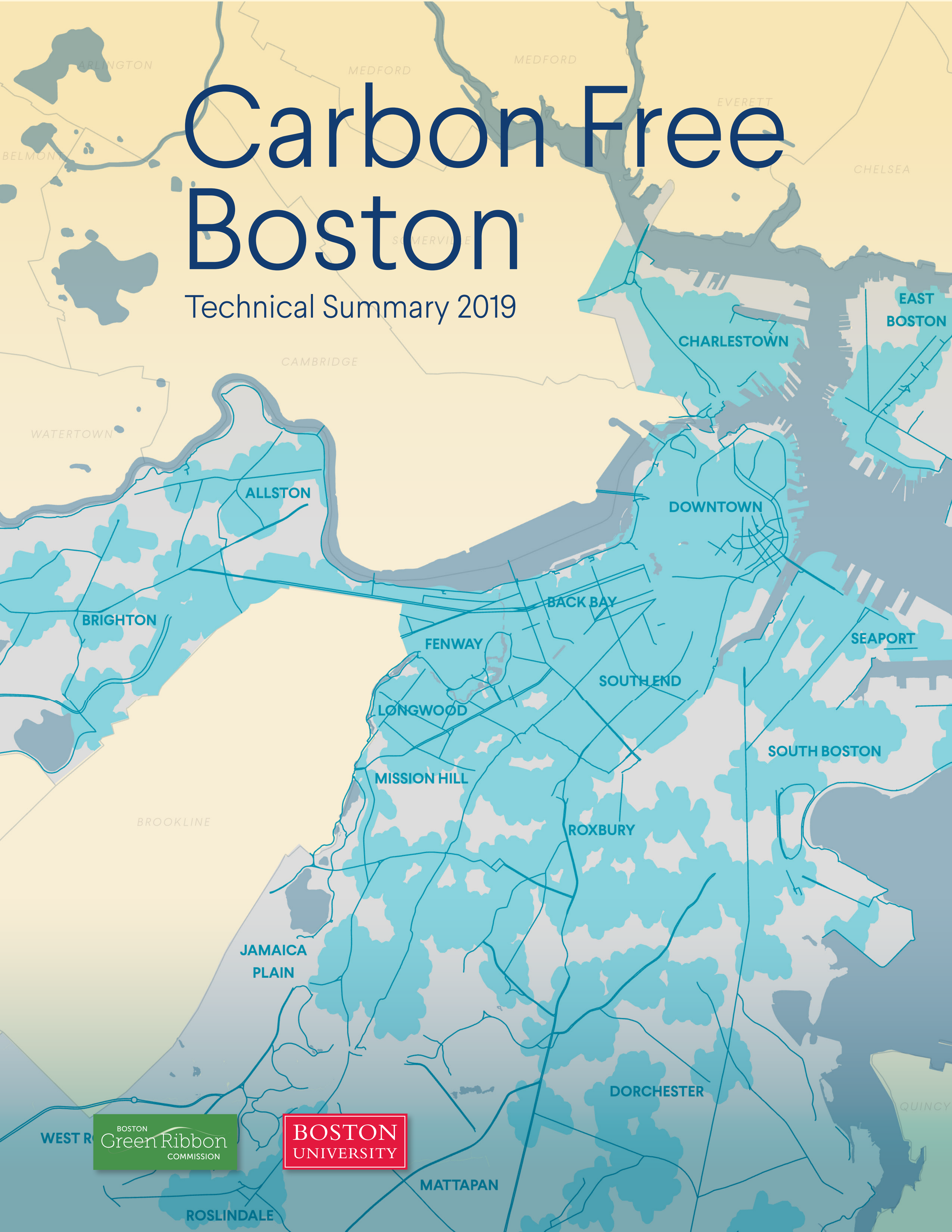
Carbon Free Boston

Technical Summary 2019



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Carbon Free Boston: Technical Summary

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Part of a series of reports that includes:

Carbon Free Boston: Summary Report
Carbon Free Boston: Social Equity Report
Carbon Free Boston: Buildings Technical Report
Carbon Free Boston: Transportation Technical Report
Carbon Free Boston: Waste Technical Report
Carbon Free Boston: Energy Technical Report
Carbon Free Boston: Offsets Technical Report

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1 OVERVIEW

This technical summary is intended to argument the rest of the *Carbon Free Boston* technical reports that seek to achieve this goal of deep mitigation. This document provides below: a rationale for carbon neutrality, a high level description of *Carbon Free Boston's* analytical approach; a summary of cross-sector strategies; a high level analysis of air quality impacts; and, a brief analysis of off-road and street light emissions.

2 SCIENTIFIC RATIONALE FOR CARBON NEUTRALITY

In 2016 Mayor Martin J. Walsh committed Boston to achieving carbon neutrality by 2050 as part of the Metropolitan Mayor's Commitment, a metro-region effort to curb emissions an improve climate preparedness. As a C40 city, Boston has also committed to aggressive climate action including rapid decarbonization as part of C40's Deadline 2020 effort.

These local and international efforts have been spurred by the recognition that climate change presents a fundamental threat to the social, economic and environmental wellbeing of cities and nations across the world. Local impacts from climate change have been assessed by the *Climate Ready Boston* report. The City of Boston and major property owners have already begun to incorporate climate resiliency into waterfront, building, and critical systems planning and development efforts. While cities will need to adapt to changing climates, the need to reduce emissions to avoid the most catastrophic impacts of climate change is essential.

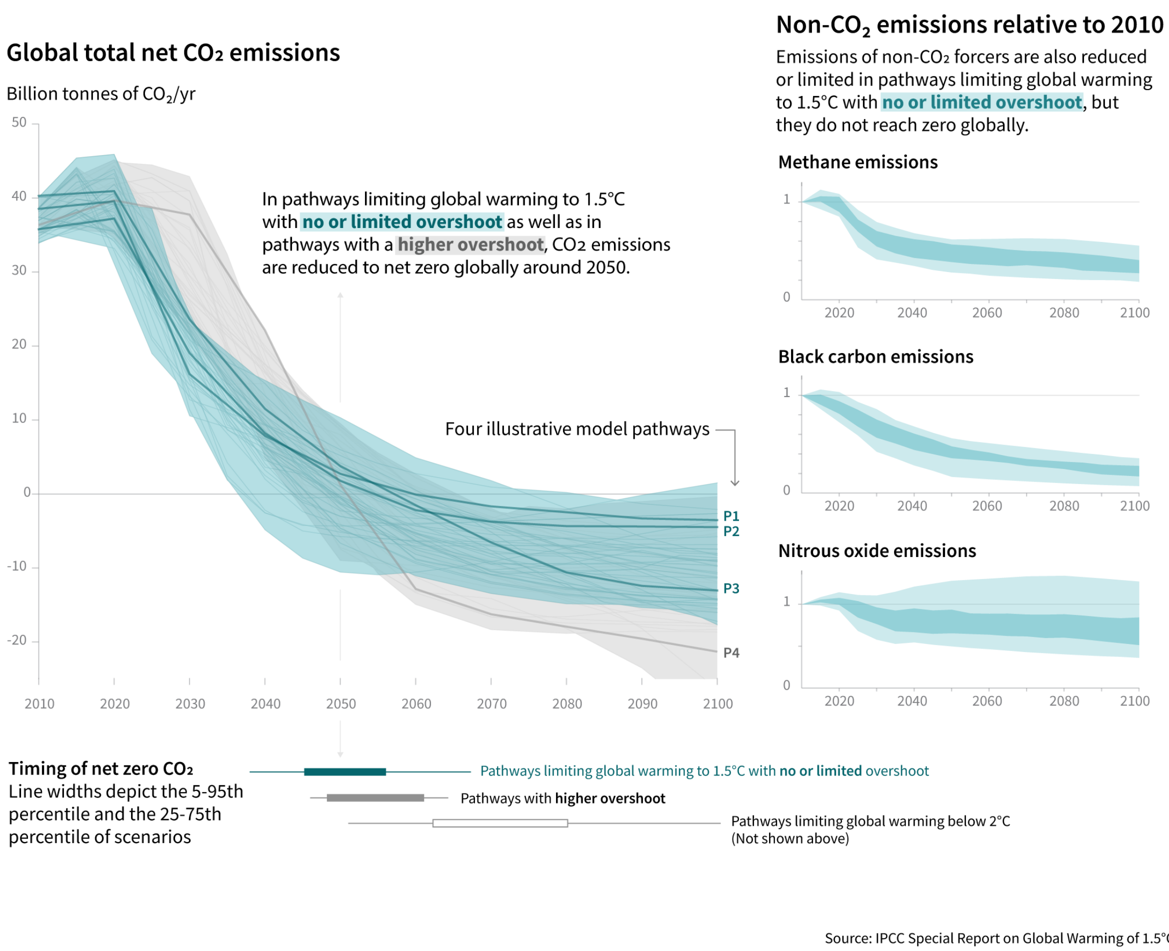
Since the beginning of the industrial age, humans have been driving a net increase in the atmospheric concentration of several greenhouse gases as a result of the use of fossil fuels, land use change, agricultural intensification, and industrial processes. These gases mostly include CO_2, N_2O, CH_4 and a number of synthetic gases. The increase in atmospheric concentrations of these gases subsequently causes an increase in the radiative forcing of the atmosphere, which is a measure of the atmosphere's ability to trap thermal energy or heat. This has resulted in an approximate 1°C rise in global average land surface temperatures and a 0.5 °C rise in global average sea surface temperature over the past 100 years. Depending on projected emissions scenarios total temperature rise is expected to range between 1.5 and 3.2 °C by midcentury, and 1.5 and 5.4 °C by 2100. These temperature rises will be experienced differently across the globe and will lead to sea level rise, changing weather patterns and extreme weather events. Further scientific basis, projected impacts, global mitigation pathways, and adaptation needs associated with anthropogenic climate change have been documented in extensive detail elsewhere, most notably the Intergovernmental Panel on Climate Change's (IPCC) series of periodic Assessment Reports [1] and a number of special reports (e.g., [2]).

The potential for substantial human and economic losses as a result of rapid global climate change has spurred institutions around the world to act to reduce emissions and increase climate preparedness. Global efforts have been facilitated by the United Nation's Framework Convention on Climate Change (UNFCC), which established the first major global treaty focused on combatting climate Change, the Kyoto protocol. In 2015 the UNFCC adopted the Paris Agreement which set a target of keeping temperature rises to below 2°C and purse efforts to limit the temperature increase to 1.5°C. These targets are based in the rationale that keeping temperature rises below 2°C would likely avoid the catastrophic consequences of climate change, while a 1.5°C target would substantially reduce the risks associated with climate change.

Following the Paris accords, the IPCC's released a report focusing on the 1.5°C target in October 2018 [2]. This report found that while limiting temperature rises to 1.5°C would significantly reduce the risks associated with climate change, reducing greenhouse gas emissions at a pace necessary to achieve this target would require "rapid, far-reaching and unprecedented changes to all aspects of society". Emissions would need to fall approximately 45 percent from 2010 levels by 2030 and emissions to be net zero by 2050 (Figure 1).

Figure 1. Global emissions pathways with a likelihood of achieving the 1.5 °C target

Reproduced from [2]



This last point of *net zero* deserves special discussion. As part of the Special Report, the IPCC analyzed a number of emissions scenarios necessary to achieve the 1.5°C target. Nearly all of them required some form of negative emissions to achieve this target. These negative emissions fall into two technological categories: enhancing biological uptake via agricultural and afforestation approaches; and bioenergy carbon capture and storage. These two categories are not mutually exclusive and could potentially require significant conversion of agricultural lands to forest or bioenergy crops. The report also examined overshoot pathways which would allow for a delayed start in emissions reductions, but would still require a rapid midcentury decline and substantial negative emissions. Thus a slower pace of decarbonization would ultimately require more negative emissions using unproven technologies that could potentially stress global food production and land systems.

In contrast to an overshoot pathway, other 1.5°C scenarios identified the need for rapid decarbonization to occur during the time period of 2020-2030. This implies that action needs to start immediately and the focus should be on sectors of the economy amenable to rapid decarbonization. Such action will need to happen globally, but faster reductions by developed countries with high carbon intensities are necessary from an equity standpoint – the relative social and economic costs of rapid decarbonization are likely to be lower in such cities. There is thus a need for developed cities like Boston to lead the way in the mitigation of greenhouse gases in a manner that is equitable both globally and locally.

The benefits of deep decarbonization will be felt globally, while the costs are incurred locally. However, there are numerous local benefits that can be realized though the transition away from fossil fuels. There is also mounting evidence that the combustion of fuels incurs substantial social costs though worsened air quality [3]. Investments in public transportation can significantly boost regional economic activity. Support for biking and walking can deliver health benefits and save lives. More comfortable buildings can boost worker productivity. Energy efficiency can lower housing costs. These factors can lead to a more desirable urban core that attracts people and jobs where their carbon foot prints are lower than in the suburbs. Carbon mitigation thus presents an opportunity improve the quality of life for the city's current and future residents and visitors. Doing so can improve air quality, public health, ease burdens on vulnerable populations, and enhance community wellbeing.

3 ANALYTICAL APPROACH

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 two key energy demand sectors (buildings and transportation), the City's energy supply, and waste. These activities represent the well-quantified sources of emissions in the City, and they align with the focus of most other urban climate action plans.[1] Our analysis notably omits activities such as air travel at Logan airport and the consumption of goods and services[2]. Emissions from these activities are significant and can be reduced, but have largely been outside the scope of the City's GHG accounting. Future work could quantify these consumption emissions and seek to educate the public and relevant authorities on potential mitigation options.

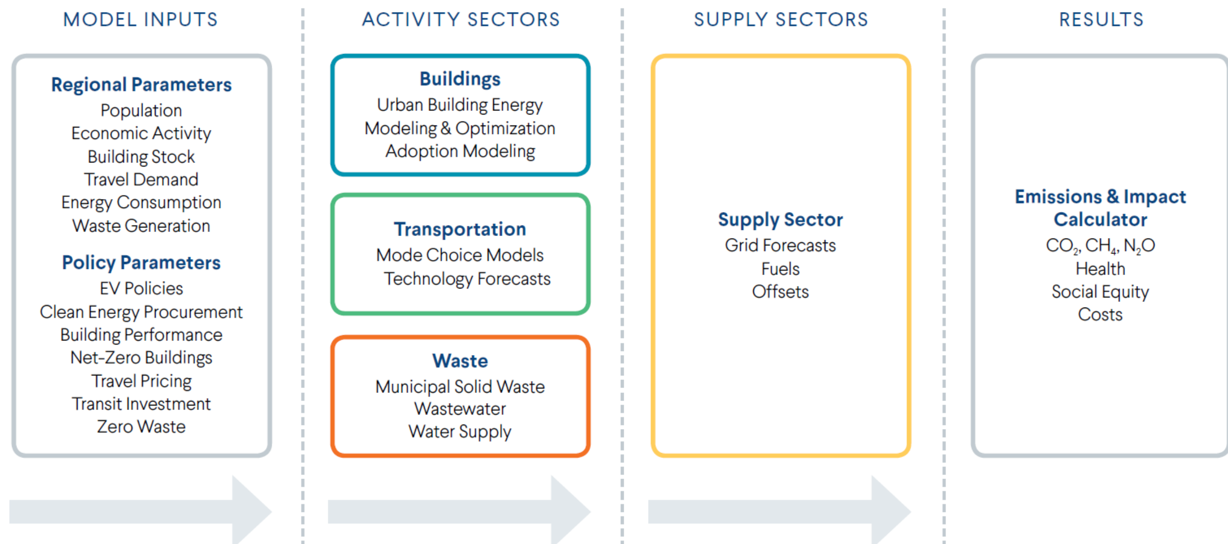
Our analysis uses a systems-modeling approach to evaluate GHG reduction pathways in the buildings, transportation and waste sectors (Figure 2). These models characterize how Boston's residents, businesses, workers, and visitors use buildings, travel, and generate waste. Current and emerging technologies are used to calculate energy needs and emissions from these activities. We assess a range of specific strategies and polices in terms of their effect on energy use and GHG emissions. In each

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

[2] Consumption emissions are challenging to estimate due to regional and temporal heterogeneity in supply chains that extend far beyond Boston and the City's oversight. It is thus difficult to accurately assess and forecast the impact of consumption-focused actions, although some general trends may emerge (e.g., a plant-heavy diet is less carbon intensive than a meat-heavy diet.)

sector we distill our analysis to a "Pathway to Carbon Neutrality to 2050," which represents a balance of the application of efficiency, electrification and renewable energy measures. These pathways serve as a reference point for the City of Boston to develop a more directed pathways as part of its Climate Action Plan Update.

Figure 2. Modeling Framework for *Carbon Free Boston*



For important activities such as public transit, renewable electricity, building energy use, waste disposal, and personal vehicles, we characterize historic trends in people's behavior and technological progress in our modeling approach. 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 trends.

Our pathways are not predictions of the future; they are used describe underlying driving forces, feedbacks, sensitivities, and bounds. Many of the parameters in a forward-looking model rest upon uncertain assumptions about future technology, costs, human behavior, and policies. These uncertainties span multiple time horizons and scales of jurisdictional authority. Federal and state regulations can significantly influence emissions because they influence the GHG intensity of the electrical grid, building codes, and vehicle emission standards, among others. The trajectory of state and federal policies will affect the decisions that the City needs to take reach its emissions target. Engaging with these and cross-governmental entities could help to accelerate the changes that will be needed to achieve carbon neutrality.

More detailed, sector-specific descriptions of methodologies, data sources and assumptions are included in each sector's respective technical report. A companion social equity report provides a complementary analysis of potential impacts of deep emissions reductions on vulnerable populations.

3.1 Defining Emissions Sources and Boundaries

We use the *Global Protocol Community-Scale Greenhouse Gas Emissions Inventories* (GPC) framework as the basis for our analysis. We quantify 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 from the City's natural gas distribution system. The net impact of the various greenhouse gases is estimated using each gas' global warming potential – an index that measures the radiative forcing that follows the emission of a gas, accumulated over a chosen time horizon, relative to CO_2.

3.1.1 Geography and Emissions Scope

The city limit of Boston is the geographic boundary that identifies activities that generate emissions in our analysis. Direct GHG emissions are from sources located within the City boundary; 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. Electricity is acquired from the ISO-New England grid in which natural gas generators play a large role in GHG emissions. Steam is also imported from the Veolia-Kendall generation station in Cambridge that is powered by natural gas.

Within Boston we distinguish between residential and commercial activity to demonstrate the relative contribution from each sector, and 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.

3.2 GHG Accounting Differences Between 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* [4]in a couple of notable ways, although both approaches are follow the *Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC)* [5].

For transportation, the City's *Community Greenhouse Gas Inventory* captures all vehicle activity occurring inside Boston's geographic boundaries, whereas this analysis assesses trips that have at least one endpoint within the City's boundary. This trip-focused approach, enables 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 assigns 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 captures more miles traveled and emissions than the *Community Greenhouse Gas* Inventory, and allows us to assess the effectiveness of strategies to reduce emissions from regional travel.

In the waste sector, we evaluate the impact of policies on downstream emissions associated with the final disposition of solid waste and waste water. 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 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.

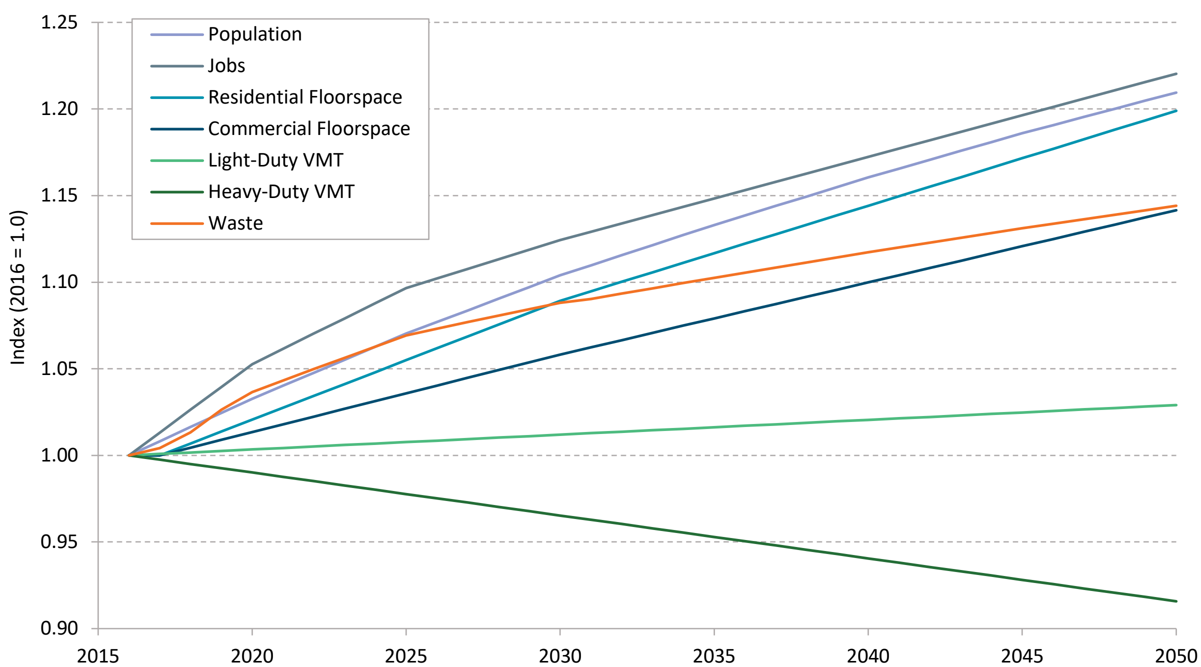
3.3 Future Assumptions

3.3.1 Population and Economic Growth

Growth forecasts (Figure 3) defining future population, building stock growth and transportation demand are derived from a series of prior locally-focused analyses. We use the *Metropolitan Area Planning Council's 2014 Regional Growth Projections* report[6] that forecasts city-level population changes and housing demands through 2040. This report serves as the basis for the *CTPS Charting Progress to 2040: A Long-Range Transportation Plan for the Boston Region* that provides the trip-demand data that underlies our transportation model. Trip-demand values for 2041 to 2050 are extrapolated from prior-year growth. The MAPC's Regional Growth Projections, coupled with long-term population projections developed by the Boston Planning and Development Agency, serve as the basis for 2050 residential and commercial growth projections reported in the *Imagine Boston 2030* report [7]. We use that data for our forecasts of changes in building stock. Future transportation scenarios are derived from *Go Boston 2030* [8]. More detail on how these forecasts are applied are described in each sector's methodology chapter. Boston's recent growth in population and economic activity exceed the projections in these studies. We account for this and other uncertainty with alternative growth and development scenarios in each sector.

Figure 3. Projections of Key Drivers in *Carbon Free Boston*

Population growth, new buildings, and overall economic growth will increase the demand for energy, which will increase GHG emissions. But existing and new policies, technologies, and behaviors are potential counterweights to those forces. Action by the City is needed to ensure that those measures are put in place. An index value of 1.0 means that a metric remained constant at 2016 levels over time; higher (lower) index values mean that the metric grew (shrank) over time. VMT refers to vehicle miles travelled. Waste refers to the municipal solid waste generated by the residential and the commercial sectors. See text for sources.

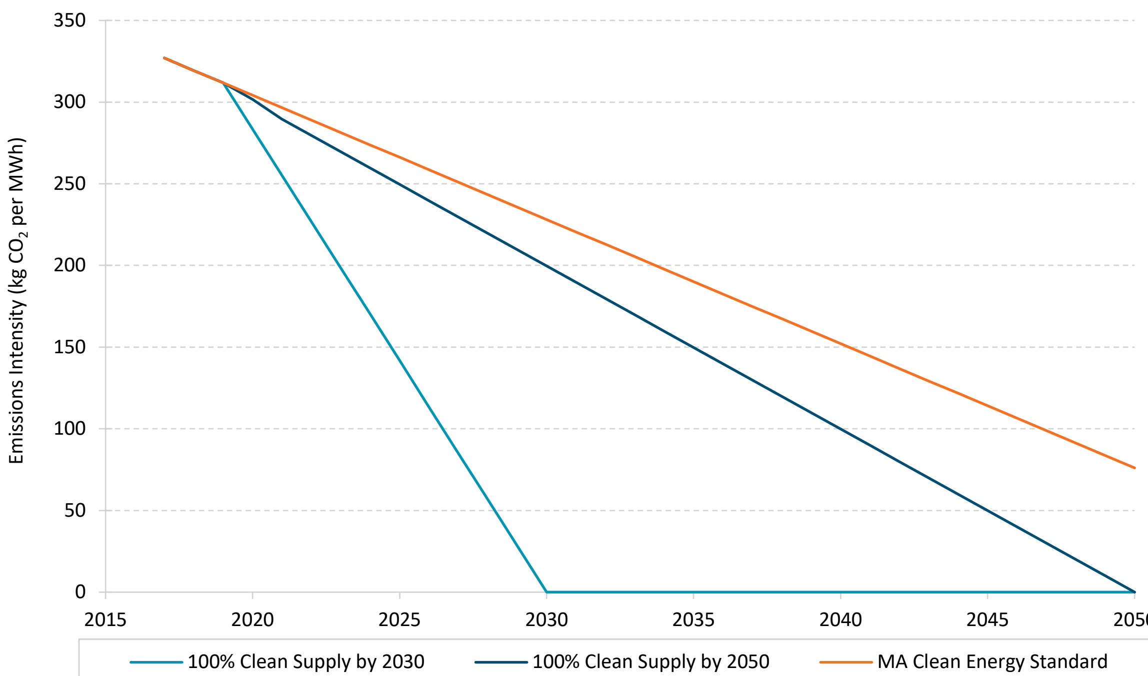


3.3.2 Future Energy Supply

The future electricity supply of Boston will be strongly influenced by the Commonwealth of Massachusetts regulations: 310 CMR 7.74 Reducing CO2 Emissions from Electricity Generating Facilities[9]; and, 310 CMR 7.75 Clean Energy Standard (CES)[10]. These regulations will move the Commonwealth towards an 80 percent reduction in GHG emissions relative to 2005 levels by 2050 as required by the Global Warming Solutions Act[11]. The CES requires that 80 percent of all electricity sold to Massachusetts customers should be come from renewable or clean sources. CMR 7.74 stipulates a sector wide 80 percent reduction on emissions from 21 large fossil fuel-fired power plants and by placing emissions caps on all new fossil fuel-fired plants. 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 4). We also assessed the effects of the procurement of zero GHG electricity in quantities such that the City's total supply (grid purchases plus procurement) is 100 percent zero GHG by 2030 or 2050.

Figure 4. Carbon Emissions Intensity of Electricity Purchased by Boston

The orange line is the estimated intensity that will occur under the Massachusetts Clean Energy Standard that requires that 80 percent 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 percent GHG-free electricity by 2030 or by 2050. Source: model calculations.



These 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 [12]. Legislation in the Washington D.C. City Council seeks to attain 100 percent renewable energy by 2032. In August 2018 the California legislature passed legislation requiring a 100 percent renewable portfolio standard by 2045 [13, p. 10]These alternative scenarios enable a comprehensive analysis of possible futures for Boston. While they are a high-level representation of generation technologies, legal requirements, and procurement strategies, they enable a comprehensive review of the impacts of demand-focused policies in the transportation and buildings sectors.

These alternative scenarios enable a comprehensive analysis of possible futures for Boston. While they are a high-level representation of generation technologies, legal requirements, and procurement strategies, they enable a comprehensive review of the impacts of demand-focused policies in the transportation and buildings sectors. For example, a faster rate of decline in the carbon-intensity of city-supplied energy would increase the prioritization of electrification strategies relative to demand-reduction strategies.

We did not evaluate alternative scenarios for future carbon intensity of fuel supply. While injection of hydrogen or renewable natural gas into the gas distribution system could lower its carbon intensity, carbon neutrality would require a fully decarbonized natural gas system. The same logic applies to renewable diesel fuel oil, which is typically blended with 5-20 percent biodiesel. Technical constraints limit the drop-in use of hydrogen in natural gas pipes or biodiesel in some vehicles and backup systems. Our assessment of renewable fuels (see Carbon Free Boston Energy Technical Report) also identified longstanding challenges to the development of bioenergy sources and low-value synthetic fuels due to indirect effects and cost limitations respectively. The development of such technologies should be supported, and there are a number of potential actions (e.g., collection of organic wastes for bioenergy generation) that the City could pursue to promote the development of sustainable renewable fuels. However, supplies of sustainable renewable fuels are likely to be limited, and there may be opportunity costs to using their feedstocks and energy inputs to generate low-value energy products such as methane. Thus sustainable renewable fuels should be prioritized to high value applications. In our Pathway to 2050, we have assumed sufficient electrification that emissions associated with the remaining fuel demand could be met by limited application of renewable fuels.

3.4 Pathway to Carbon Neutrality by 2050

Strategies to reduce GHG emissions in 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 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. The results presented in this report reflect our judgment, which was informed by our advisory groups, on a pathway to carbon neutrality in each sector that represents a credible and proactive blueprint for immediate action, even if full implementation takes longer.

We gauge strategies along several dimensions:

1. We emphasize energy efficiency and electrification 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. We recognize that energy efficiency and building electrification face significant funding and implementation challenges, especially at the necessary scale and speed necessary to attain carbon neutrality in a disparate, aging building stock. However, challenges in the area of financing and implementation 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 breakthroughs are largely outside the City's control, and it is much less clear how to integrate them into near-term City actions.

2. The strategies offer demonstrable potential benefits that include job creation, improved public health and safety, lower energy costs, reduced traffic ingestion, regional acceleration of renewable energy, and buildings that are more resilient to the effects of climate change.
3. The strategies offer the potential to improve equity outcomes in the City's socially vulnerable populations. Strategies to reduce GHG emissions should acknowledge historic inequities, equitably distribute costs and benefits, and otherwise insure that every Bostonian has access to safe, affordable, and clean energy.
4. The institutions--economic, political, religious, educational, legal, medical, social welfare--necessary to plan and implement a path to carbon neutrality currently exist, and can be plausibly adapted if need be.

3.4.1 Scenario Analysis

The pathway to carbon neutrality that we explain in the subsequent chapters is the result of this sequence of assessments in each sector:

1. **Baseline**: We define 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 include the City's green building and large-building energy efficiency requirements, and federal vehicle fuel efficiency standards. The baseline also includes projections of future economic conditions and population growth in the City.
2. **New Action on Energy Efficiency (Current Grid):** We then assess 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 evaluate the impact of electrification of buildings and transportation under the current grid emissions intensity.
4. **Massachusetts *Clean Energy Standard*:** We then apply the efficiency and electrification strategies in (2) and (3) with the grid intensity that will exist in each year through 2050 if the state's clean power law is followed to the letter. We separate this effect to illustrate the influence that this important state action has on Boston's energy decisions.
5. **100% Clean Supply:** Next, we assess the impact of the purchase by the City of a quantity of GHG-free electricity such that, when combined with the electricity purchased from the grid, the City's total supply of electricity is effectively 100 percent free of GHGs.
6. **Residual Emissions:** Finally, we calculate and discuss in each sector a set of residual GHG emissions that remain after implementation of all the action in 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 water treatment have no ready technological solution. In the Offsets chapter we discuss how residual GHG emissions could be managed by the City to reach carbon neutrality.

The pathways to carbon neutrality in 2050 described in the following chapters provide a comprehensive and systematic framework for the City to launch action to reduce GHG emissions. These pathways achieve carbon neutrality, but they also depict how to do that in a way that kindles vigorous economic development, technical innovation, and workforce development, and also makes Boston resilient in the face of climate change. In *Resilient Boston* and *Imagine Boston 2030*, the City identified social equity as a lens through which it views all of its planning, policymaking, and governing. Consistent with this, the pathway to carbon neutrality has the potential to improve the health and well-being for all Bostonians by increasing the quality, cost, and access to transportation, building, waste, and energy services.

4 THE SIMULTANEOUS NEED FOR DEMAND REDUCTION, ELECTRIFICATION AND 100% CARBON FREE ENERGY SUPPLY

As noted above, deep decarbonization needed to achieve the 1.5°C target need to reflect three elements (1) a rapid decline in emissions from 2020-2030; (2) net carbon neutrality by 2050; and, (3) negative emissions after 2050. The latter is somewhat beyond the focus of this work, but may be facilitated by the development of offset programs as described in the *Carbon Free Boston Offsets Technical Report*. Achieving the preceding two requirements will require aggressive actions in transforming energy supply and demand sectors.

The *Carbon Free Boston* technical reports explored the relative impacts three different strategies for decarbonization:

1. Reduction in the demand for energy in terms of efficiency gains and energy consumption.
2. Electrification of fossil fuel-based energy systems such as vehicles and building thermal loads.
3. Procurement of 100% carbon free energy.

Each of these options have various tradeoffs in terms of cost, implementation potential and schedules, and technological solutions. There is also some overlap between these sectors, as electric vehicles and air source heat pumps are inherently more efficient than their fossil fuel-based counterparts – however in this report we have distinguished energy conservation measures (building efficiency, mode shift) from energy technology changes such as EVs and heat pumps.

4.1 DEMAND REDUCTION

Our assumptions underlying the implementation of demand reduction are greatly ambitious reflecting the largest scale implementation of aggressive vehicle trip pricing, transformative public transit, and deep energy retrofits. New buildings are a prime opportunity to limit increases in energy demand and subsequently emissions by adopting net zero policies, but nearly 86,000 buildings within Boston will need to be retrofitted. With both the new and existing stock, energy will still be required for building operations. Energy conservation retrofits will take time for several reasons. First is that there will likely be a policy lag that is necessary to prepare owners and regulators for building requirements. Second, such a requirement may be implemented on a schedule to minimize burdens and economic impact. For example in our analysis we illustrate the impact of requirement that 3 percent of the building stock is retrofitted in a given year to align with an assumed 30-year cycle in building. More accelerated requirements will likely be disruptive for building owners and occupants. Further, it will take time to realize the full potential of enabling policies such as workforce training and financing that will be necessary to tackle the scale of the transition.

Likewise, demand reduction in the transportation sector will face similar challenges, most notably due to the high number of long-commute trips with very little mode shift potential. Several easy fixes such as improved bicycle facilities, dedicated bus lanes and fare reduction can deliver some modest benefits, but again, have little impact on longer, more carbon-intensive trips. Investments in more significant projects such as expansion of the T and commuter rails will require a number of years for planning and development before their potential is realized. Vehicle pricing strategies will likely need to be phased in to avoid potential backlash and allow people impacted by such policies to adjust to such policies. Despite these challenges, expected improvements in the efficiency of internal combustion engine-based vehicles driven by federal vehicle standards are a major contributor to reductions in the baseline scenario.

Demand reduction can deliver significant benefits such as ongoing cost savings and improvements in human comfort and health. However such actions, especially if done rapidly, tend to require significant upfront investment. Thus it is likely that such actions will need to be implemented strategically, requiring more planning; and on an ongoing basis.

4.2 Electrification

Electric vehicles may be the most cost effective (in terms of carbon abatement) strategy for its potential level of impact. The average automobile age in the united states is approximately 10 years, meaning that there are a significant number of vehicles on the road that are greater than 10 years old [14]. This suggests that there will be a decade-plus lag between the start of a vehicle electrification effort and complete transition of the entire fleet. Since vehicle electrification is a likely predicate for carbon neutrality, policy design must take into account this potential lag. For example, prohibitions on ICE-vehicle sales or registrations must begin between 2030 and 2035, while an outright ban on ICE vehicles from operating within city should be announced at least 10-15 years before such a ban is implemented. Currently the market share of EV sales is only about 2 percent nationwide. Even with an aggressive push to increase market share, the predominant number of vehicles on the road in 2030 will still be powered by the internal combustion engine and fossil fuels. Further, despite the large efficiency improvements offered by EVs, a greener electricity supply, will be needed for greater emissions reductions.

The electrification of the buildings sector faces similar challenges as many heating systems typically have long lifetimes (20-30 years). However, there may be some opportunities for rapid install of air source heat pumps (e.g., ductless minisplits) that could provide primary heat and be backed-up by existing systems. Longer-term solutions could be implemented alongside an energy conservation retrofit. Generally heat pumps are less carbon intensive than existing fossil fuel-based thermal systems, however this is currently not the case during winter peak energy demand events when oil is often used to generate electricity. As a result thermal electrification does not deliver significant benefits under the current grid. Further reductions in the carbon intensity of the electricity supply, including at peak events, will be needed to reduce emissions if electrification is pursued.

4.3 Clean Electricity Procurement

As described in the *Carbon Free Boston Energy Technical Report*, the City of Boston could in theory require the procurement of 100 percent carbon free electricity through various mechanisms. Such a procurement could come from a wide variety of sources (wind, solar, hydro, and nuclear) within or beyond the ISO-NE grid. Presumably, a good portion of it would need to be developed over the course of several years, however this would likely occur faster than the electrification and efficiency actions in transportation and buildings sectors. Currently, this approach has been adopted by several Boston institutions as their largest, most significant, and most cost effective step to decarbonization.

If the demand for carbon free energy becomes large due to other entities pursuing similar strategies, costs for procurement and the timeline for achieving it may increase. However, this may still remain the most cost effective and rapidly scalable decarbonization action, even if widely demanded.

The key limitation of clean electricity procurement is that it will only affect emissions generated from the use of electricity and thus does not address the in-boundary consumption of fossil fuels. Strategies for the procurement of sustainable renewable fuels could also be pursued, however these fuels may be more constrained due to limitations in sustainable feedstocks. This is discussed in further detail in the *Carbon Free Boston Energy Technical Report*.

4.4 SYNTHESIS

Figure 6 and Table 1 show the emissions reductions associated with pathways focused solely on demand reduction, electrification, and procurement as well as those that combine the strategies. Emissions reductions are maximized when the overarching strategies are combined rather than pursued alone. Notably, early procurement of clean electricity (100 percent by 2030) is the only strategy – either pursued alone or in tandem with other policies – that can achieve rapid emission reductions over the next decade. This is based on the assumption that new renewable energy can be more readily acquired than rapidly converting current vehicular and building energy assets.

The City of Boston has set an interim target of 50 percent of its 2005 emissions by 2030, to align with the goal of rapid decarbonization. This target is approximately 3.6 Mt of CO_2 under the City's current inventory approach [4] which is equivalent to approximately 4 Mt of CO_2 under our analytical framework.[3] Only the 100 percent clean energy procurement by 2030 strategy, either alone or in tandem with the other actions, is capable of achieving the interim target. After 2030, getting towards full neutrality will require sustained action in demand reduction and in electrification.

[3] The *Carbon Free Boston* analysis focused on a wider set of emissions to more explicitly assess the impact of strategies using analytical modeling. The differences between these two approaches are noted earlier in this text and described in detail in the Transportation and Waste sector technical reports.

Figure 5. Example trajectories of alternative illustrative single and combined strategy mitigation pathways

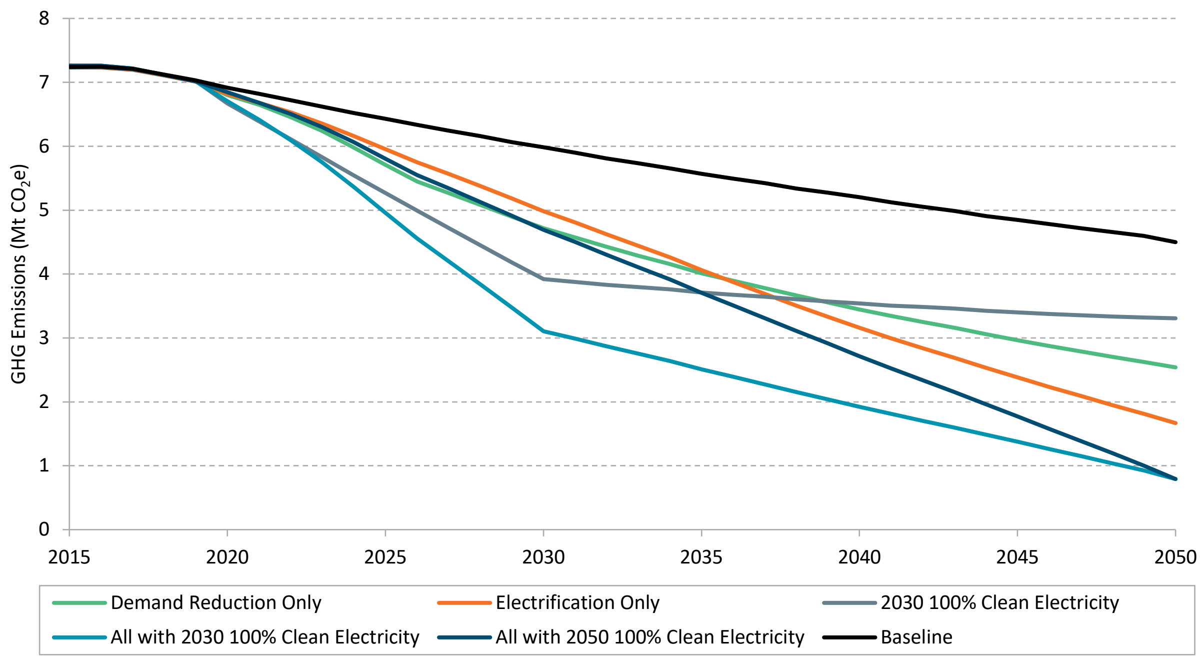


Table 1. Total emissions reductions associated with alternative strategy pathways

	2018-2050 Emissions Reductions	
	Mt CO_2e	Percent from baseline
Demand Reduction Only	42.1	-20%
Electrification Only	46.2	-22%
100% Clean Electricity	45.4	-22%
All with 2050 100% Clean Electricity	57.7	-27%
All with 2030 100% Clean Electricity	82.2	-39%

5 AIR QUALITY IMPACTS OF LOW ANTHROPOGENIC EMISSIONS FROM BOSTON

The process of fuel combustion generates a number of gases other than CO_2 alongside particulate matter. This is due to impurities in the fuel and chemical reactions that occur during the combustion process. Examples of these pollutants are shown in Table 2. The type and magnitude of such emissions can vary significantly by fuel source and by combustion method or technology. For example natural gas generates significantly less of these air pollutants than the combustion of diesel fuel oil. The presence of a catalytic converter or scrubber reduces such pollutants from exhaust streams. Despite such technologies, urban areas are prone to high concentrations of such pollutants due to the density of combustion activity (e.g., automobiles and heating systems) [15].

A decarbonization pathway that includes deep electrification and the near cessation of fossil fuel combustion will significantly reduce in boundary emissions of carbon dioxide and these other gases. Such a shift will have a significant impact on air quality. We explore here the impacts of zeroing out such gases in the Boston area only, by running an atmospheric dispersion model on air quality impacts. While there is mounting evidence that indoor air quality is impaired by combustion services such as natural-gas based cooking, we do not assess such impacts here.

Table 2. Common air pollutants emitted from combustion processes and their potential impacts of concern

Pollutant	Potential Impacts
Carbon Monoxide (CO)	headaches; nausea; fatigue; death at high concentrations
Sulfur Dioxide (SO_2)	respiratory impacts, preterm birth, premature death; contributes to aerosol formation which can have variable impacts on radiative forcing.
Nitrogen Oxides (NO_x: NO, NO_2)	ozone generation; respiratory impacts; heart disease, acid rain, increases radiative forcing.
Fine Particulate Matter ($PM_{2.5}$)	respiratory impacts; asthma; lung cancer; cardiovascular disease; premature delivery; premature death; stunting of vegetation; decreases radiative forcing.
Coarse Particulate Matter (PM_{10})	similar to PM2.5, but health effects tend to be less severe
Volatile Organic Compounds (VOCs)	irritation; headaches; nausea; liver & kidney damage; central nervous system damage; suspected carcinogens

Boston's air quality can be categorized as good, but not great. Its geography, climate and concentration of combustion-based activity yields modest levels of unhealthy air pollutants. This is in stark contrast to mega-cities in developing countries (Beijing, Delhi) that routinely face hazardous conditions, or even developed cities that regularly have unhealthy air quality events (Paris). Despite Boston's overall good air quality, some neighborhoods such as those located next to congested roadways are likely to experience poorer air quality conditions, leading to more detrimental impacts [15].

The impacts on air quality resulting from the removal of anthropogenic sources from the city of Boston are examined through the use of a chemical transport model, the Community Multiscale Air Quality (CMAQ) Model. Two model simulations are performed for the entire year of 2011 (a typical year). The base case simulation includes all emissions sources. The second scenario is identical to the base case, except that anthropogenic emissions from Boston are set to zero. CMAQ is applied continentally using a 36km grid resolution with an inner domain using a fine resolution. The inner modeling domain is 120km X 120km, centered on Boston, with a spatial resolution of 4km. Figure 6 shows the modeling domain and the extent of the zero emissions area.

Removal of Boston emissions results in reductions of annual average $PM_{2.5}$ concentrations. The most significant reductions are found in Boston where the emissions were set to zero. Maximum decrease in the annual average $PM_{2.5}$ was 8.5 $\mu g/m^3$. There are only negligible reductions observed in other parts of the modeling domain. Figure 7 shows the spatial distribution of $PM_{2.5}$ concentration reductions. Examining the yearlong trends for both scenarios at a grid cell in the center of the city, reductions in

$PM_{2.5}$ concentrations occur throughout the year. The same seasonal patterns are observed in both cases. Figure 8 shows a time series for $PM_{2.5}$.

Removal of Boston emissions results in an increase in maximum daily 8-hour average (MDA8) ozone concentrations in the city throughout the whole year. On high ozone days, increased concentrations are also seen over areas to the North and Northwest of the city. Figure 9 shows the spatial distribution of the change in MDA8 ozone on the four highest ozone days observed at the Dudley Square monitor (ID# 250250042). Changes in the highest MDA8 ozone observed throughout the year are similar. Some ozone reductions do occur, typically over the water (Figure 10). Examining the yearlong trends for both scenarios at a grid cell in the center of the city, increases in MDA8 ozone concentrations occur throughout the year. The same seasonal patterns are observed in both cases. Figure 11 shows the MDA8 ozone time series. The increased ozone is due to lower NO_x in the city. In high NOx environments, the reaction of NO with O_3 to produce NO_2 and O_2 can be an important sink of ozone, and NO_2 scavenging of the OH radical reduces ozone formation as well. Decreased NO_x reduces both ozone and OH radical scavenging, leading to higher ozone concentrations. This same result may not occur in simulations of more recent years. As emissions of all criteria pollutants continue to decrease, the position of a city on the ozone isopleth can change, resulting in different responses to controls. In particular, the reductions in NO_x are leading to the region becoming increasingly NO_x-limited.

Figure 6. Modeled domain with emissions zero out area shown in white.

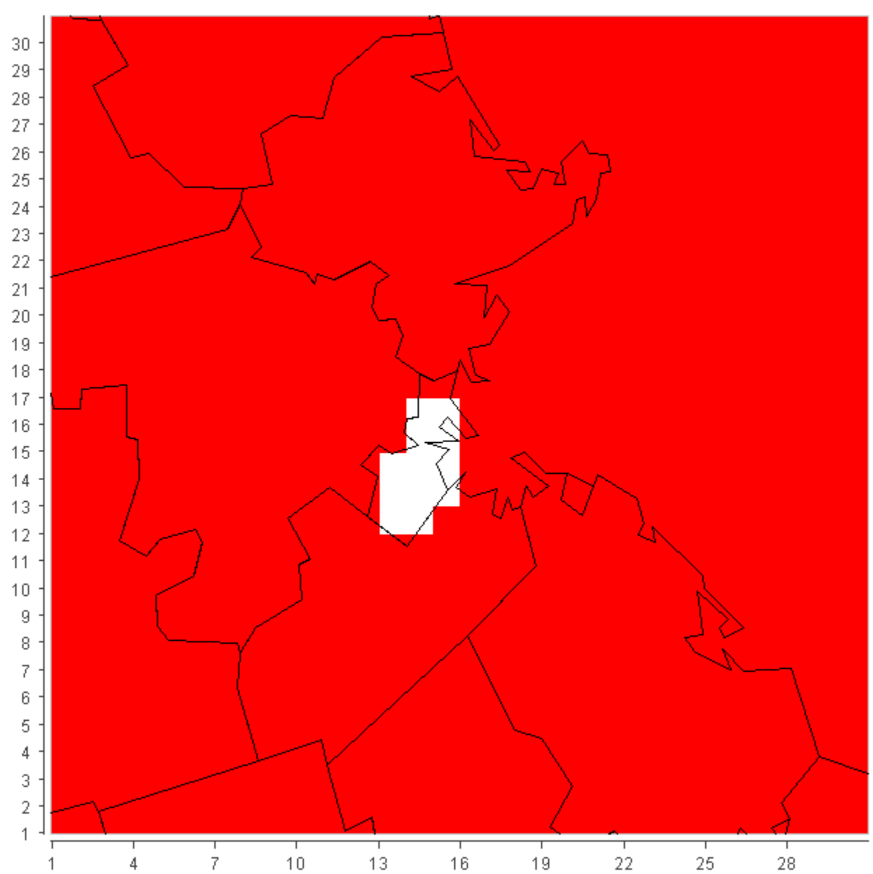


Figure 7. Change in annual average $PM_{2.5}$ concentrations by removing Boston emissions

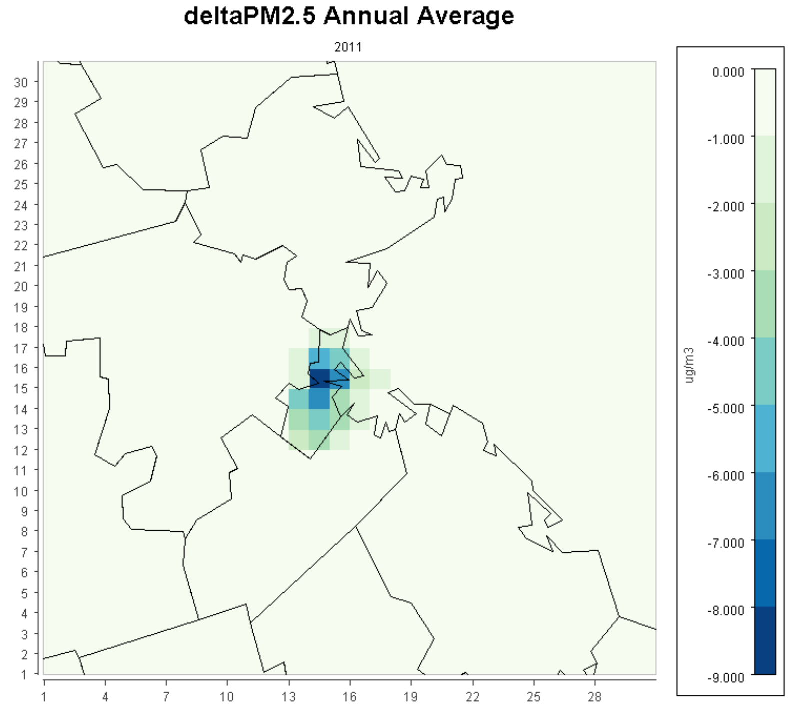


Figure 8. Daily average $PM_{2.5}$ concentrations at a grid cell in the center of Boston

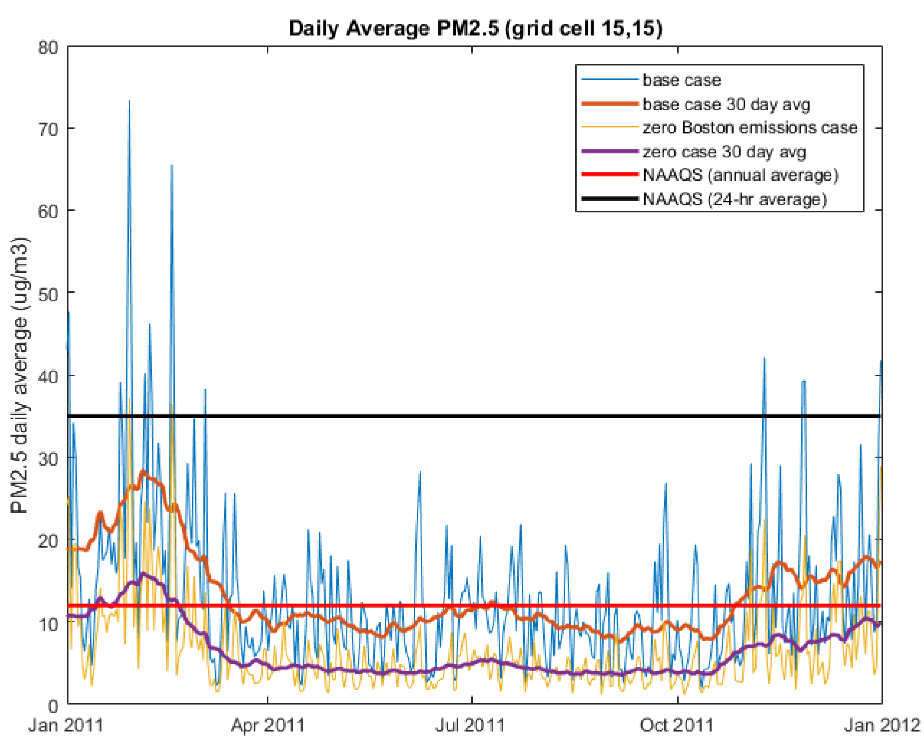


Figure 9. Change in simulated MDA8 ozone concentration on days with the four highest observed MDA8 ozone at the Dudley Square monitor (ID# 250250042)

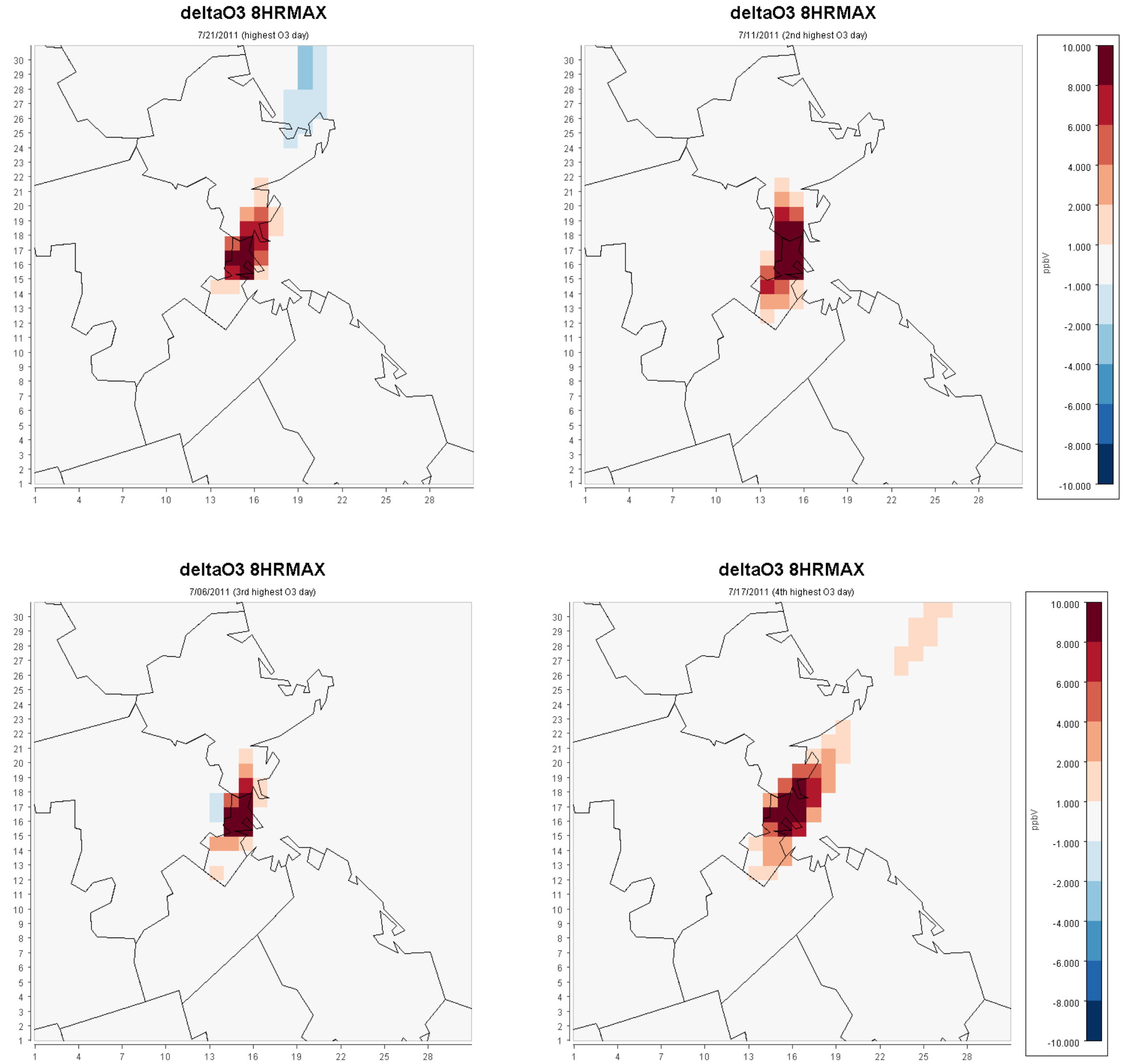


Figure 10. Change in the highest simulated MDA8 ozone concentration throughout the entire year

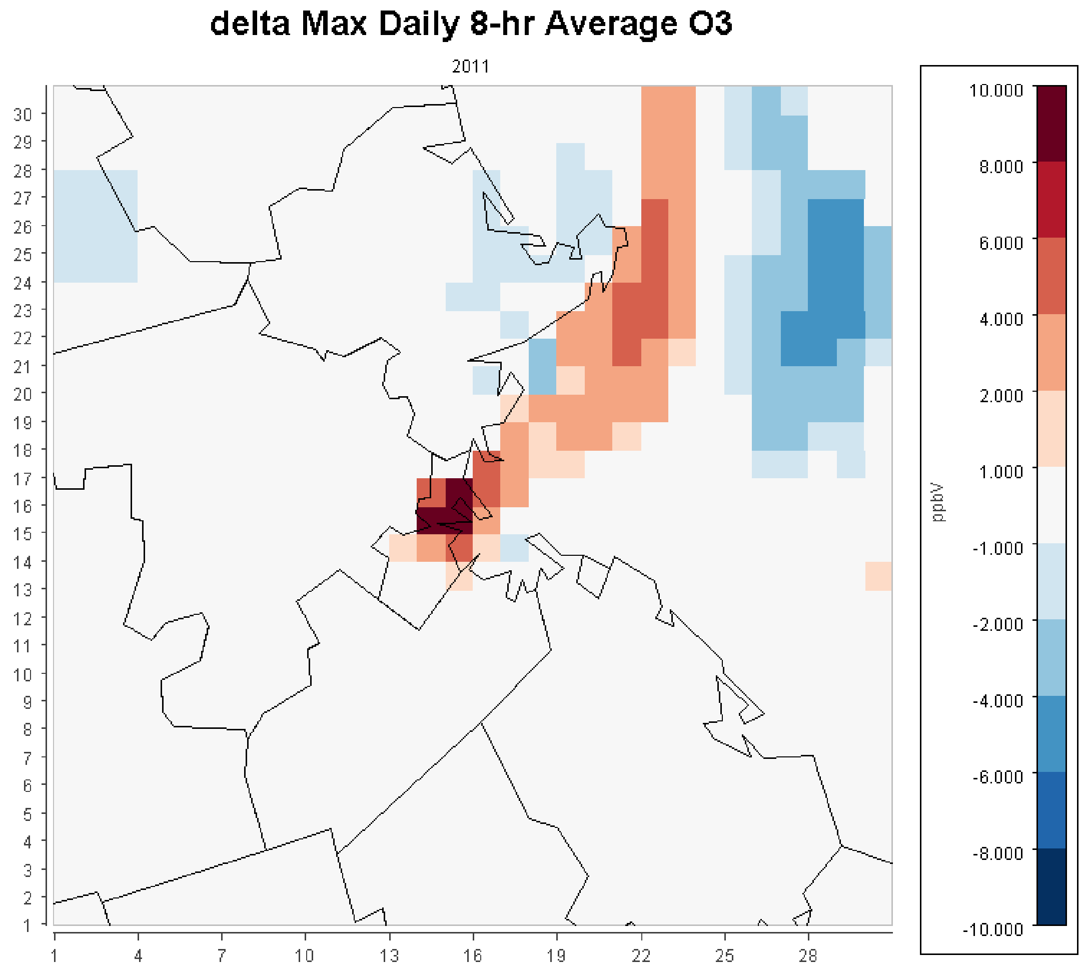
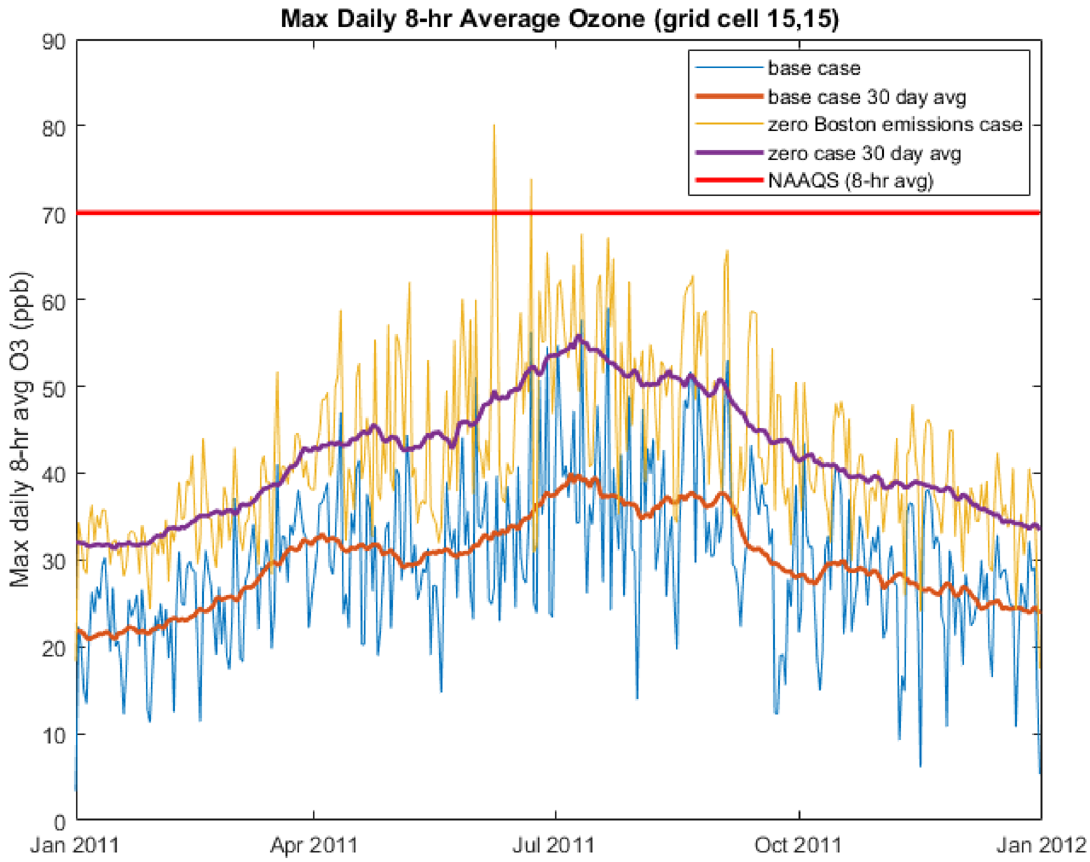


Figure 11. MDA8 ozone concentrations at a grid cell in the center of Boston



5.1 HEALTH IMPACTS OF REDUCED POLLUTION

It has been well established that many of the non-GHG pollutants presented above can impart deleterious health outcomes that can have economic consequences [15]. To assess these impacts we used the Co-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA) [16]. COBRA uses a simplified atmospheric dispersion model to evaluate the exposure to individuals in a given region.[4] From exposure, factors are applied to calculate mortality, hospital admittance, and costs. For this analysis we zeroed out all major pollutants from combustion in the Suffolk County, MA region of COBRA.

In this analysis, ambient air concentrations of PM2.5 decreased from a baseline of 6.7 ppb to 5.6 ppb. Despite eliminating fossil fuel combustion in this illustrative exercise, Boston (and Suffolk county) is still exposed to pollutants transported from outside the county and natural and non-combustion sources of these pollutants. This may suggest that even though reduction in the city may be ambitious, efforts pursued by other entities may further reduce the generation of air pollutants upwind. Benefits from the elimination of fossil fuel combustion in Boston are dominated by reductions in mortality associated with

[4] Due do different methodologies atmospheric dispersion estimates for PM2.5 are different in COBRA from the above method.

increased air quality Table 3. In general, such improvement also lowers hospital admittances for respiratory and cardiac issues while enabling more activity.

Table 3. COBRA output for the elimination of combustion induced pollutants from Suffolk County.

Annual Factors	Reduction in Cases	Cost Saving
Mortality (low estimate)	31.3	$ 311,038,920
Mortality (high estimate)	70.4	$ 700,547,379
Infant Mortality	0.0	$ 465,637
Nonfatal Heart Attacks (low estimate)	4.7	$ 620,682
Nonfatal Heart Attacks (high estimate)	42.9	$ 5,701,133
Hospital Admits, All Respiratory	12.9	$ 387,381
Hospital Admits, Cardiovascular (except heart attacks)	12.8	$ 556,390
Acute Bronchitis	47.7	$ 25,971
Upper Respiratory Symptoms	878.6	$ 33,107
Lower Respiratory Symptoms	609.8	$ 14,525
Emergency Room Visits, Asthma	26.1	$ 12,497
Minor Restricted Activity Days	31346.5	$ 2,423,639
Work Loss Days	5456.8	$ 978,204
Asthma Exacerbation	926.7	$ 60,654

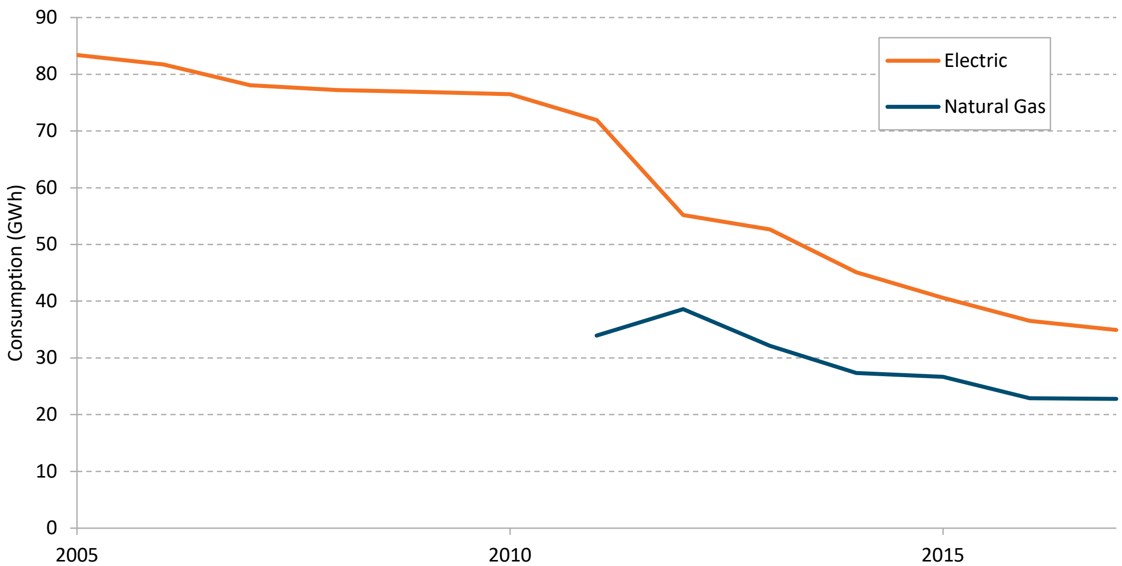
There exists significant uncertainty in such analyses, but the benefits of improved air quality are substantial. Future work should seek to better quantify and reduce uncertainty around health impacts. Incorporation of the cost savings from improved air quality into cost benefit analysis of electrification and retrofit pathways could help to demonstrate the value of these actions. Even with such accounting, new frameworks will be needed to realize the benefits of reduction in harmful air pollutants. Currently, such costs are realized predominantly by the health care sector, far from the entity responsible for emissions.

6 OTHER SECTORS

6.1 STREETLIGHTS

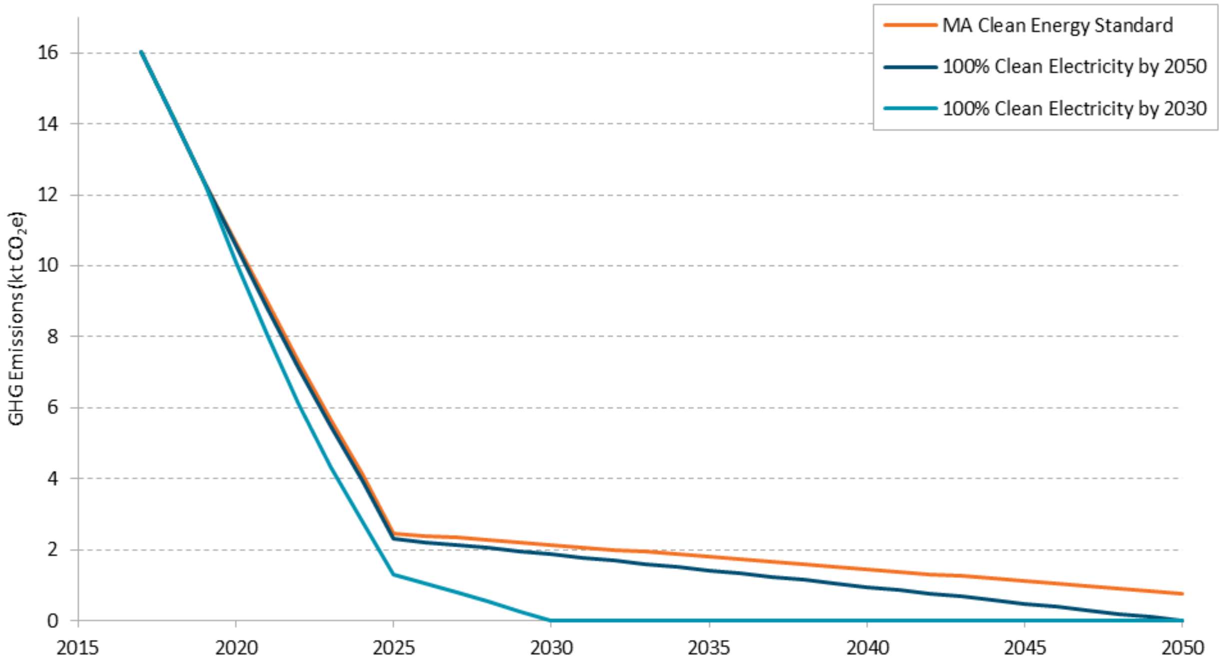
Streetlights throughout the city currently contribute roughly 0.25 percent of the Boston's total GHG emissions. Early street illumination was provided by natural gas which is still used in the North End and Bay Village neighborhoods. For many years energy intensive arc lamps and incandescent bulbs were used to generate light at night. Since 2010 the City has been converting many of its electric lights to more efficient LEDs as wells as installing automatic igniters to avoid the need to keep natural gas lamps lit during the day. Currently, there are about 65,000 electric streetlights and 2,800 gas streetlights in Boston [17]. There is a significant decline in energy consumption between 2010 and 2017 when the City began replacing traditional filament bulbs with LEDs and retrofitting natural gas lamps to only burn during dark hours (Figure 12).

Figure 12. Historical energy consumption in street lighting.



The City has several critical choices to make regarding decarbonizing streetlights. Conversion of the historic natural gas lighting districts to electricity would be the most impactful and cost effective, but may be met with opposition from residents who appreciate the aesthetic. Accelerating the conversion of filament-based lighting would also reduce costs and save energy. These lights could be replaced with LED-based systems that incorporate solar charging or smart systems. Smart systems could deliver cost savings though improved shutdown periods or allow for the incorporation of aesthetic elements such as coloring that could be employed during events such as celebrations for Boston's sports teams. Ultimately once electrified, the carbon intensity of street lighting is driven by the carbon intensity of the electricity used to power the streetlights, reflecting the value of a clean energy procurement for reducing emissions from street lighting (Figure 13). Since most street lighting is operated and paid for by the City, procurement of electricity used for streetlights may face lower regulatory hurdles than a city-wide clean energy procurement.

Figure 13. Forecasted emissions from streetlights



6.2 OFF-ROAD EMISSIONS

Off-road vehicular mobile and stationary uses contributed 80 kt CO_2e in 2015 based on 840,000 GJ of energy use [4]. Off-road uses consist of transport, boilers and space heaters, fire extinguishing services (which includes fire rescue, training, and other related services), generators, ground support equipment, and snowmelters and are fueled by natural gas, diesel oils, fuel oils, and other petroleum products**.** Figure 14 shows the consumption of these end uses, compiled from activities for which there is off-road emissions data available which is mostly from activities at Logan Airport. The majority of energy use show that boilers and space heaters, ground support equipment, and snowmelters are the primary users of energy. It is notable that warmer years with little snow such as 2012 stand in contrast to extremely cold and snowy years such as 2015 when demand for snow melting correlated with Boston's record snowfall.

In general, off-road transportation has successfully achieved efficiency measures. Gas oil no. 6 has been mostly phased out over the last decade leading to higher efficiencies and lower emissions (Figure 15). Additionally, the transition from portable diesel fired snowmelters to natural gas and steam driven snowmelters lowered greenhouse gas emissions intensities. Through participation in the Federal Aviation Administration (FAA) Voluntary Airport Low Emissions (VALE) Program, Logan Airport has used nearly $6,000,000 in grant funding, in addition to local funding, to introduce 18 CNG buses, 32 hybrid electric/diesel buses, gate power for 8 gates, and most recently the purchase and installation of 50 dual-port charges for 99 pieces of ground source equipment.

Figure 14. Time series of overall GJ by use

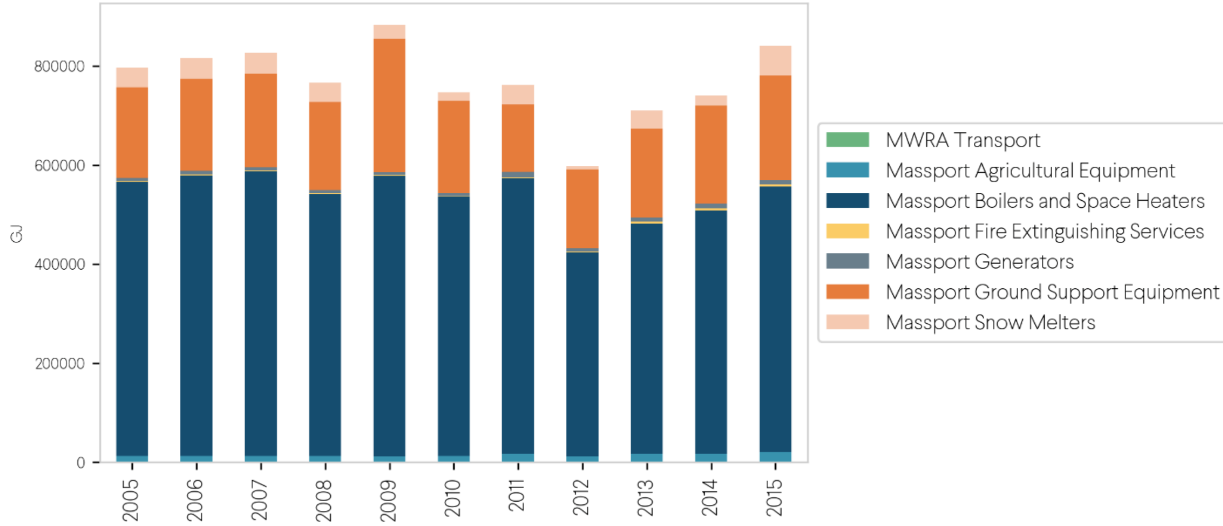
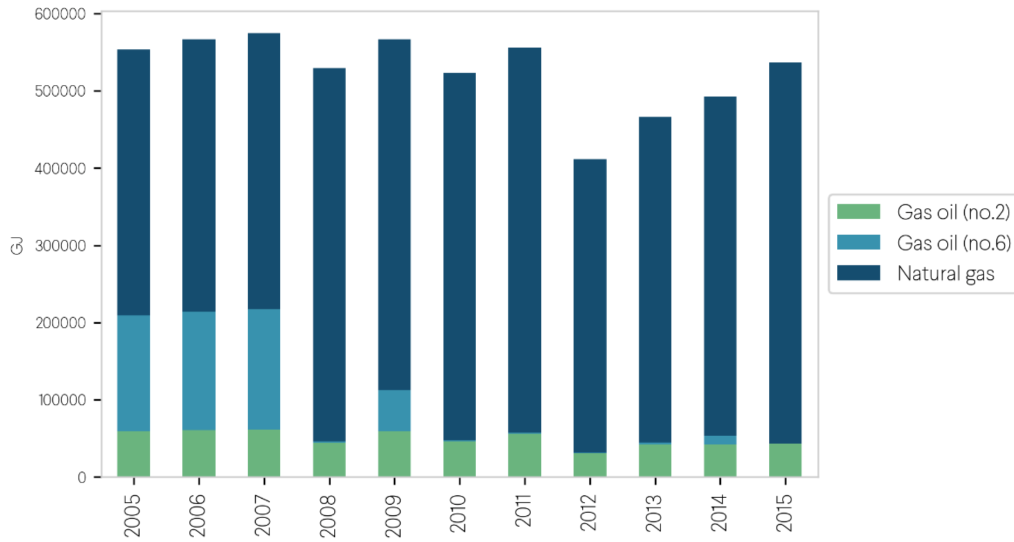


Figure 15. Energy use in GJ for Boilers and Space Heaters by Fuel Type



While progress has been made, more can be done to reduce the overall impact of off-road infrastructure as the demand for these services grow. For example, Logan Airport is serving 44.8 percent more passengers since 2002 and the corresponding 46 percent reduction in GHG emissions per passenger aligns shows roughly the same amount of emissions from year to year. Massport is working towards taking the next steps towards not just maintaining emissions and usage as they continue to serve more people and function in their integral regional role, but to reduce usage and emissions. However, unlike in other sectors, it's not clear what technology can be readily electrified. Electrification of snowmelters and large space heaters, for example would require significant electricity demand during cold events and peak electricity demand. Such critical activity may be prime candidates for the use of limited supplies of sustainable renewable fuels or offsets.

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