** $MtCO_2e$	**$5.1**
Methane	**5.6** $MtCO_2e$	**$1.8**
Efficiency and Fuel Switching	**4.5** $MtCO_2e$	**$2.9**
Household Device	**3.4** $MtCO_2e$	**$5.2**
Transportation	**1.9** $MtCO_2e$	**$0.3**
Gases	**1.4** $MtCO_2e$	**$5.7**
Other	**0.5** $MtCO_2e$	**$4.0**

Based on 717 transactions representing 48.8 MtCO2e in 2016. Source: *Unlocking Potential: State of the Voluntary Carbon Markets 2017* by Forest Trends.

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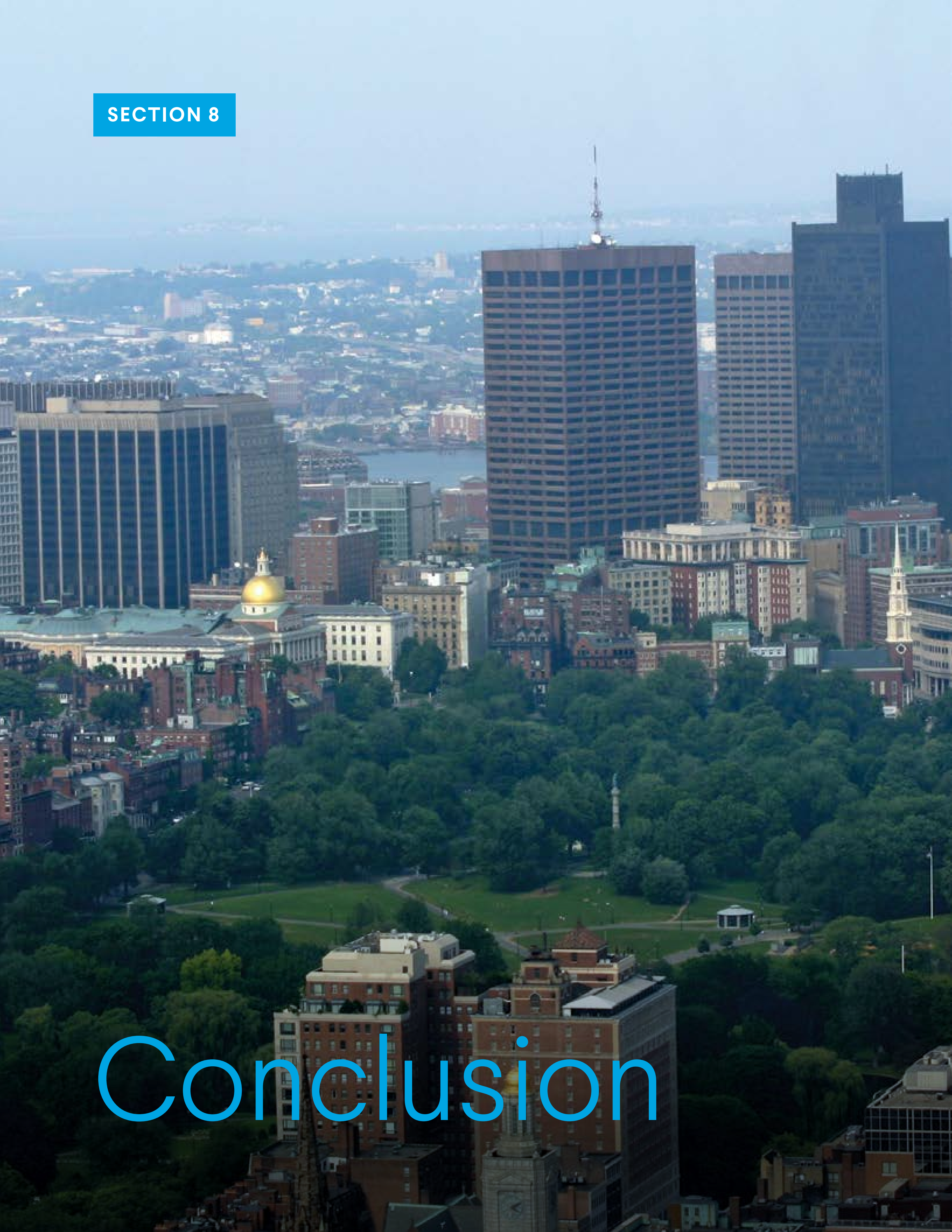
[19] The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) spurred creation of different programs, based on assigned carbon caps that were ratified by each participating country, thus making its achievement mandatory. The Kyoto Protocol established a cap-and-trade system, and to increase the cost-effectiveness of emissions reductions, established the Clean Development Mechanism (CDM) and Joint Implementation carbon markets. Fifteen -EU countries formed the EU Emissions Trading Scheme (EU-ETS). (Stockholm Environmental Initiative, 2018)



SECTION 8

Conclusion

The Path to a Carbon-Neutral Boston

The Essential Elements of a Carbon-Neutral Boston

About two-thirds of Boston's GHG emissions come from buildings, including the electricity used and the heating oil and natural gas burned to warm living space, produce hot water, and prepare food. The bulk of the remaining emissions come from the energy used to transport people and goods. For Boston to be carbon neutral, we must alter the way we design and operate our buildings, heat our homes, power our businesses, and get from place to place. The "we" here is a collective "we." Every Bostonian must work with the City government, state and regional planners, designers, building owners, and energy utilities to make this happen.

At a high level, what must be done is clear. The results of our assessment define a straightforward vision for carbon neutrality that depends on three self-reinforcing strategies, all of which must be pursued in a synergistic and socially equitable manner:

- **Maximizes Efficiency:** A carbon-neutral city minimizes the demand for energy. Every building is a high-performance building; travel shifts from single-occupancy vehicles to public transit, biking, walking, and shared modes; and waste diversion is maximized.
- **Electrifies Activity:** A carbon-neutral city converts most systems that currently run on fossil fuels, such as cars, furnaces, and stovetops, to use electricity instead. Heating systems are converted to heat pumps and electric boilers where feasible. Light- and medium-duty vehicles are powered by electric motors.
- **Runs on Clean Energy:** A carbon-neutral city purchases electricity that is 100 percent GHG-free, and it fully utilizes the potential for in-city renewable generation, such as rooftop solar. Sustainably sourced renewable fuels are used in highly efficient district energy systems, emergency backup energy systems, and heavy-duty vehicles.

Accelerating the Path to Carbon Neutrality

These strategies are a common theme through each of the pathways to carbon neutrality we described in the Buildings, Transportation, Waste, and Energy chapters. Together, they produce a 90 percent citywide reduction in GHG emissions by 2050 relative to 2015 (Figure 48). However, a straight-line path to carbon neutrality from 2015 to 2050 will not result in sufficiently rapid reductions in GHG emissions to support the effort to keep global temperature increases below 1.5°C, nor does it not meet the City's interim target of a 50 percent reduction in GHG emissions by 2030 relative to 2005.

Our analysis indicates that Boston can help meet that global climate goal and its own 2030 and 2050 emissions targets if it makes procurement of GHG-free electricity an immediate high priority. Figure 48 shows a pathway in which the City procures 100 percent GHG-free electricity by 2030. This path produces a steep decline in emissions that is generally consistent with a 1.5°C mitigation strategy, with emissions in 2030 57 percent lower than 2015, and within 10 percent of the 2050 neutrality target by 2050.

Energy Efficiency and Clean Electrification Are Keys to Carbon Neutrality

We emphasize energy efficiency and clean electrification (including City procurement) because the necessary technologies are in some cases already available and cost-effective, and the remaining enabling technologies are likely, in our judgement, to become economical at scale before 2050. Even when available and economical, we also recognize that energy efficiency and building electrification face significant funding and implementation challenges, especially at the scale and speed necessary to attain carbon neutrality in a disparate, aging building stock. However, challenges in the area of financing and implementation are those that are within the span of control of the City and its stakeholders. They can be overcome through larger efforts, new financing approaches, and new policies. In contrast, techno-economic leaps and breakthroughs are largely outside the City's control, and it is much less clear how to integrate them into near-term City actions.

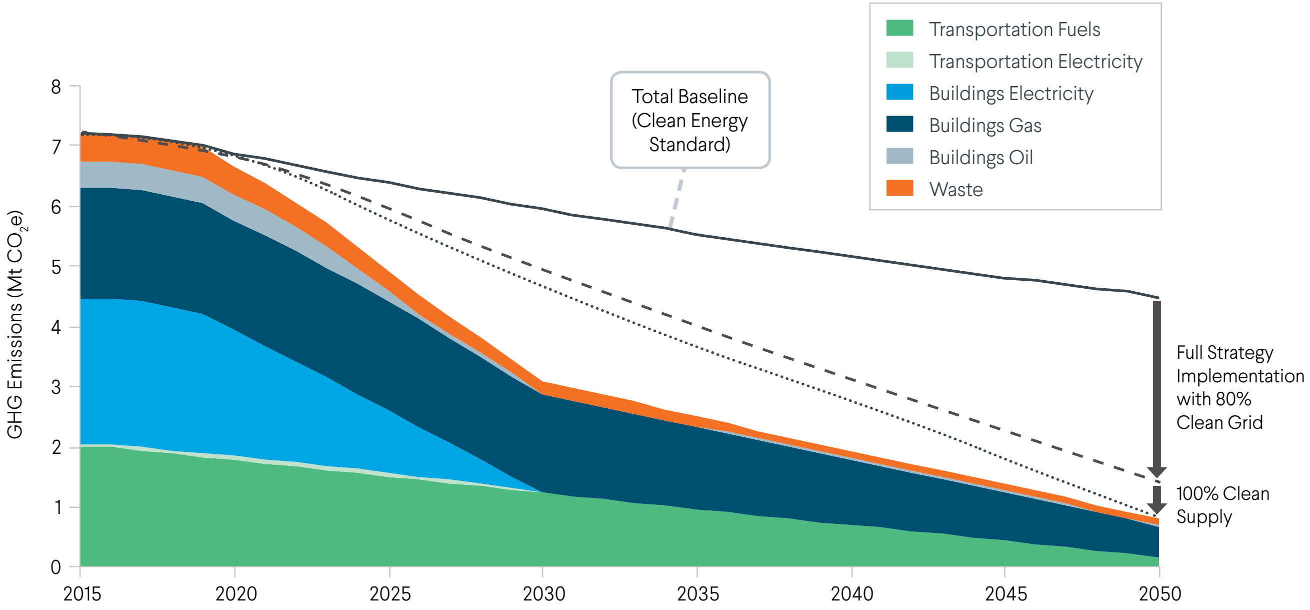
The bulk of the residual GHG emissions in 2050 are associated with fuels, so new technologies and policies are needed to provide fuel for some future uses. Because we see large technical and economic uncertainties surrounding carbon-free fuel options, and because these uncertainties are largely outside the City's control, our fundamental strategy opts for minimizing the use of these fuels, while continuing to monitor technical developments. It is entirely possible that technological breakthroughs will create a GHG-free gas or liquid fuel that is economical within the City sometime before 2050. If and when this occurs, it would certainly make sense for the City to use them everywhere they are more cost-effective.

There is no avoiding the reality that any pathway to carbon neutrality requires significant infrastructure investment and ambitious changes to the building and vehicle stocks in the city, not to mention the workforce and institutional capacity to implement this work. As technologies evolve and the City and its partners gain implementation experience, it can adjust its plans to improve the speed and cost-effectiveness of achieving carbon neutrality.

Carbon neutrality will require appropriate, and limited, third-party verified offsets to address residual GHG emissions. Prudent use of offsets is consistent with a fundamental reality of the climate challenge: a reduction in GHG emissions must be coupled with some element of carbon dioxide removal from the atmosphere, such as afforestation, to limit global temperature increase to 1.5 °C.

Figure 48. City Procurement of 100% GHG-free Electricity by 2030

The solid line is the baseline scenario under the Massachusetts Clean Energy Standard (80% clean electricity by 2050). The dashed line shows the emissions after the effect of the strategies for carbon neutrality that are described in the buildings, transportation, and waste sectors. The dotted line shows emissions if the City procures sufficient clean electricity to make its total electricity supply 100% GHG-free by 2050. A 100% GHG free supply by 2030 enables the City to meet its interim 2030 target, and is consistent with the action needed to keep global temperature increases below 1.5°C. Source: Institute for Sustainable Energy model calculations.



Benefits and Actions for a Carbon-Neutral City

Our assessment points to the fact that full implementation of the strategies will not just reduce GHG emissions—they will also further other economic, social and environmental goals of Boston. Increased public transit, walking, and biking improve public health, reduce congestion, improve public safety and strengthen social connectivity. Energy efficient buildings save people money, improve indoor air quality, and increase the value of buildings. Waste reduction, recycling and reuse create jobs and reduce pollution and resource depletion. Most strategies will require new investment that when summed together will create an enormous economic opportunity for Boston over the next few decades.

The attainment of carbon neutrality requires strong, long-term commitment and leadership from City Hall that will support action and coordination across all city agencies. Action needs to be bold and it needs to start immediately across multiple fronts: the decarbonization of all municipal activity, the reduction of waste sent to combustion, the construction of new bike lanes and sidewalks, demand management and pricing strategies to significantly reduce vehicle traffic, new performance standards for all buildings, and the procurement of GHG-free electricity.

An essential element of early action includes active, intentional engagement with the private sector, which owns and operates the vast majority of buildings and vehicles. It also necessitates engagement with state decisionmakers. The Commonwealth of Massachusetts has the authority to set building and energy codes, regulates utilities, expand and improve the MBTA, oversees vehicles standards and the major thoroughfares that bring vehicles into the city, and has authority over setting state and local tax rates and related fees. Additionally, the city can work with the Metro Mayors Coalition and other regional partners to collectively address regional infrastructure and markets as well as to advocate together at the state level for regulations that continue to support their local climate action goals. Working with other cities across the country, Boston can also push for comprehensive climate legislation, and can help promote broad, consistent policy that signals that change needs to happen everywhere.

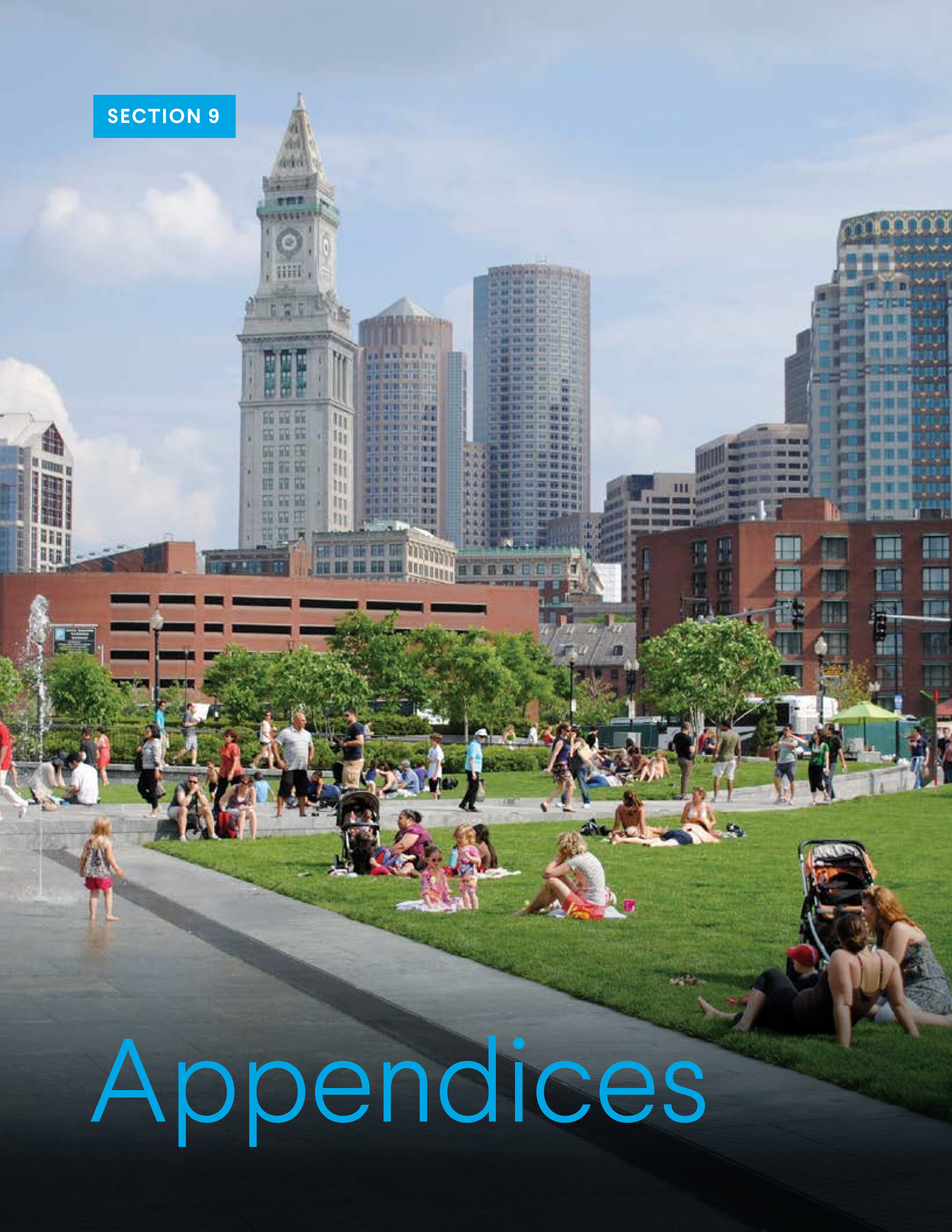
The executive order in 2007 did much more than commit Boston to reducing GHG emissions. It placed the City in the forefront of global climate action leadership. With leadership comes responsibility, and the City continues to demonstrate the action that cities must take to respond to the existential threat posed by climate change. Mayor Walsh bolstered the City's commitment in 2016 with a new goal of climate preparedness and carbon neutrality by 2050.

The *Climate Ready Boston* report was among the first rigorous and comprehensive city plans to confront the rising seas and more extreme weather caused by climate change. In 2018, the City released *Resilient Boston Harbor* with specific plans to protect the City's waterfront, including some the City's most vulnerable communities.

Carbon Free Boston extends this rich history of work with a comprehensive assessment of the options available to the City to reach carbon neutrality. The City has embraced an ambitious and critical objective; our analysis shows that achieving this objective will not be easy but is definitely within reach with a sustained, intentional effort. An effort joined by all Bostonians will create a more sustainable, more resilient, and more equitable city.

SECTION 9

Appendices



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Acknowledgments

Our work benefited enormously from the time, insights, and documents supplied from a wide range of people. Our heartfelt thanks goes to these individuals: Sanem Sergici, Laurie Burt, Jonathan Raab, Matt Stanberry, John Larsen, Michelle Manion, Bruce Biewald, Christoph Reinhart, Conor Gately, Rachel Eckles, Rafael Mares, Bud Ris, Paul Miller, Oliver Sellers-Garcia, Seth Federspiel, Susanne Rasmussen, Cammy Peterson, Timothy Reardon, Danny Musher, Zachary Tofias, Axum Teferra, Henry Lee, Cathy Pasion, Christine Donovan, Jonathan Levy, Pat Kinney, Galen Nelson, Kavita Ravi, Nathan Phillips, Lucy Hutyra, Ana María Cortés Camargo, Meredydd Evans, Page Kyle, Haidee Janak, Austin Blackmon, Elizabeth Youngblood, Andrew Belden and Israel Alvarez.

Conflict of Interest Disclosures for Project Leadership

Peter Fox-Penner holds equity in Energy Impact Partners, a utility-backed energy investment and innovation firm, and consults for Energy Impact Partners and The Brattle Group on energy technologies. Dr. Fox-Penner also conducts research in areas of interest similar to the business interests of Energy Impact Partners and The Brattle Group. The terms of this arrangement have been reviewed by Boston University in accordance with its financial conflicts of interest in research policies.

Cutler Cleveland and Michael Walsh 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.

Appendix B: Model Details

Baseline Parameters, Assumptions and Sources, for the *Carbon Free Boston* Analysis

PARAMETER	ASSUMPTION	SOURCE
GENERAL		
Population	800,000 people by 2050	MAPC 2014 Regional Growth Projections, BPDA Population Projections
BUILDINGS		
Floorspace	2016: 647 Msf 2050: 760 Msf	Boston Property Assessment 2018, MAPC 2014 Regional Growth Projections, Imagine Boston 2030, BPDA
Baseline New Building Policy	Stretch code improves linearly to achieve 12 kBtu/sf in 2045	Historical improvements in state energy code
Baseline Existing Building Policy	BERDO and MassSave Efficiency Policies average to 0.5% EUI reduction per year	BERDO and MassSave Policies
TRANSPORTATION		
Travel Activity Data (All modes)	2016: 4.1 billion VMT 2050: 4.2 billion VMT	CTPS travel demand forecasting model, MBTA
Vehicle Populations (All modes)	2016: 449,000 2050: 460,000	MA Department of Environmental Protection, City Fleet Inventory
Vehicle Fuel Efficiency	Steadily improving vehicle efficiency	Forecasts based on federal efficiency standards and other factors
2050 EV Penetration	10% of light-duty vehicles	Annual Energy Outlook
Public Transit Operations	Current transit services are held constant to 2050	MBTA, National Transit Database, General Transit Feed Specification
Active transit	Current bike and walking behavior is held constant to 2050	CTPS Model
Shared Mobility	Current market share of 6% is held constant though 2050	Current estimates of market share
WASTE		
Waste Generation	Per capita and commercial waste generation rates remain constant at 2017 levels	Boston Waste Generation Data, Zero Waste Boston Analysis
Waste Diversion	2017: 25% 2050: 25%	Boston Waste Generation Data, Zero Waste Boston Analysis
Wastewater	Process energy use remains constant but biological degradation emissions increase proportionate to population	Massachusetts Water Resource Authority Greenhouse Gas Inventory

Appendix B: Model Details

Baseline Parameters, Assumptions and Sources, for the *Carbon Free Boston* Analysis

PARAMETER	ASSUMPTION	SOURCE
ELECTRICITY SUPPLY		
Current Grid	327 kg CO_2e per MWh	2016 ISO New England CO_2e intensity
80% Clean Grid	76 kg CO_2e per MWh	2050 Mass Clean Energy Standard with 20% combined cycle natural gas
100 % Clean Grid	0 kg CO_2e per MWh	
FUEL SUPPLY		
Natural Gas	181 kg CO_2e per MWh	IPCC fuel emissions factor
Diesel/Fuel Oil	252 kg CO_2e per MWh	IPCC fuel emissions factor

BERDO: Building Energy Reporting and Disclosure Ordinance

VMT: Vehicles Miles Traveled

MAPC: Metropolitan Area Planning Council

BPDA: Boston Planning and Development Authority

CTPS: Central Transportation Planning Staff of the Boston Region Metropolitan Planning Organization

MWRA: Massachusetts Water Resources Authority

MBTA: Massachusetts Bay Transportation Authority

IPCC: Intergovernmental Panel on Climate Change

Glossary

adaptation
Adjustment or preparation of natural or human systems to a new or changing environment that moderates harm or exploits beneficial opportunities.

anthropogenic
Made by people or resulting from human activities; usually used in the context of emissions that are produced as a result of human activities.

biofuel
Gas or liquid fuel made from plant material. Includes wood, wood waste, wood liquors, peat, railroad ties, wood sludge, spent sulfite liquors, tires, agricultural crops, agricultural waste, straw, fish oils, tall oil, sludge waste, waste alcohol, municipal solid waste, landfill gases, and other waste

biogas
A gaseous mixture composed principally of carbon dioxide and methane that is generated from the biological decomposition of organic materials in the absence of oxygen. Depending on the type of organic source material and how it is processed, it also contains trace amounts of hydrocarbons other than methane, hydrogen sulfide, hydrogen, nitrogen, oxygen, carbon monoxide, ammonia, and water. Common feedstocks of biogas include landfills, wastewater treatment plants, food waste, livestock manure, and other agricultural residues or biomass.

biomass
Materials that are biological in origin, including organic material (both living and dead) from above and below ground—for example, trees, crops, grasses, tree litter, roots, and animals and animal waste.

biomethane
A form of biogas that has been processed to meet pipeline quality standards by increasing the fraction of methane via the removal of carbon dioxide, hydrogen sulfide, and other trace constituents. Such processing produces a gas that can shipped in gas pipelines and used interchangeably with conventional (fossil or geologic) natural gas. Also called "biogenic" gas.

carbon capture and sequestration (CCS)
A set of technologies that could greatly reduce carbon dioxide emissions from new and existing coal- and gas-fired power plants, industrial processes, and other stationary sources of carbon dioxide. It is a three-step process that includes capture of carbon dioxide from power plants or industrial sources; transport of the captured and compressed carbon dioxide (usually in pipelines); and underground injection and geologic sequestration, or permanent storage, of that carbon dioxide in rock formations that contain tiny openings or pores that trap and hold the carbon dioxide.

carbon dioxide (CO_2)
A naturally occurring gas, and also a byproduct of burning fossil fuels and biomass, as well as land-use changes and other industrial processes. It is the principal human caused greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a global warming potential (GWP) equal to 1.

carbon dioxide equivalent (CO_2e)
A unit of measurement that allows the effect of different greenhouse gases and other factors to be compared using carbon dioxide as a standard unit for reference. CO_2e are commonly expressed as “million metric tons of carbon dioxide equivalents (Mt CO_2e).” The carbon dioxide equivalent for a gas is derived by multiplying the tons of the gas by its associated global warming potential (GWP):
Mt CO_2e = (million metric tons of a gas) * (GWP of the gas).

carbon footprint
The total volume of GHG emissions caused by a community, organization, event, product, or person.

carbon intensity
The number of emissions of carbon dioxide released per unit of another variable, such as Gross Domestic Product (GDP), output energy use, or transport.

carbon offset
A credit for greenhouse gas reductions achieved by one party that can be purchased and used to compensate (offset) the emissions of another party. Offsets are typically measured in tons of CO_2-equivalents, and are bought and sold through a number of international brokers, online retailers, and trading platforms. Common forms are included investments in renewable energy, energy efficiency, and forestry.

clean electricity
Electricity produced from clean energy sources.

clean energy
A group of energy sources that have low-to-no direct greenhouse gas emissions including nuclear power, geothermal, carbon capture and storage, hydrokinetic energy, hydropower in addition to renewables, such as solar, wind and biomass. Distinction between clean energy and renewables is often defined by statute.

climate
(i) the average weather; (ii) the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years. The relevant quantities are most often surface variables, such as temperature, precipitation, and wind.

climate change
A change in the state of the climate that can be identified by changes in the mean or the variability of its properties and that persists for an extended period, typically decades or longer.

co-benefits
The positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare.

co-generation
An energy conversion process in which more than one useful product (e.g., electricity and heat or steam) is generated from the same energy input stream. Also referred to as combined heat and power (CHP).

combined heat and power (CHP)
See co-generation.

concentration
Amount of a chemical in a particular volume or weight of air, water, soil, or other medium.

decarbonization
(i) The declining average carbon intensity of primary energy production over time; (ii) the reduction of carbon emissions from energy supply chains and industrial processes; (iii) the process by which countries or other entities aim to achieve a low-carbon economy, or by which individuals aim to reduce their consumption of carbon.

direct emissions
Greenhouse gas emissions from sources that are owned or controlled by the reporting entity.

emissions
The release of a substance (usually a gas when referring to the subject of climate change) into the atmosphere.

emission factor
A unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity (e.g., grams of carbon dioxide emitted per gallon of gasoline consumed, or per kilowatt-hour of electricity used).

energy intensity
The ratio of energy use to economic or physical output.

energy efficiency
Using less energy to provide the same service (lighting, mobility, cooling/heating, etc).

fossil fuel
A general term for organic materials formed from decayed plants and animals that have been converted to crude oil, coal, natural gas, or heavy oils by exposure to heat and pressure in the earth's crust over hundreds of millions of years.

fugitive emissions
Emissions that are not physically controlled but result from the intentional or unintentional release of GHGs. They commonly arise from the production, processing, transmission, storage, and use of fuels or other substances, often through joints, seals, packing, gaskets, etc. Examples include HFCs from refrigeration leaks, SF6 from electrical power distributors, and CH4 from solid waste landfills.

global warming
The gradual increase, observed or projected, in global surface temperature, as one of the consequences of radiative forcing caused by anthropogenic emissions.

global warming potential (GWP)
An index measuring the radiative forcing following an emission of a unit mass of a given substance, accumulated over a chosen time horizon, relative to that of the reference substance, carbon dioxide (CO_2). The GWP thus represents the combined effect of the differing times these substances remain in the atmosphere and their effectiveness in causing radiative forcing.

greenhouse effect
Trapping and build-up of heat in the atmosphere (troposphere) near the Earth's surface. Some of the heat flowing back toward space from the Earth's surface is absorbed by water vapor, carbon dioxide, ozone, and several other gases in the atmosphere, and then radiated back toward the Earth's surface. If the atmospheric concentrations of these greenhouse gases rise, the average temperature of the lower atmosphere will gradually increase.

greenhouse gas (GHG)
Any gas that absorbs infrared radiation in the atmosphere. GHGs evaluated in this study include carbon dioxide, methane, and nitrous oxide. Other GHGs include ozone, chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride.

heating value
The amount of energy released when a fuel is burned completely.

in-boundary emissions
GHG emissions released within the jurisdictional boundary of a community. Examples include GHG emissions from natural gas combustion in household furnaces and gasoline combustion in motor vehicles driven on roads within the community's jurisdictional boundary.

indirect emissions
Greenhouse gas emissions that are a consequence of the activities of the reporting entity, but occur at sources owned or controlled by another entity. For example, emissions are described as indirect to a city if they relate to the purchase of electricity that is generated outside of the boundaries of a city.

inventory
A comprehensive, quantified list of a community's or organization's GHG emissions and sources.

inventory boundary
An imaginary line that encompasses the GHG emissions included in the inventory. It results from the chosen organizational and operational boundaries.

kilowatt hour (kWh)
The electrical energy unit of measure equal to one thousand watts of power supplied to, or taken from, an electric circuit steadily for one hour. (A watt is the unit of electrical power equal to one ampere under a pressure of one volt.)

landfill
A land waste disposal site in which waste is generally spread in thin layers, compacted, and covered with a fresh layer of soil each day.

landfill gas
Biogas that is produced from the decomposition of organic materials within landfills.

life cycle analysis
Assessment of the sum of a product's effects (e.g., GHG emissions) at each step in its life cycle, including resource extraction, production, use and waste disposal.

lifecycle emissions
GHG emission sources associated with all stages of the life cycle of materials, energy, and services; includes the "upstream" supply chain (e.g., resource extraction, production, transport), use, and end-of-life management (including transportation and recycling).

liquefied natural gas (LNG)
Natural gas that has been converted to liquid form by compression at moderate pressure and cooled, improving the cost and safety of non-pressurized storage or transport.

liquefied petroleum gas (LPG)
A group of hydrocarbon-based gases derived from crude oil refining or natural gas fractionation. They include propane, propylene, normal butane, butane, butylene, isobutene A-14 and isobutylene.

methane (CH_4)
A colorless, odorless flammable gas that is the main constituent of natural gas. It is the simplest member of the alkane series of hydrocarbons. It is a greenhouse gas with a global warming potential estimated to be 86 over 20 years (GWP20) and 34 over 100 years (GWP100).

fugitive methane emissions
A type of fugitive emission in which uncombusted natural gas, consisting primarily of methane, escapes into the atmosphere from the natural gas infrastructure system (production, processing, transmission, and distribution).

metric ton (tonne)
Common international measurement for the quantity of greenhouse gas emissions. A metric ton is equal to 2,205 pounds or 1.1 short tons.

mitigation (of climate change)
A human intervention to reduce the sources or enhance the sinks of greenhouse gases.

mobile combustion
Emissions from the combustion of fuels in transportation sources (e.g., cars, trucks, buses, trains, airplanes, and marine vessels) and emissions from off-road equipment, such as what is used in construction, agriculture, and forestry.

municipal solid waste (MSW)
Residential solid waste and some non-hazardous commercial, institutional, and industrial wastes.

natural gas
A naturally occurring mixture of principally methane and small fractions of hydrocarbon and non-hydrocarbon gases found in porous geologic formations beneath the Earth's surface, often in association with petroleum (oil). It is sometimes referred to as "geologic," "fossil," "conventional," or "thermogenic" natural gas, to distinguish it from biomethane ("biogenic" gas).

negative emissions
Any technology that removes CO_2 or other greenhouse gases from the atmosphere so as to reduce anthropogenic climate change. Examples include enhanced soil weathering, afforestation and reforestation, and enhanced primary production in the ocean.

nitrous oxide (N_2O)
One of the six primary GHGs, consisting of two nitrogen atoms and a single oxygen atom, possessing a GWP100 of 298 and a GWP20 of 268, and typically generated as a result of soil cultivation practices, particularly the use of commercial and organic fertilizers, fossil fuel combustion, nitric acid production, and biomass burning.

power-to-gas (PtG, P2G)
An energy conversion process that converts electrical power to a gaseous fuel. One example includes the production of hydrogen via electrolysis.

propane
A normally straight chain hydrocarbon that boils at -43.67 degrees Fahrenheit and is represented by the chemical formula C3H8.

radiative forcing
A measure of the influence of a particular factor (e.g., greenhouse gas, aerosol, or land use change) on the net change in the Earth's energy balance. Measured in units of watts per square meter (W/m2) at the top of the Earth's atmosphere.

reforestation
Planting of forests on lands that have previously contained forests but that have been converted to some other use.

renewable electricity
Electricity generated from renewable energy sources.

renewable energy
A group of energy sources that have low-to-no direct greenhouse gas emissions generated from renewable resources, such as solar, wind and biomass, but generally excludes nuclear, carbon capture and storage, and geothermal energy sources. Distinction between clean energy and renewables is often defined by statute.

renewable energy certificates/credits (RECs)
A market tradable commodity that represents proof that one megawatt-hour (MWh) of electricity was generated from a third-party verified renewable energy resource, such as a solar renewable energy certificate (SREC) that is generated from solar energy resource.

renewable gas
Hydrogen and methane produced from renewable electricity as well as renewable natural gas.

renewable natural gas
See biomethane.

residual fuel oil
A general classification for the heavier oils, known as No. 5 and No. 6 fuel oils, that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations.

scope(s)
a reporting framework that categorizes direct (scope 1) emissions (e.g., smoke stacks or tailpipes that release emissions within an organizational boundary), indirect energy-related (scope 2) emissions (e.g., the use of purchased or acquired electricity, heating, cooling, or steam regardless of where the energy is generated), and other indirect (scope 3) emissions not covered in scope 2 (e.g., upstream and downstream emissions from the extraction and production of purchased materials and fuels).

scope 1 emissions
Direct emissions of greenhouse gases from owned or controlled sources. For a city, examples include emissions from energy use in buildings or from transportation within the city boundaries.

scope 2 emissions
Indirect emissions of greenhouse gases from the generation of purchased energy. For a city, examples include the emissions associated with the purchase of electricity, heat, or steam that is generated from sources outside the city boundary.

scope 3 emissions
Other emissions of greenhouse gases not covered in scopes 1 or 2. Examples include the extraction and production of purchased materials and fuels, and transport-related activities in vehicles not owned or controlled by the reporting entity.

sequestration
The uptake of carbon containing substances, in particular carbon dioxide, in terrestrial or marine reservoirs.

short ton (ton)
Common measurement for a ton in the U.S. and equivalent to 2,000 pounds or about 0.907 metric tons.

social cost of carbon
The net present value of climate damages (with harmful damages expressed as a positive number) from one more ton of carbon in the form of carbon dioxide, conditional on a global emissions trajectory over time.

stationary
Neither portable nor self-propelled, and operated at a single facility.

stationary combustion
Emissions from the combustion of fuels to produce electricity, steam, heat, or power using equipment (boilers, furnaces, etc.) in a fixed location.

therm
A measure of one hundred thousand (105) Btu.

verification
An independent assessment of the reliability (considering completeness and accuracy) of a GHG inventory.

Abbreviations

°C	Degrees Celsius
°F	Degrees Fahrenheit
BERDO	Building Energy Reporting and Disclosure Ordinance
BPDA	Boston Planning and Development Agency
BWSC	Boston Water and Sewer Commission
CCA	Community Choice Aggregation
CFB	Carbon Free Boston
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
ECM	Energy Conservation Measure
EV	Electric Vehicle
GHG	Greenhouse Gas
GPC	Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories
GRC	Boston Green Ribbon Commission
GWP	Global Warming Potential
ISE	Boston University's Institute for Sustainable Energy
ISO-NE	Independent System Operator of New England
MAC	Marginal Abatement Cost
MAPC	Metropolitan Area Planning Council
MBTA	Massachusetts Bay Transportation Authority
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
MWRA	Massachusetts Water Resources Authority
N_2O	Nitrous Oxide
NO_X	Nitrogen Oxides
$PM_{2.5}$	Particulate Matter (2.5 micrometers or less)
PPA	Power Purchase Agreement
PV	Photovoltaic
REC	Renewable Energy Credit (or Certificate)
RNG	Renewable Natural Gas
t CO_2e	Tonne (Metric ton) of CO_2e
TAG	Technical Advisory Group
TDM	Transportation Demand Management
VMT	Vehicle- Miles of Travel
VPPA	Virtual Power Purchase Agreement
W	Watt
Wh	Watt-hour
WtE	Waste-to-Energy

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