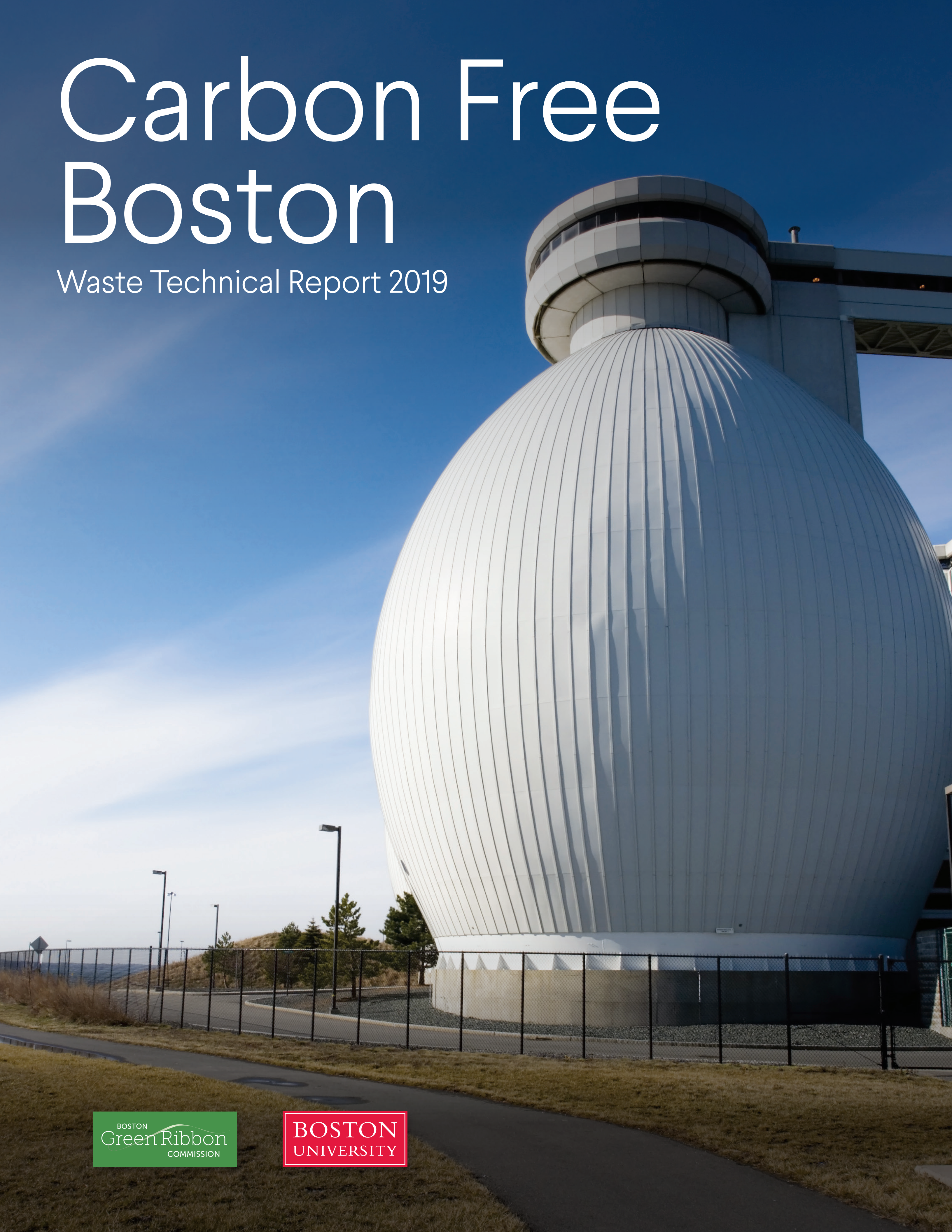
Carbon Free Boston

Waste Technical Report 2019



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Carbon Free Boston: Waste Technical Report

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Carbon Free Boston: Summary Report
Carbon Free Boston: Social Equity Report
Carbon Free Boston: Technical Summary
Carbon Free Boston: Buildings Technical Report
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1 OVERVIEW

For many people, their most perceptible interaction with their environmental footprint is through the waste that they generate. On a daily basis people have numerous opportunities to decide whether to recycle, compost or throwaway. In many cases, such options may not be present or apparent. Even when such options are available, many lack the knowledge of how to correctly dispose of their waste, leading to contamination of valuable recycling or compost streams. Once collected, people give little thought to how their waste is treated. For Boston's waste, plastic in the disposal stream acts becomes a fossil fuel used to generate electricity. Organics in the waste stream have the potential to be used to generate valuable renewable energy, while metals and electronics can be recycled to offset virgin materials. However, challenges in global recycling markets are burdening municipalities, which are experiencing higher costs to maintain their recycling.

The disposal of solid waste and wastewater both account for a large and visible anthropogenic impact on human health and the environment. In terms of climate change, landfilling of solid waste and wastewater treatment generated emissions of 131.5 Mt CO_2e in 2016 or about two percent of total United States GHG emissions that year. The combustion of solid waste contributed an additional 11.0 Mt CO_2e, over half of which (5.9 Mt CO_2e) is attributable to the combustion of plastic [1]. In Massachusetts, the GHG emissions from landfills (0.4 Mt CO_2e), waste combustion (1.2 Mt CO_2e), and wastewater (0.5 Mt CO_2e) accounted for about 2.7 percent of the state's gross GHG emissions in 2014 [2].

The City of Boston has begun exploring pathways to Zero Waste, a goal that seeks to systematically redesign our waste management system that can simultaneously lead to a drastic reduction in emissions from waste. The easiest way to achieve zero waste is to not generate it in the first place. This can start at the source with the decision whether or not to consume a product. This is the intent behind banning disposable items such as plastic bags that have more sustainable substitutes. When consumption occurs, products must be designed in such a way that their lifecycle impacts and waste footprint are considered. This includes making durable products, limiting the use of packaging or using organic packaging materials, taking back goods at the end of their life, and designing products to ensure compatibility with recycling systems. When reducing waste is unavoidable, efforts to increase recycling and organics diversion becomes essential for achieving zero waste.

Pursuing such zero waste strategies will have impacts beyond reducing carbon emissions. First such strategies will likely reduce the cost of waste management and disposal, relieving tax payers of these burdens. Second, bag bans and packaging requirements will spur producers to use sustainable solutions and help to promote innovation in product packaging and materials design. Accelerating such a transformation will have global impacts by shifting the materials used in our lives to be more sustainable, and limit their accumulation in natural systems such as our waterways and oceans.

The City of Boston's consumption and waste streams extend far beyond the city's boarders. Changes to these external systems, outside of the City's control, will have a large influence over the footprint of people and businesses in the city. Despite this large external influence, there remain a large opportunity for the City and its constituents to take action to reduce their waste and waste-GHG footprints as described below.

2 SUMMARY OF KEY FINDINGS

1. The combustion, recycling, and composting of Boston's municipal solid waste (MSW) in 2017 generated 393 kt CO_2e, equivalent to about 6 percent of the city's total GHG emissions. The combustion of MSW in waste-to-energy (WtE) facilities accounts for most of those emissions.
2. Full implementation of the Zero Waste Boston initiative doubles as an effective strategy to reduce GHG emissions. The waste diversion strategies proposed by Zero Waste Boston, combined with enhanced source reduction and education efforts, will reduce annual waste-related GHG emissions by 81 percent by 2050 relative to a baseline scenario.
3. A zero-waste strategy should ensure equal access to information, technology, and financial resources. Regulations, financial incentives, and voluntary programs to increase waste diversion should ensure equitable distribution of costs and benefits. Potential impacts from new facility siting and transportation patterns caused by waste diversion programs should be minimized and equitably distributed. Marginalized communities should benefit from the new jobs created by recycling, composting, reuse, and other waste diversion activities.
4. GHG emissions from water delivery and wastewater treatment represent approximately one percent of the city's total GHG emissions. The Massachusetts Water Resources Authority (MWRA) produces a significant amount of renewable energy from solar, wind, hydropower, and the anaerobic digestion of wastewater at its Deer Island Wastewater Treatment Plant. Increased capture of energy from wastewater could halve current emissions. Some emissions from the processing of wastewater may be very difficult to mitigate from a technical perspective; such emissions are candidates for offsets.
5. The City would benefit from accounting for waste in its GHG inventory, and doing so would position Boston as a leader in explicitly linking waste reduction and greenhouse gas mitigation. This reporting would provide information on the role of wastes in the city's overall emissions, enable the city to evaluate the GHG impact of waste management strategies, and illuminate the relationship—especially the synergy—between waste management and GHG mitigation strategies.

3 BOSTON'S MSW MANAGEMENT SYSTEM

Boston's residents and businesses produced about 1,156,000 short tons of solid waste in 2017 with nearly 80 percent generated by the commercial[1] sector and the remaining 20 percent by households (Table 1). Discarded materials follow one of two routes: *diversion* (reuse, recycling, or biological treatment of organics), and *disposal* (landfill or combustion). 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.

Table 1. Boston's 2017 Municipal Solid Waste Generation (1000 short tons)

Values may not sum to totals due to rounding. *Source*: Data from Boston Department of Public Works and Zero Waste Boston.

	Residential MSW	Commercial MSW	Citywide Total
Disposal	190	684	874
Diversion	50	232	282
Recycling	38	72	109
Organics Diversion	9	49	57
Other Diversion	4	112	115
Total Generation	**240**	**916**	**1,156**

Metrics on waste generation in the commercial sector are somewhat more uncertain as businesses enter into contracts with private haulers [3]. As required by the City's 2008 *Commercial Trash Hauler Ordinance*, private haulers must obtain a waste collection permit in order to operate within Boston's city limits and report tonnages of materials collected [3]. However, the *Ordinance* only applies to collection services that use large containers, and thus it excludes smaller generators that use wheeled carts. To compensate for this lack of data the Zero Waste Boston [4] analysis uses standardized industry generation factors and employment data [5] to estimate commercial generation and diversion tonnages using employment data. Thus, values for Commercial MSW generation are somewhat more uncertain than the residential sector, but is consistent with other cities.

The residential sector's waste collection services are contracted by the City to haulers, which are required to report the tonnage of discarded materials collected. Boston is divided into five collection districts to organize the collection services of the city's residential disposal, recycling, and yard waste streams. All of the city's residential disposal waste is collected and transported to Waste-to-Energy (WtE) combustion facilities outside of the city boundary (Figure 1). 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 WtE facilities. At these facilities, the waste is combusted to generate electricity that is used by the New England grid.

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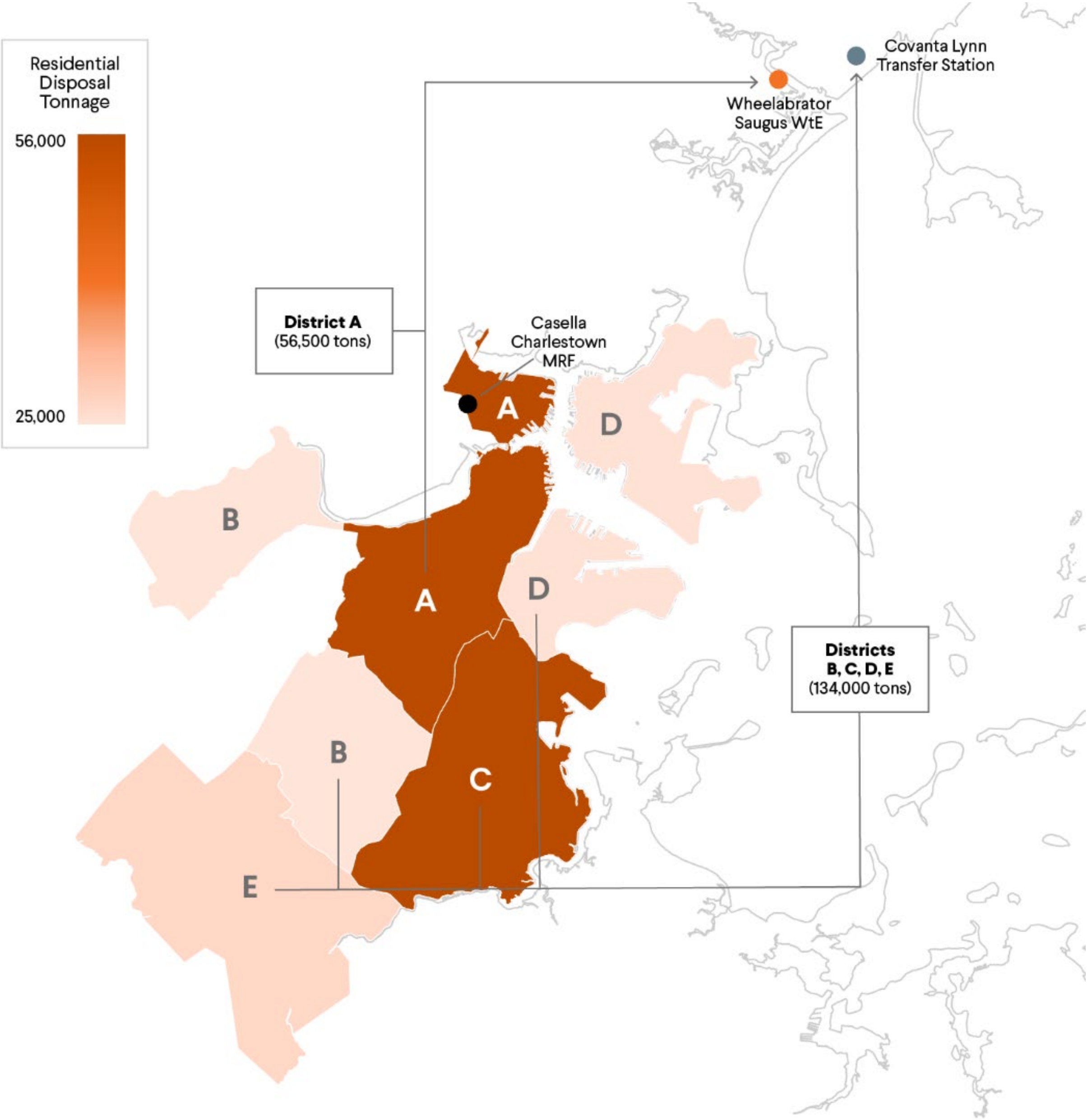
[1] We define our commercial sector as industrial, commercial and institutional and other non-household waste generators.

Figure 1. Boston’s Residential Disposal Tonnages and Destination Pathways in 2017

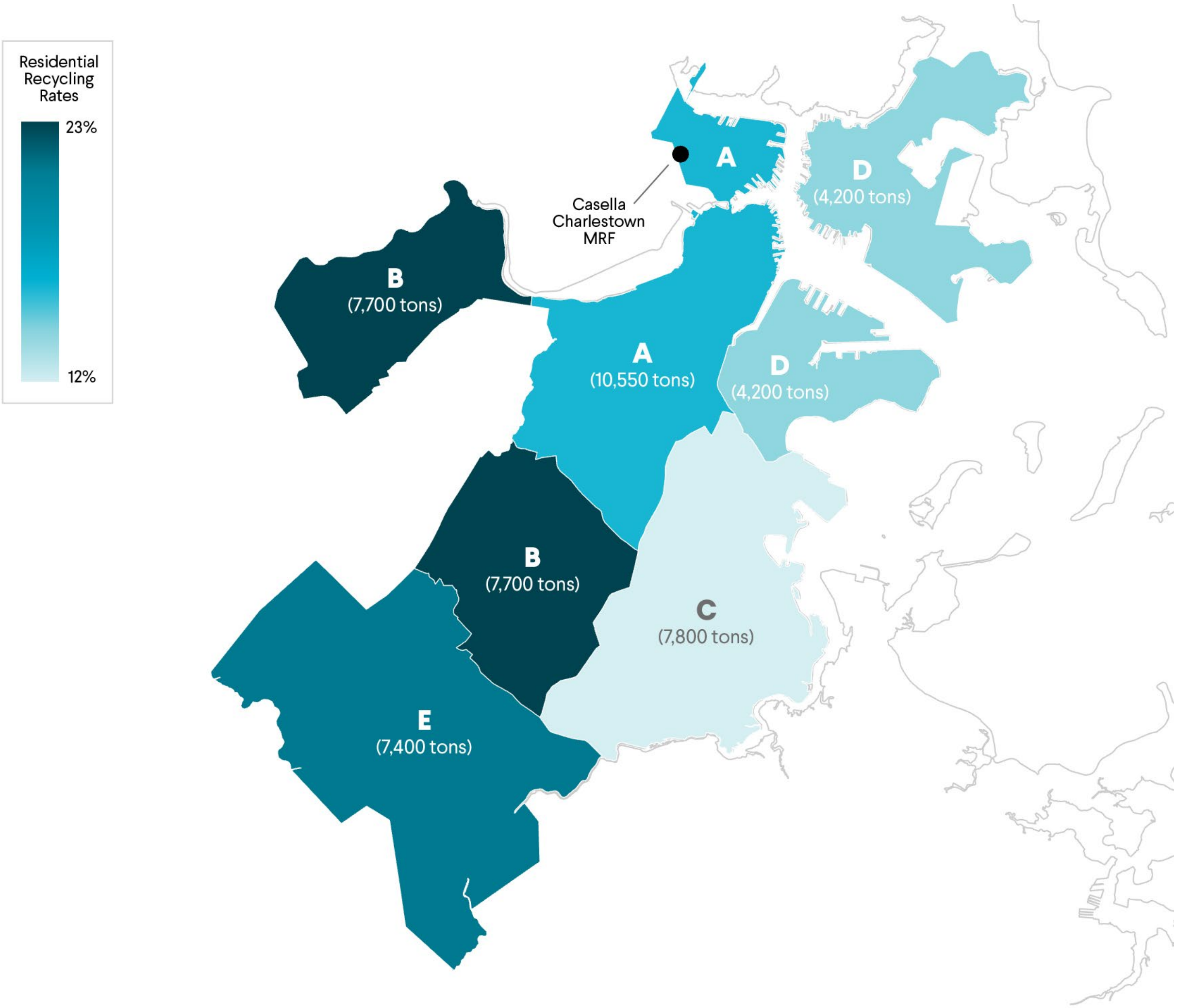
MSW collection districts: (A) Charlestown, Chinatown, Downtown, Bay Village, Back Bay, Beacon Hill, South End, North End, Roxbury, Fenway, Mission Hill, Financial District; (B) Jamaica Plain, Allston/Brighton; (C) North & South Dorchester, Mattapan; (D) East & South Boston; and (E) West Roxbury, Hyde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



Boston’s residential recycling is processed within the city at Casella’s material recovery facility (MRF) in Charlestown. Recycling rates among collection districts range from 12 to 23 percent (Figure 2). The recycling rates reported for each district are gross estimates based on curbside collection amounts. The net quantity actually recycled is equal to the gross quantity less the quantity of “contamination,” i.e., the non-recyclable materials that are removed and sent to disposal. The rate of recycling contamination in 2017 was 20 percent of the gross curbside pickup [6].

Figure 2. Boston's Residential Recycling Rates and Tonnages in 2017

Source: Data from Boston Department of Public Works.



3.1 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" [7]. A major step towards this goal was launched in 2018 in the form of *Zero Waste Boston*, a planning initiative that aims to "…transform Boston into a zero-waste city through planning, policy, and community engagement" [4]. Boston has adopted the following definition of "Zero Waste" [8]:

> *"Zero Waste is a goal that is ethical, economical, efficient and visionary, to guide people in changing their lifestyles and practices to emulate sustainable natural cycles, where all discarded materials are designed to become resources for others to use.*
>
> *Zero Waste means designing and managing products and processes to systematically avoid and eliminate the volume and toxicity of waste and materials, conserve and recover all resources, and not burn or bury them.*
>
> *Implementing Zero Waste will eliminate all discharges to land, water or air that are a threat to planetary, human, animal or plant health."*

This definition provides the general guidelines for businesses and communities to follow to begin their zero-waste planning process. A commonly adopted benchmark for achieving zero waste is to divert at least 90 percent of waste from landfills and MSW combustors. Diversion refers to all waste diversion activities including 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.

WHAT IS A MRF?

As an integral part of the MSW management system, recycling diverts waste away from the disposal stream and reduces the need to extract virgin raw materials [9]. A material recovery facility (MRF, pronounced "murf") acts as an intermediate, but crucial step in the recycling process by receiving and preparing recyclable waste to be manufactured into new products.

MRFs can be designed to accommodate single-stream, dual-stream, or pre-sorted recyclable waste collection methods. Regardless of the specific collection process, all MRFs are equipped with a series of manual and mechanical sorters to separate incoming recyclable waste into various marketable commodities. Manual sorting prevents any unwanted materials from entering and potentially damaging mechanical equipment as well as recovers any recyclable materials missed during the separation process [10]. Optical sorters, disk screens, and magnets are among the primary equipment utilized to separate the incoming recyclable stream into fiber, glass, metals, and plastics streams. Each individual material stream is inspected for contaminants prior to baling to ensure high-quality materials for manufacturers.

The presence of non-recyclable materials in the recycling stream causes major issues for MRFs in terms of operating costs, materials processing, and workplace safety [11]. Recycling contamination occurs due to the lack of education and appreciation of proper waste sorting methods. Residual, non-recyclable materials gathered at MRFs are transported and deposited into landfills or combustion facilities for final disposal.

The Zero Waste Boston initiative presented 30 strategies to help Boston achieve its zero-waste goals [4]. 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 accelerate their transition to zero waste equitably and manageably.

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 (Table 2). 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 on these households.

Table 2. Zero Waste Boston project scoping initiatives to achieve 80 percent diversion.

These are distinct from the 30 strategies presented in the final Zero Waste Boston Report. *Source*: Zero Waste Boston [12]

Zero Waste Scoping Initiatives [a]		Diversion Impact (1000 TPY)[b]	Total Net Annual Costs (1000 $)[b]	Diversion Rate Increase (%)
A1.	Organics Diversion	186	$4,750	16 %
A2.	Reuse Collection & Facilities	22	$240	2 %
A3.	Residential Collection System	28	$380	2 %
A4.	Neighborhood Drop-off Centers	4	$560	>1 %
A5.	Zero Waste Research	6	$110	1 %
A6.	City Leads by Example	7	$130	1 %
A7.	City-Owned Facilities	NA	$2,500	NA
B1.	Reduction and Recycling Mandates	161	$1,760	14 %
B2.	ICI Hauler & Generator Requirements	110	$1,250	10 %
B3.	Product/Packaging Waste Reduction	19	$210	2 %
B4.	Environmentally Preferable Purchasing	10	$120	1 %
B5.	Zero Waste Venues & Events	5	$160	>1 %
B6.	Reusables Disposal Ban	6	$70	1 %
B7.	Construction & Demolition Requirements	6	$160	1 %
C1.	Outreach and Technical Assistance	17	$1,170	1 %
C2.	Behavior Change Marketing	26	$1,260	2 %
C3.	Awards & Certifications	3	$60	>1 %
C4.	Community Grants	9	$120	1 %
C5.	Zero Waste Market Development	13	$255	1 %
	Total	**638**	**$15,265**	**55 %**

[a] (A) Services; (B) Rules; and (C) Outreach & Education

[b] TPY (short tons per year) and total net annual cost calculations assume constant total waste generation between 2017 and 2050. Total net annual cost is defined as the direct annual costs for implementing each initiative plus the potential reduction in disposal costs.

CASE STUDY: LOCAL ADVANCES IN ORGANICS DIVERSION

Organics diversion is a challenging waste management strategy to implement in densely populated areas due to limited space for processing facilities and limited capacity for additional collection services. Various efforts in the Boston area have been carried out in recent years to make urban organics diversion a real possibility for the region.

In April 2018, the City of Cambridge began offering a curbside organics program to an estimated 25,000 households. Around 6 to 7 tons of source-separated organics are collected per day by two City-owned collection vehicles, leading to an estimated 8 percent decrease in disposal waste tonnage [34]. With the continued success of the program, the City is currently looking into expanding collection services to include larger residential buildings with 13 or more units as well as increasing participation along current collection routes.

Waste Management has recently built a customized Centralized Organics Recycling (CORe) facility in Boston's Charlestown neighborhood to preprocess the region's residential and commercial organic waste. Boston's CORe facility removes contamination and produces a high-quality organic feedstock that is ripe for anaerobic digestion at the Greater Lawrence Sanitary District's wastewater treatment facility in North Andover [35]. The CORe process produces an engineered bioslurry that has a higher energy-content than the average feedstock of wastewater treatment facilities. Although the CORe facility currently accepts about 50 tons of organic waste per day, it has the capacity to support up to five times the amount as demand for these services increases [35].

As the "zero waste" concept gains momentum these organics diversion strategies are essential for achieving diversion rate targets.

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 and 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 of the city's geographic boundary, 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. While pollutants from these facilities are stringently regulated, the combustion process still releases harmful pollutants such as particulate matter, lead, mercury, and dioxins. The ash stored in the landfills at these sites contains the same pollutants.

4 ASSESSMENT OF GHG EMISSIONS FROM MSW

4.1 EMISSIONS ACCOUNTING FRAMEWORK

Boston's MSW is burned at electricity-generating combustion facilities outside the city that feed into the ISO New England grid. The GHG intensity of a kilowatt-hour of purchased electricity by any user in New England is a weighted average of the electricity from multiple sources with different emissions intensities, with WtE being one of the sources. This provides the basis for how the City currently accounts for waste its GHG inventory: multiply all the electricity consumed in the city by the average GHG intensity of the ISO New England grid. In this approach, the GHG emissions from the disposal of the city's waste is not reported separately. Rather, it is embodied in the emissions calculated for electricity use. This approach is consistent with the accounting guidelines set by the *Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories* (GPC).

We develop an alternative accounting approach that directly assesses the GHG emissions from the disposition of the city's solid waste. We assess the emissions impacts from different waste management decisions by directly attributing emissions to the functional unit of waste rather than to electricity generation. We do so in order to assess the impacts of waste policy on GHG emissions. Our approach could provide insight to the effects of future policies and activities on GHG emissions that would not be observed in the City's current accounting standard.

Our approach extends the GHG accounting boundary to include some Scope 3 emissions. Nearly all the emissions from the generation and treatment of MSW occur outside the city's boundaries at WtE facilities. The only emissions occurring in-boundary are due to waste collection throughout the city and processing of recyclables at the Charlestown MRF. Emissions from these activities are evaluated in the aggregate fleet activity and industrial buildings class in the transportation and buildings sectors, respectively. These emissions are relatively small compared to emissions associated with final waste treatment that occur outside the city's boundary.

Our approach is not intended to preclude the City's application of the GPC methodology, but is necessary to analyze the GHG reduction potential of policies focused on the generation and management of waste. One option for the City to consider is to continue reporting emissions with the current method, but add a separate account that reports GHG emissions based on the quantity, composition, and disposition of waste – as a producer of that waste. This would enable the City to explicitly evaluate the GHG impact of waste management strategies. In particular, accounting for waste would illuminate the relationship—especially the synergy—between waste diversion and GHG mitigation strategies. This seems to be especially important in light of the *Zero Waste Boston* initiative. Representation of waste in the GHG inventory would also align the City with the practices of the Commonwealth, the United States Environmental Protection Agency, and with the guidelines for waste in the *Protocol for the Quantification of Greenhouse Gas Emissions from Waste Management Activities* [13], a GPC-sanctioned accounting methodology.

4.1.1 Comparison with State DEP and U.S. EPA Waste Accounting

The Massachusetts Department of Environmental Protection (MassDEP) and United States Environmental Protection Agency (EPA) report emissions from the combustion of MSW in the Energy sector [1,2].[2] This accounting methodology reports emissions from combustion in the category of electric power generation. Six out of the seven MSW combustors in Massachusetts are WtE facilities where MSW is used as a fuel to generate electricity for distribution to the grid [2]. Emissions for MSW combustion are calculated under the methodologies prescribed by the Greenhouse Gas Reporting Program (GHGRP) and stored in the EPA Facility Level Information on GreenHouse Gases Tool (FLIGHT).

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[2] The Massachusetts DEP displays all their MSW and wastewater data in a single Waste category in of the inventory. The actual GHG emissions associated with waste combustion are reported in the Electric Power section.

Since 2010 Massachusetts has utilized the FLIGHT database in their GHG inventory for waste-related emissions. Although the GHGRP works well at the state- and national-level, it is not appropriate at more granular scales where MSW streams cannot be aggregated at the facility-level. The WtE facilities utilized by Boston also receive waste from other municipalities, making it difficult to differentiate how the emissions are allocated. By taking a bottom-up approach, our analysis focuses on the emissions associated with the city's MSW generation, which allows for an independent analysis of alternative waste management practices and diversion rates.

4.1.2 Classification of Waste Emissions

Municipal solid waste generates GHG emissions in all stages of its management: from collection to final treatment [14]. These emissions are divided among three categories [14]:

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 through 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.

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.

Direct emissions are easily mapped to a specific method of waste treatment, and in principle are directly measurable, e.g., the combustion of waste to generate electricity. Indirect emissions associated with the purchase of electricity are affected by amount of electricity being demanded and the GHG intensity of the grid. Direct and indirect emissions exhibit temporal and regional heterogeneity due to variations in performance among combustion facilities and grid carbon intensities, or due to different rates of GHG generation in composting and material application due to regional climate differences. A bottom-up approach to MSW provides decision-makers with information on GHG impacts associated with each waste management alternative [15].

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. Avoided emissions are a fundamentally different metric than direct and indirect emissions. They often vary greatly by location and can change significantly over time due to regional and temporal heterogeneity in displaced energy and material generation processes. The calculation of avoided emissions due to energy recovery from waste combustion is very sensitive to assumptions regarding the design and efficiency of the WtE plant, and the characteristics of those avoided electricity generations sources [16]. In particular, the emissions avoided due to energy recovery are very sensitive to the GHG intensity of the grid in the area of study. Moreover, both electricity generation and the provision of raw virgin materials have become less GHG-intensive, which correspondingly decreases the avoided emissions. This trend is likely to continue for the foreseeable future.

Energy recovery refers to the generation of energy from waste materials either through direct combustion or biomethane production from waste decomposition. In the case of WtE technologies, energy recovery can prevent or “avoid” emissions from a grid-connected power plant or other facility that would be assumed to otherwise burn fossil fuels to generate energy. Material recovery refers to the capture of recyclable waste materials from the waste stream and converting them into marketable commodities. This process reduces the demand for raw virgin materials, which avoids upstream emissions associated with material extraction and processing. Nutrient recovery refers to the avoided emissions associated with the displacement of synthetic or mineral fertilizers due to the application of compost and digestate biomass to agricultural soils.

The term “carbon storage” refers to three separate processes: (i) forest carbon storage; (ii) soil carbon storage; and (iii) landfill carbon storage. The source reduction and recycling of paper and wood materials reduces the need to harvest additional trees, which in the short term, results in more forest carbon storage [17]. Soil carbon storage occurs in two ways: (i) direct storage of carbon in depleted soils, and (ii) carbon stored due to incomplete microbial decomposition of organic materials [17]. The latter mechanism also causes organic materials in landfills to store carbon. Although soil and landfill carbon storage refer to the storage of biogenic carbon, these types of carbon storage would not occur under natural conditions and are therefore considered to be an anthropogenic sink [17]. The fossil carbon stored in landfilled waste materials (e.g., plastics) does not generate any additional carbon storage benefit.

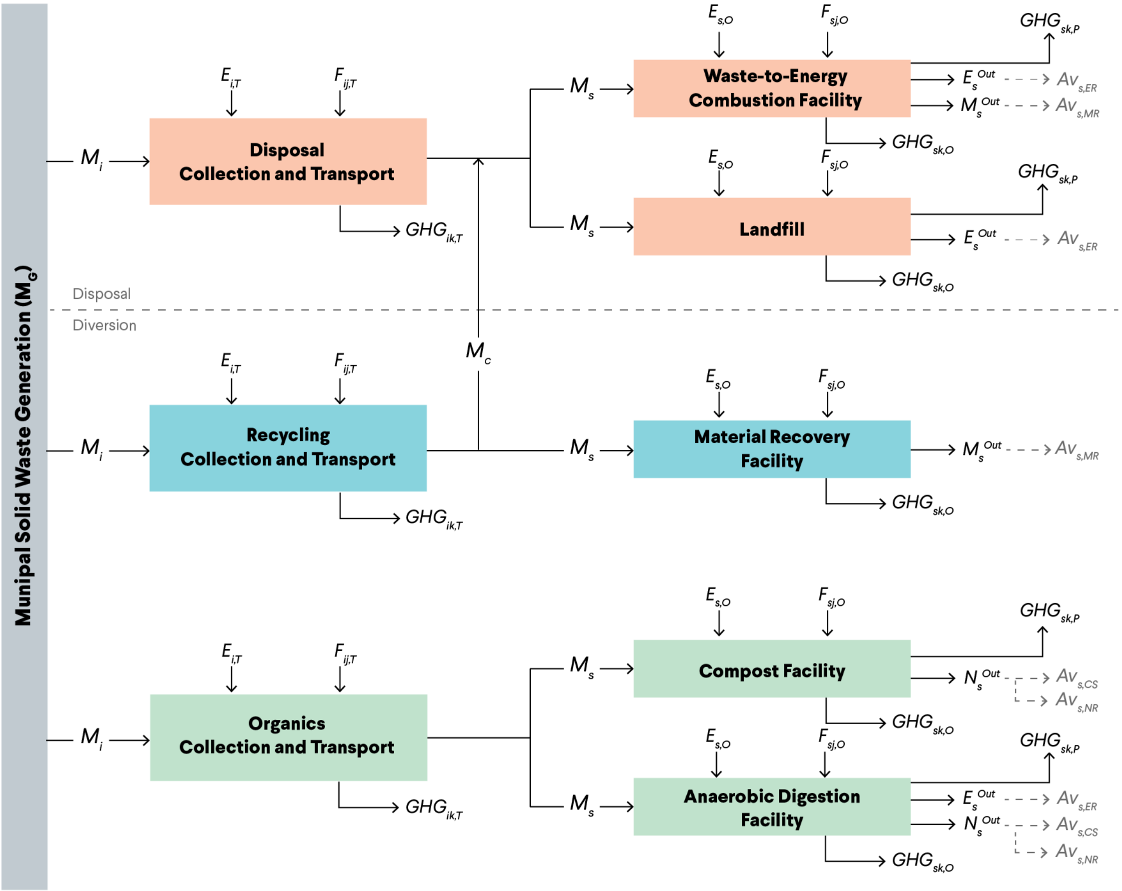
GHG accounting protocols such as the GPC stipulate that avoided emissions should be reported separately [18]. Avoided emissions can play a role in elucidating the climate benefits associated with different waste management pathways as long as their limitations are understood. Although, estimates of avoided emissions are highly uncertain and variable, understanding the potential for avoided emissions allows for a broader evaluation of the potential impacts of alternative waste treatment options. Thus, their evaluation should take into account relevant influencing factors and uncertainty.

4.1.3 The Characterization of Energy, Materials and Emissions

Once MSW enters the waste stream, discarded materials follow a diversion pathway by being recycled or biologically treated, or a disposal pathway by via landfilling or combustion (Figure 3). Within these two pathways are three waste streams: (i) recycling (paper, metal, plastics, glass, etc.); (ii) organics (food waste, yard trimmings, etc.); or (iii) mixed MSW, or disposal. The proportion of material (*M*) that flows through each waste stream or management practice relies on the management decisions and policies of the governing body. At each stage in its management, the discarded materials require electricity (*E*) and fuel (*F*) inputs for its collection, processing, and final treatment.

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.). Materials can contain biogenic carbon (paper and organics), fossil carbon (plastics), or no carbon (glass and metals). The source of carbon (fossil or biogenic) in a material determines whether the emission has a net global warming potential (fossil) or not (biogenic). Breakdown of organic carbon in landfills can produce methane, which even if sourced from biological carbon, has large global warming potential.

Figure 3. Energy, Material, and Emission Flows in the MSW Management System



Variables:

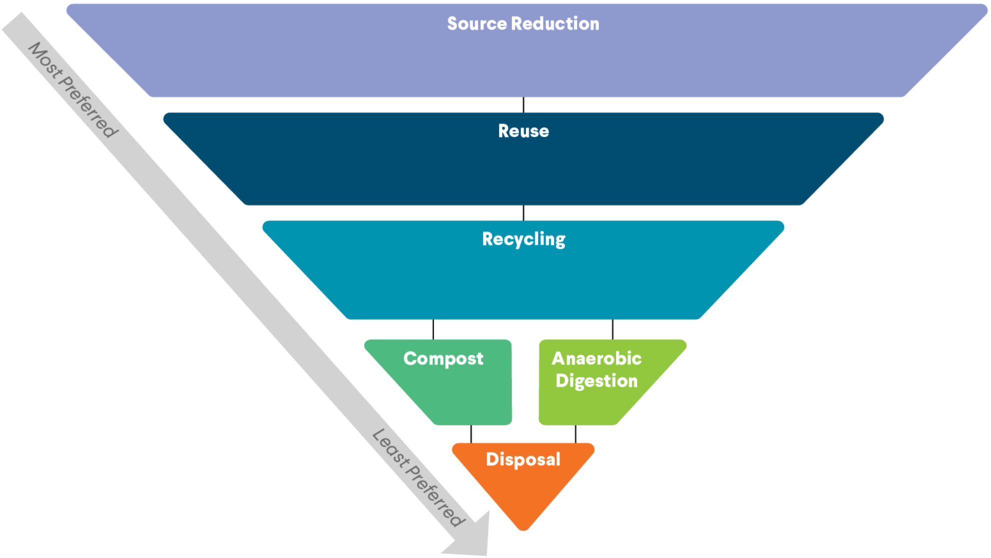
M = material input (short tons)
M^{Out} = material output (short tons)
F = fuel input (gallons)
E = electricity input (kWh)
E^{Out} = energy generation from WtE technologies (kWh, GJ)
N^{Out} = nutrient output (short tons)
GHG = greenhouse gas emissions (tCO_2e)
Av = avoided emissions (tCO_2e)

Subscripts:

c = contamination from recycling waste stream
i = waste stream (i.e., disposal, recycling, or organics)
j = fuel type (i.e., diesel, gasoline, etc.)
k = greenhouse gas (CO_2, CH_4, or N_2O)
s = waste management practice (i.e., combustion, MRF, etc.)
G = MSW generation across all waste streams
T = waste collection & transport
O = waste facility operations
P = waste processing
ER = energy recovery
MR = material recovery
NR = nutrient recovery
CS = carbon storage

The waste management hierarchy outlines the preferability of technologies and practices within the MSW management system (Figure 4). Source reduction is the most preferable management option followed by reuse, recycling, recovery, and disposal. This representation of the MSW management system exemplifies a "zero-waste" perspective in which a majority of the waste stream is diverted, and disposal is only used as a last resort. However, it is important to note that 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 N_2O and biogenic CO_2 if combusted, and releases CH_4, N_2O, and biogenic CO_2 if landfilled or biologically treated – the magnitude of these emissions factors can vary significantly depending on process conditions. Any efforts to reduce or divert waste need to take into account these material-treatment dynamics that drive emissions.

Figure 4. The Waste Management Hierarchy



Source Reduction

Source reduction and reuse prevent potential waste materials from entering the waste stream and causing downstream GHG emissions. Source reduction provides GHG emission benefits by avoiding the upstream emissions associated with raw material acquisition and manufacturing processes [17]. Due to the large uncertainty in upstream emissions impacts, our analysis only includes the GHG emission benefits associated with downstream waste management.

Collection and Transfer

The MSW management process begins with the collection and transport of waste. GHG emissions associated with this step arise from the combustion of diesel fuel by collection vehicles; emissions vary by vehicle type and route characteristics [19]. After collection, waste is transported either directly to processing and disposal facilities, or to transfer stations that reduce transport costs by consolidating waste for long distance transport. Waste transfer stations use fuel and electricity and release GHGs, but their contribution is small compared to other stages of the MSW management system.

Recycling

Once collected, the recycling waste stream is sent to a MRF to be processed for recycling. A MRF separates recyclables into commodities according to market specifications, and removes contaminants [20].[3] MRFs and recycling facilities use energy to process the incoming waste stream, which directly (fuel) and indirectly (electricity) release GHGs. Recycling creates potential avoided emissions in the form of material recovery and forest carbon storage.

Organics

The organics waste stream undergoes biological treatment to recover nutrients and/or energy by means of aerobic composting and/or anaerobic digestion. Aerobic composting is the decomposition of organic waste to produce compost, a nutrient-rich soil conditioner. Anaerobic digestion generates biogas and digestate, a nutrient-rich sludge [21]. Anaerobic digestion can support a WtE system that uses biogas to generate heat and/or electricity. Over the course of a few weeks, anaerobic digestion can yield a significantly higher methane production per unit of waste than a landfill can produce in 6 or 7 years [21]. Such sources of renewable natural gas will be critical components of decarbonization efforts providing a low-to-zero carbon fuel source to services that will be difficult to electrify or switch from fuels.

Organic waste decomposition and biomethane combustion emit direct emissions in the form of CH_4, N_2O, and biogenic CO_2. The decomposition or combustion of biomass leads to the release of biogenic CO_2; however, since this carbon was originally part of the biogenic carbon cycle, it has a global warming potential (GWP) of zero [22]. Solid products from biological treatments (e.g., compost and digestate) can be applied to soils as either a fertilizer substitute or as a soil conditioner. In terms of potential avoided emissions, aerobic composting primarily yields carbon storage and nutrient recovery benefits, while anaerobic digestion also yields energy recovery benefits. The avoided emissions associated with these biological treatment technologies present substantial potential benefits from a GHG perspective.

Disposal

In general, the mixed MSW fraction of the waste stream is sent to a combustion facility or to a landfill. Mixed MSW can be sent to a specialized MRF to extract and divert additional materials before being sent to final disposal; usually this is not economically viable. Combustion of MSW can reduce the mass and volume of the waste by 70 and 90 percent respectively [21]. Waste combustion releases direct process GHG emissions in the form of CO_2, N_2O, and biogenic CO_2. If the heat from combustion is captured, it can be used directly or to generate electricity, potentially avoiding emissions via energy recovery.

Waste combustion can also yield potential avoided emissions in the form of material recovery. Waste combustion ash is conventionally disposed in ash landfills, but changes in technology and regulation have led to its increased use in road construction and cement production [21]. Ferrous and non-ferrous metals left over after waste combustion can be recovered and sent to recycling facilities.

Sanitary landfilling is the controlled disposal of MSW that employs leachate management practices [21]; unsanitary landfilling does not employ these environmental precautions. If not properly managed, landfills can discharge leachate that has serious potential human health and environmental impacts

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[3] Recycling contamination occurs when non-recyclable items are mixed in with recyclable items, when recyclable items contain certain residues (a greasy pizza box), or when recyclables are mixed in inappropriate ways (metal cans in plastic bags).

[23].[4] Waste decomposition at landfills releases direct GHG emissions in the form of CH_4. Landfill gas (LFG) recovery is another important landfill management practice. Depending on the LFG management practice (e.g., LFG venting, LFG flaring, LFG recovery for energy generation), landfilling contributes to GHG emissions at various magnitudes [14]. LFG venting refers to the direct release of CH_4 into the atmosphere. The combustion of LFG, through flaring or energy generation, converts a portion of the CH_4 emissions into biogenic CO_2, effectively reducing the GHG impact of a given landfill. LFG recovery provides a *renewable* energy source, but even the best designed landfills will still often leak methane. Landfills offer a unique avoided emission relative to combustion in the form of carbon storage of biogenic carbon that is not converted to methane [24].

Tradeoffs Associated with Treatment Options

Each waste pathway has significant environmental, economic and public health impacts that will influence the desirability of a particular pathway. Combustion of MSW avoids the large land demands of landfills but can yield other atmospheric emissions such as carbon monoxide and sulfur dioxide, heavy metals, and various organic compounds of concern to human health and environmental quality [25]. Appropriate pollution control technology is required to reduce potential harm. Even well-engineered landfills can leach harmful compounds into local water resources [26]. Biological treatment options often cause undesirable odors, and if contaminated may spoil their application site. Such tradeoffs need to be evaluated as treatment options are considered.

4.2 MSW GENERATION AND COMPOSITION

We employ a bottom-up approach to evaluate changes in GHG emissions as waste streams change due to various waste diversion policies. Boston's MSW generation (M_G) is composed of the material inputs (M_i) entering each of the disposal, recycling, and organics waste streams. The residential and commercial sectors are treated separately due to their distinct MSW characteristics. The Boston Public Works Department collects and reports data on the generation of residential MSW. We use Zero Waste Boston's [4] data and methodology to estimate commercial generation and diversion tonnages. Nearly half of the commercial sector's diversion tonnage in Boston is categorized as "Other Diversion", which can include various diversion pathways. To evaluate this pathway, we allocated materials to the recycling and organics waste streams according to the recoverability of each material type.

Waste characterization studies conducted at the Saugus, SEMASS, and Haverhill WtE facilities in 2016 were used to define Boston's disposal stream by material type. Similarly, composition measurements were obtained from Casella Charlestown MRF to define the city's recycling stream. According to Casella, about 20 percent of all recycling material inputs received by their facility is contamination (M_c) and must be diverted back into the disposal stream [27]. The material inputs (M_s) for each MSW management practice are calculated as:

$$M_{WtE} = M_{disposal} + M_c \tag{1}$$

$$M_{MRF} = M_{recycling} - M_c \tag{2}$$

$$M_{compost} = M_{organics} \tag{3}$$

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[4] Leachate is a liquid that passes through a landfill and contains extracted dissolved and suspended matter waste. It results from precipitation entering the landfill and from moisture that exists in the waste itself.

Equations 1 – 3 show the relationship between collected material inputs (M_i) in each waste stream and processed material inputs (M_s) at each MSW management facility. Note that recycling contamination is removed from the recycling stream and reallocated to the disposal stream.

4.3 GHG QUANTIFICATION METHODOLOGY

We assess the GHG emissions associated with Boston's MSW management system under two management scenarios: (1) Baseline, and (2) a Zero Waste Pathway. The baseline scenario assumes that future MSW generation is driven only by population (residential MSW) and employment (commercial MSW) with diversion rates held constant at existing levels. The Zero Waste Pathway assumes that 80 percent diversion will be achieved by 2030 in line with Zero Waste Boston's proposed policy initiatives and 90 percent diversion will be achieved by 2040 with increased source reduction and education and outreach efforts. The model assesses both of these scenarios from 2017 to 2050.

We use emissions and energy-yield factors for each material type from EPA's Waste Reduction Model (WARM) [17]. We disaggregated and then modified some of the assumptions and data in WARM to improve accuracy and flexibility. In particular, we used more granular description of emissions types and management practices, and updated data to represent the regional electricity grid mix and new information on the warming potentials of GHGs [22]. Notably, this allows us to explicitly break out emissions by type (e.g., direct or avoided). This is especially important for understanding the relative contribution of different types of GHG emissions and their relative uncertainty associated with each treatment pathway.

4.3.1 Collection and Transport

Waste collection vehicles in Boston are assumed to be uniform in vehicle miles traveled (VMT), fuel economy, and fuel type across all three waste streams. Waste collection and transport data was derived from the EPA's Motor Vehicle Emission Simulator (MOVES) model [28]. According to MOVES, the VMT for waste collection trucks is approximately 6,571 miles per vehicle per year with an average fuel economy of 5.6 mpg of diesel in 2017 and 6 mpg in 2030. Using the national population of 0.55-0.6 refuse trucks per 1,000 population from MOVES, we estimate that the city has about 375 collection vehicles servicing its residential and commercial sectors. Fuel consumption ($F_{ij,T}$) for each waste stream was calculated as:

$$F_{ij,T} = \left(\frac{VMT*CV}{MPG}\right) * \left(\frac{M_i}{M_G(17)}\right) \qquad (4)$$

where:
VMT = vehicle miles traveled (miles traveled per vehicle)
CV = # of collection vehicles
MPG = average fuel economy (miles per gallon)
M_i = material input into each waste stream (short tons)
$M_G(17)$ = ΣM_i, total MSW generation tonnage for 2017 (short tons)

Equation 4 uses 2017 metrics to estimate fuel consumption for each waste stream in any given year. The number of collection vehicles needed in any given year is assumed to be proportionate to the amount of waste collected by each waste stream. The emissions factor for diesel fuel (EF_j) used to calculate GHG emissions for waste collection and transport is 0.01016 t CO_2e per gallon [22]. The direct transportation emissions ($GHG_{ik,T}$) for each waste stream are calculated as:

$$GHG_{ik,T} = EF_j * F_{ij,T} \qquad (5)$$

4.3.2 Emissions from MSW Management Practices

Once Boston's MSW streams were defined by material type and by management practice, the material breakdowns captured from waste audits [27, 29] for each waste stream were mapped to WARM classifications. Materials that could not be mapped to WARM classifications were excluded from our analysis.[5] The mapping process requires some critical evaluation of reported materials and their compatibility with WARM classifications. Plastics are a particular point where material classification can significantly impact estimated emissions. WARM utilizes a carbon intensity of 2.79 t CO_2e per short ton waste for HDPE (high-density polyethylene), LDPE (low-density polyethylene), or PP (polypropylene) plastics, and a value of 2.04 t CO_2e per short ton waste for PET (polyethylene terephthalate) plastics. Some waste audit categories clearly indicate the material type (e.g., #1 PET plastic). Others indicate an unquantifiable mixture of plastic types or material composites (e.g., Bulk Rigid Plastic Items, Other Plastic Film). These can often comprise a significant portion of the waste stream. In this case we mapped these to WARM's mixed plastic classification which represents a weighted average of plastic streams. Due to the uncertainty associated with some of these audit categories approximately 70 percent of plastics gets allocated to the Mixed Plastics WARM classification. An unreported sensitivity analysis demonstrated that allocating some of these audit categories to more higher-intensity plastics yield unrealistic aggregate emissions intensities for WtE combustion facilities. While our mapping results in realistic, albeit high values for aggregate facility emissions (discussed below in comparison to actual facilities), we acknowledge that this remains a large source of uncertainty due to data limitations. More accurate audits of the properties of the mixed or composite materials would help to reduce uncertainty.

As mentioned earlier, direct and indirect emissions ($GHG_{sk,O}$) associated with in-boundary facility operations (e.g., Casella's Charlestown MRF) were excluded from the waste sector analysis and are included in the buildings sector. The facility operating emissions associated with out-of-boundary facilities (e.g., Covanta's and Wheelabrator's WtE facilities) are not considered to be directly attributable to Boston and are thus excluded.

Table 3 displays the emissions associated with each management practice.

WARM provides a set of emissions factors (EF_s) by material type and by MSW management practice. The direct process emissions ($GHG_{sk,P}$) and avoided emissions (Av_s) for each MSW management practice (s) are calculated as:

$$GHG_{sk,P} = EF_{s,P} * M_s \tag{6}$$
$$Av_{s,ER} = EF_{s,ER} * M_s \tag{7}$$
$$Av_{s,MR} = EF_{s,MR} * M_s \tag{8}$$
$$Av_{s,NR} = EF_{s,NR} * M_s \tag{9}$$
$$Av_{s,CS} = EF_{s,CS} * M_s \tag{10}$$

The relative certainty of the emissions factors is briefly addressed in Table 3. We note that there can be significant variability and uncertainty embodied in the emissions coefficients used here. In particular, avoided emissions from carbon storage can be both largely variable and uncertain. In the case of carbon storage from composting, this is due to variability in land management practices, local climate, soil conditions, and rate of compost application. Uncertainty is primarily due to a lack of agreement in the

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[5] These include household hazardous waste (e.g., lightbulbs, batteries, paint, etc.), bulky materials, and restaurant fats/oils/greases.

literature about the appropriate time horizon to measure carbon storage, as carbon is slowly emitted over the course of time. WARM uses a 10-year time frame which results in a much larger carbon storage credit across material types than other accounting methods [30]. For consistency across our approaches we use the reported values for WARM, but caution that our estimates for carbon storage are highly uncertain and may only represent best case scenarios with best management practices. Decisions that are influenced by the carbon storage potential of compost should seek to better quantify carbon storage potential in the specific application of the compost.

4.3.3 Comparison with Measured Emissions from Waste Combustion

Covanta reports a national average emission intensity of 0.38 t CO_2e per short ton of MSW from its WtE facilities from 2015 to 2017 [31]. Those emissions are reported to the EPA, and the average GHG intensity is based in part on the direct measurement of emissions from units at some facilities. Our methodology generates an average emission intensity of 0.44 t CO_2e per short ton of MSW. The discrepancy is due in large part to different methodologies. We use a bottom-up approach that relies on (i) waste tonnage data reported by the City; (ii) composition of waste based on data at the three WtE facilities that receive the city’s waste (and waste from other municipalities); and (iii) the emissions intensity that WARM assigns to each type of waste. Error is introduced by the imperfect mapping of our waste composition data (an approximation of Boston's actual waste composition) to WARM waste classifications. As a result, we anticipate that the emissions we report for combustion are likely higher than those observed and reported at the Covanta facilities. A fertile area for future research is the application of measured data to improve the accuracy of bottom-up methods such as WARM.

Table 3. Emissions Associated with Each MSW Management Practice

Variability refers to the potential for some emissions processes to vary across time, space and processes. Certainty refers to the relative potential confidence in the reported emissions.

Management Practice	Emissions Type	Activity	Variability & Certainty
Collection & Transport†	Direct Emissions	Fuel Use	Constant & certain.
Combustion	Direct Emissions	Emission of fossil carbon from waste + ignition fuel + N_2O from combustion	Variable by site, time, grid region and waste stream. Generally certain (but bottom-up methodologies may not capture some variability).
	Energy Recovery	Net energetic content of waste stream	
	Material Recovery	Recycling of metals in ash	Variable, dependent on regional market conditions at a given time. Certain (but bottom-up methodologies may not capture variability).
Landfill	Direct Emissions	CH_4 from anaerobic decomposition	Variable, dependent on landfill-specific design and contents. Uncertain in part due to variability, but also due to limited knowledge about decomposition in landfills.
	Energy Recovery	Combustion of landfill gas	
	Carbon Storage	Biogenic carbon stored in landfill	
Recycling	Material Recovery	Recycling of plastics, glass metals	Variable but certain, dependent on regional market conditions at a given time.
	Carbon Storage	Forest carbon storage	Variable and uncertain, dependent on forestry management practices in source locations at a given time.
*Composting**	Direct Emissions	CH_4, N_2O from Biodegradation	Highly variable, highly uncertain due to lack of agreement in the literature about time horizons, and management practices which impact emissions.
	Carbon storage	Soil carbon storage from compost application	
*Anaerobic Digestion**	Direct Emissions	CH_4, N_2O from Biodegradation, and combustion	Variable and uncertain, depending mostly on facility design assumptions.
	Carbon storage	Soil carbon storage from digestate application	Uncertain, dependent on application practices, management, cultivation, time horizon, etc.
	Avoided Emissions	Credit for displacement of fossil methane and synthetic fertilizer	Methane: Constant and certain Fertilizer: Dependent on fertilizer source

*We do not include N_2O emissions associated with land application of compost or digestate. These emissions are mostly due to the application of nitrogen in any form, rather than the bulk material, and would likely be similar with the use of synthetic fertilizer.

†Emissions coefficients for these practices are obtained from WARM, except for Collection & Transport.

5 RESULTS

5.1 THE IMPACTS OF ZERO WASTE BOSTON ON WASTE FLOWS

In 2017, approximately 75 percent of Boston's MSW stream was sent to combustion facilities for final treatment, with the remaining 25 percent entering diversion pathways (Figure 5 top). For instance, food waste accounts for 23 percent (263,000 short tons) of the total waste stream (i.e., total MSW generated), but only 8 percent (22,000 short tons) of that is diverted from the disposal stream. Similar potentials exist for the paper, plastic, metal, and glass fractions of the waste stream that, for the most part, are recyclable or potentially recyclable. The flow between other materials and recycling represents the portion of the recycling stream that is recycling contamination, which amounts to 20 percent.

A zero-waste Boston would divert 90 percent of its waste stream from disposal and only send 10 percent of its waste to disposal (Figure 5 bottom). Less than 4 percent (39,000 short tons) of paper, plastic, metal, glass, food waste, and other organic materials would remain in the disposal stream, which is mainly due to composite materials that cannot easily be recycled or biologically treated. Recycling contamination, in this case, is based off of a "fixed mass" contamination rate, which reflects improved education on recycling practices over time. [6] Note that Zero Waste Boston's strategies would shift disposal from the largest current waste pathway to the smallest by 2050 (Figure 6).

In order to effectively increase Boston's waste diversion, decision-makers must know the material composition of the city's disposal stream. The effectiveness of additional recycling and composting efforts relies on the presence of additional recyclable and compostable materials within the disposal stream. As described earlier, the majority of Boston's food waste is sent to disposal. In fact, food waste alone accounted for 27.4 percent of the disposal stream in the 2017 baseline, representing the largest material fraction (Figure 7).

Zero Waste Boston's strategies would dramatically reduce the fraction of food waste in the disposal stream. With little food waste remaining in the disposal stream, additional efforts to address materials in the disposal stream must be implemented to hit the diversion targets. Under an 80 percent diversion target, the two largest fractions of the remaining disposal stream are potentially recyclable plastics and problem materials.[7] These material types cannot easily be managed through diversion pathways like recycling and biological treatment. Instead, these materials must be prevented from entering the waste stream through source reduction efforts. By identifying this diversion strategy, the City could increase the diversion rate to 90 percent within the next 2 to 3 decades.

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[6] A "fixed mass" contamination rate only applies to the baseline recycling stream tonnage. Any additional recycling stream allocations, as a result of diversion efforts, do not contribute to the magnitude of recycling contamination.

[7] These include composite materials that are mainly composed of recyclable or compostable materials (e.g., paper, plastics, metals, glass, organics, etc.), but also contain other materials that prevent them from being directly recycled or composted.

Figure 5. 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.

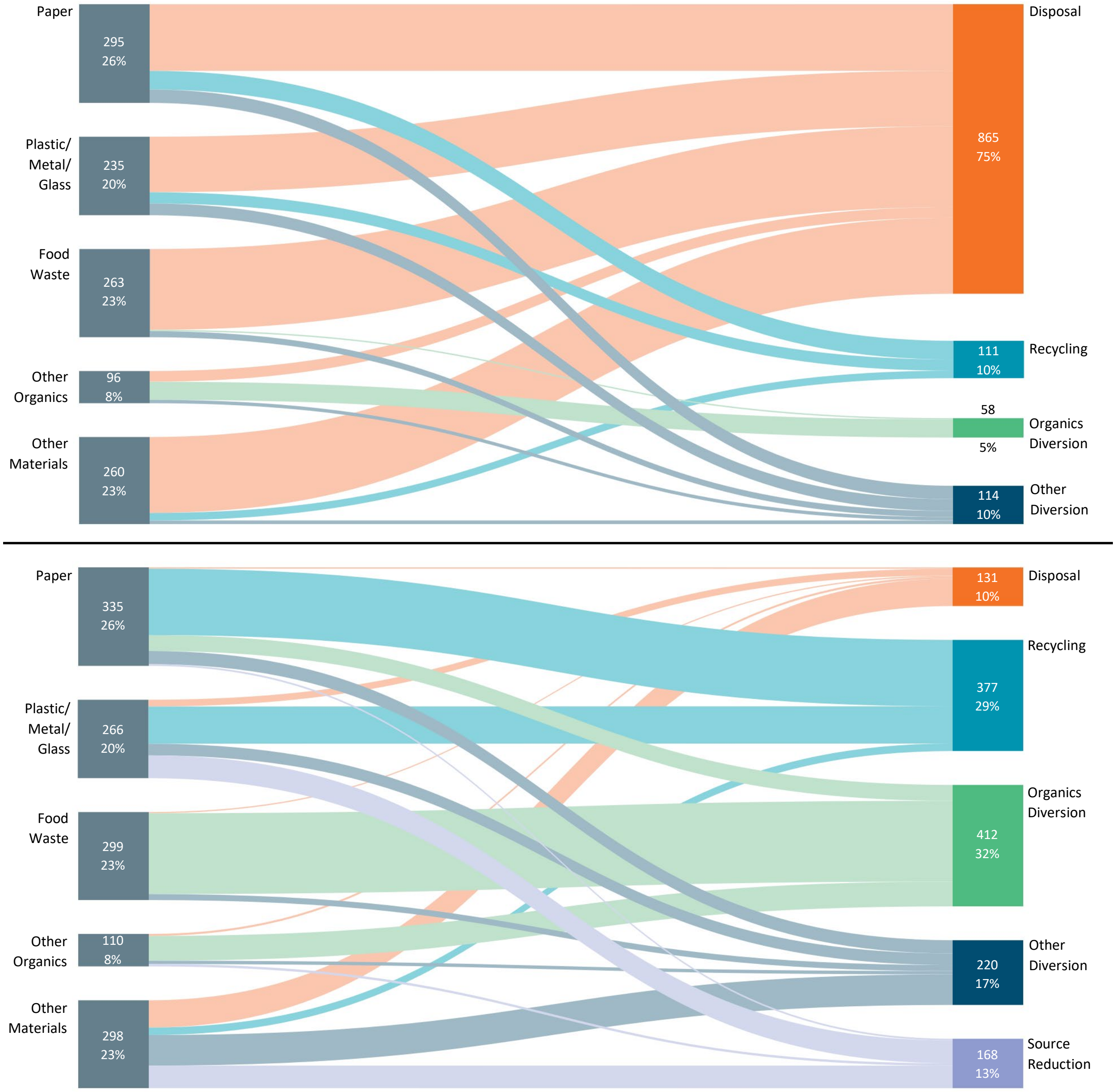


Figure 6. Boston's MSW Generation Trajectory from 2015 to 2050

This trajectory includes the waste diversion impacts associated with *Zero Waste Boston*'s proposed initiatives. *Sources*: Calculations based on data from Boston Department of Public Works, Zero Waste Boston, and Massachusetts Department of Environmental Protection.

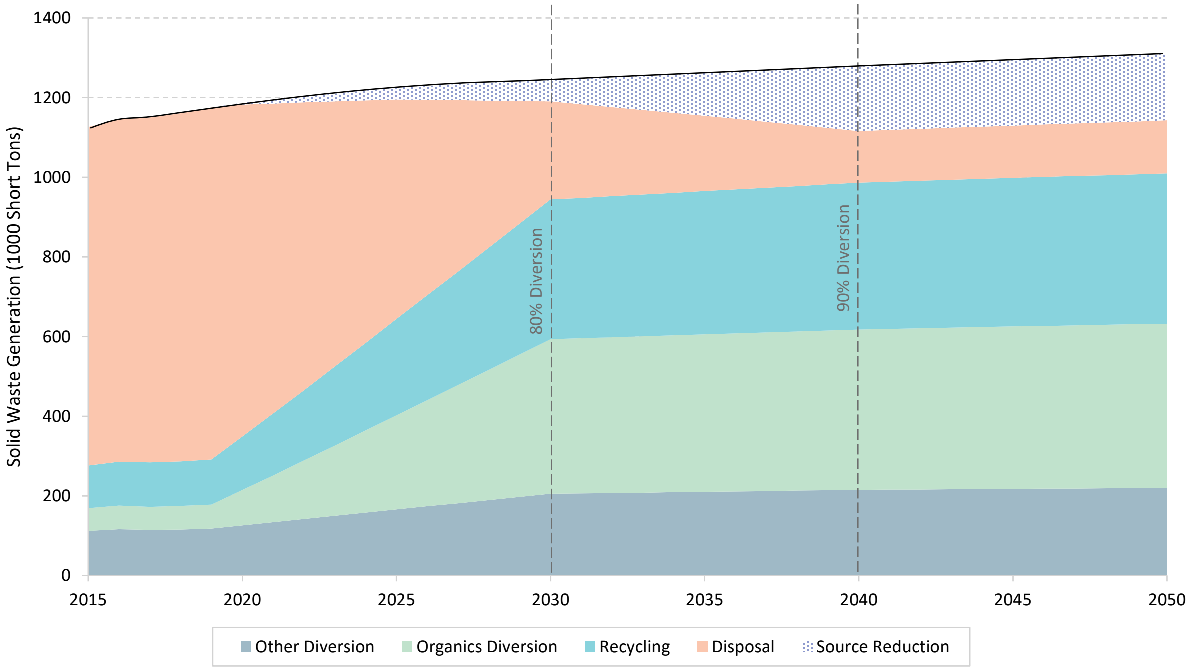
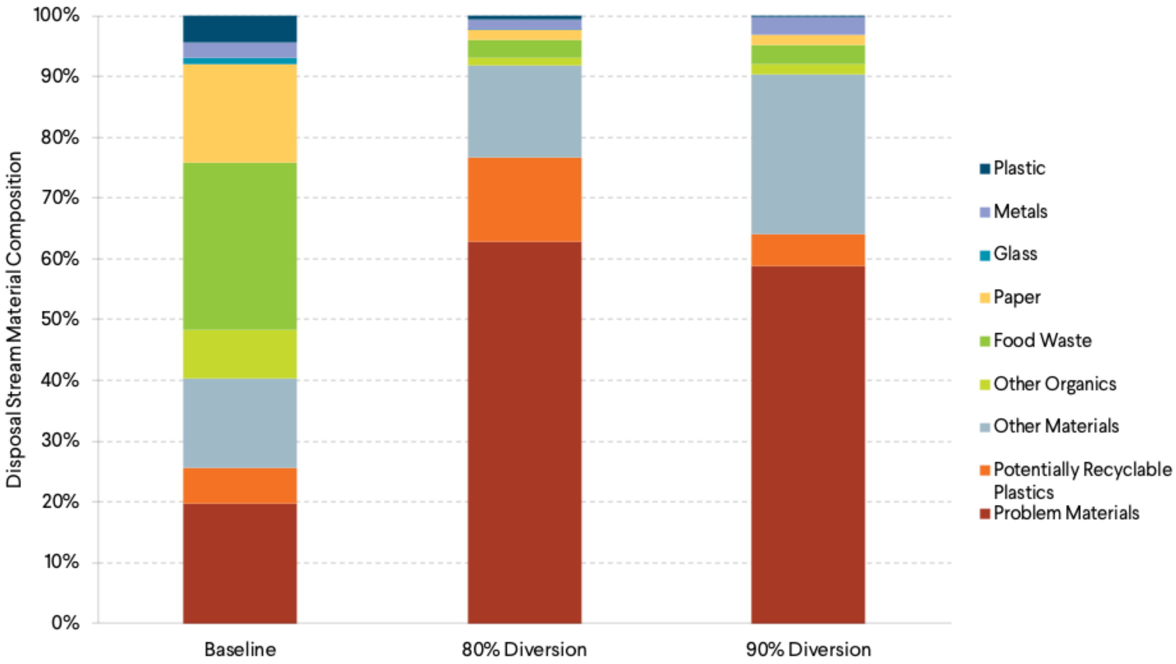


Figure 7. Boston's Disposal Stream Composition by Material Type

The disposal stream composition is given under three different diversion scenarios to demonstrate how the disposal stream is influenced by waste diversion initiatives. *Sources*: Calculations based on data from Boston Department of Public Works, Zero Waste Boston, and Massachusetts Department of Environmental Protection.



5.2 2017 BASELINE EMISSIONS

The processing (i.e., waste combustion, composting, etc.) of the city's solid waste generated an estimated 392.8 kt CO_2e in 2017, equivalent to about 6 percent of the total emissions reported in the City's 2015 emissions inventory (Table 4). The collection and transport of waste materials contributed an additional 4.4 kt CO_2e. Waste combustion accounts for 97.5 percent of Boston's solid waste GHG emissions. The direct emissions attributable to waste collection and organics composting accounts for just 2.5 percent (9.8 kt CO_2e) of total GHG emissions. Boston's commercial sector is estimated to account for about 79 percent (314.1 kt CO_2e) of the city's solid waste emissions, which is comparable to its fraction of total MSW generation.

Table 4. Baseline Direct Transportation and Process Emissions in 2017 (kt CO_2e)

Source: Institute for Sustainable Energy model calculations.

	Residential	Commercial	Citywide Total
Collection & Transport	0.9	3.5	4.4
Combustion	81.6	305.8	387.4
Recycling	-	-	-
Compost	0.6	4.8	5.4
Total GHG Emissions	**83.1**	**314.1**	**397.2**

In the accounting system used in this report, recycling does not contribute to direct process emissions because the waste materials entering the MRF do not go through thermal or biological treatment. It is important to note that MRFs do contribute to direct and indirect emissions through facility operations; however, these emissions are accounted for within the buildings sector and thus excluded from the waste sector's analysis.

We use WARM to present estimates for potential avoided emissions through energy recovery, material recovery, and carbon storage. A majority of the city's current avoided emissions are produced via recycling, with approximately 420.7 kt CO_2e in emissions savings (Table 5).

Table 5. Baseline Avoided Emissions in 2017 (kt CO_2e)

Values may not sum to totals due to rounding. *Source*: Institute for Sustainable Energy model calculations.

	Energy Recovery	Material Recovery	Carbon Storage
Combustion	174.5	54.3	-
Recycling	-	116.4	304.3
Compost	-	-	20.7
Total GHG Savings	**174.5**	**170.7**	**324.9**

5.3 THE IMPACTS OF ZERO WASTE BOSTON ON GHG EMISSIONS

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 any new action by the City. The baseline scenario assumes that per capita and tons per employee per year generation rates remain constant through 2050. Our reliance on downscaled state commercial waste data and compositional estimates leads to significant uncertainty in the magnitude of commercial waste generation and emissions. Nevertheless, the assumption of constant per capita rates of generation is a reasonable departure point for analysis.

5.3.1 Baseline Scenario

The baseline scenario assumes that the city's overall diversion rate remains constant at its current level of about 25 percent, while total generation grows due to increases in population and employment. This results in a 14 percent increase in waste generation and direct process emissions from the 2017 baseline (Table 6). The combustion of MSW continues to be the city's largest source of waste-related GHG emissions.

Table 6. Citywide Baseline Direct Transportation and Process Emissions (kt CO_2e)

Values may not sum to totals due to rounding. *Source*: Institute for Sustainable Energy model calculations.

	2017 Baseline	2050 Baseline	2017-2050 Change
Collection & Transport	4.4	4.7	6.8 %
Combustion	387.4	440.8	13.8 %
Recycling	-	-	-
Compost	5.4	6.1	13.0 %
Total GHG Emissions	**397.2**	**451.7**	**13.7 %**

The combustion of the city's waste will generate increasingly small avoided emission benefits as the regional electricity grid substantially decarbonizes through 2050. Currently, the combustion of biogenic carbon-rich MSW generates less GHGs per MWh than the combustion of fossil fuels. As natural gas electricity generation is replaced with clean energy sources, MSW combustion becomes one of the more 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 (Table 7).

Table 7. Citywide Baseline Avoided Emissions (kt CO_2e)

Values may not sum to totals due to rounding. *Source*: Institute for Sustainable Energy model calculations.

	2017 Baseline	2050 Baseline	2017-2050 Change
Energy Recovery	174.5	46.1	-73.6 %
Material Recovery	170.7	193.3	13.6 %
Carbon Storage	324.9	368.5	13.4 %
Total GHG Savings	**670.2**	**608.0**	**-9.3 %**

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

5.3.2 Zero Waste Pathway

We assess the impacts of zero waste policies with the simplifying assumption 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 initial 80 percent diversion target is met by Zero Waste Boston's 30 strategies, which have associated capture rates that estimate the percentage of materials that each initiative would divert from the disposal stream.[8] Note the city's current diversion rate is about 25 percent, so the Zero Waste Boston actions would increase diversion by 55 percentage

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[8] ZWB proposal posits an ultimate 90 percent diversion rate by 2050. However, at the time of this writing, policy-specific details were available only for an 80 percent rate of diversion.

points relative to today. This includes source reduction, while a reduction in materials entering the waste stream is modeled here as a diversion pathway. The additional 10 percent diversion increase is met by enhanced source reduction and education and outreach efforts.

A 90 percent diversion rate is anticipated to cause annual direct emissions to drop by approximately 80.9 percent relative to the 2050 baseline (Table 8). Although direct emissions from organics composting are expected to increase with increased diversion, overall direct emissions are still expected to decline under the Zero Waste Pathway due to less solid waste being treated at WtE combustion facilities. In fact, direct emissions from waste combustion are expected to decline by 85.6 percent, which is equivalent to a GHG reduction of 377.4 kt CO_2e. It is also important to note that source reduction efforts cause the direct emissions associated with the collection and transport of MSW to slightly decline.

Table 8. Citywide Zero Waste Pathway Direct Transportation and Process Emissions (kt CO_2e)

Values may not sum to totals due to rounding. *Source*: Institute for Sustainable Energy model calculations.

	2050 Baseline	2050 Zero Waste	Percent Change
Collection & Transport	4.7	4.1	-12.8 %
Combustion	440.8	63.4	-85.6 %
Recycling	-	-	-
Compost	6.1	18.8	208.2 %
Total GHG Emissions	**451.7**	**86.4**	**-80.9 %**

In addition to the effect of a cleaner electricity grid on avoided emissions from energy recovery, less MSW entering the disposal stream is expected to cause a decline of an additional 86.6 percent (Table 9). On the other hand, the avoided emissions from material recovery and carbon storage increase dramatically due to more recycling and composting, which cause the total avoided emissions to more than double.

Table 9. Citywide Zero Waste Pathway Avoided Emissions (kt CO_2e)

Values may not sum to totals due to rounding. *Source*: Institute for Sustainable Energy model calculations.

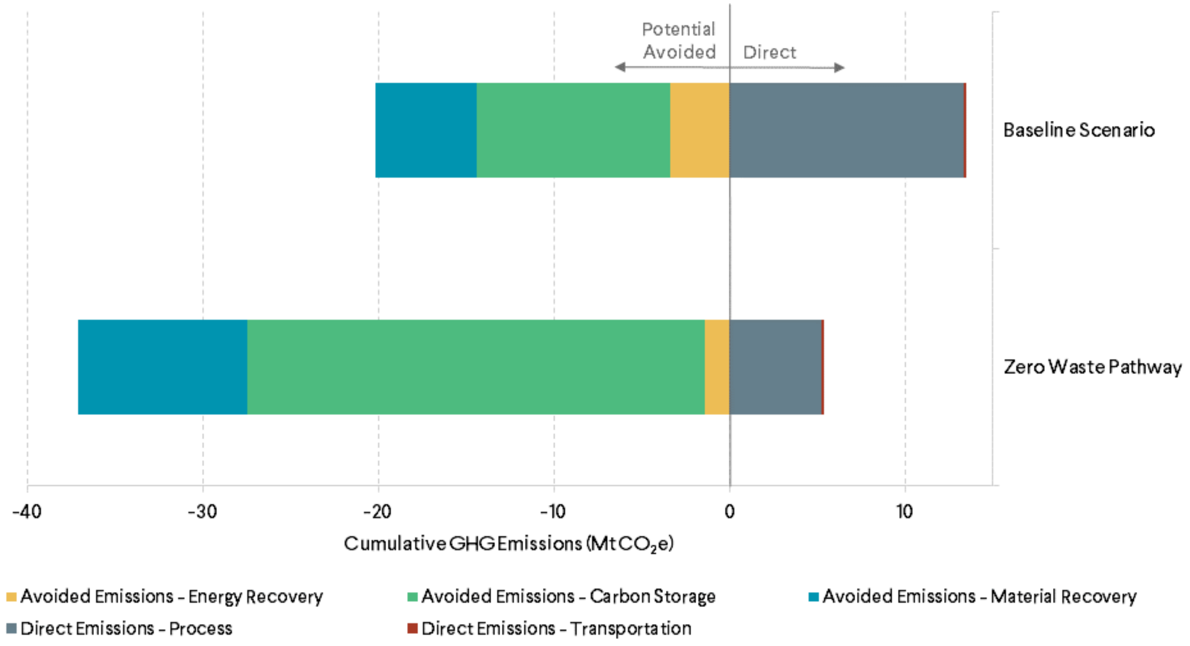
	2050 Baseline	2050 Zero Waste	Percent Change
Energy Recovery	46.1	6.1	-86.6 %
Material Recovery	193.3	346.1	79.0 %
Carbon Storage	368.5	971.0	163.5 %
Total GHG Savings	**608.0**	**1323.3**	**117.6 %**

Focusing only on the direct emissions associated with composting can obscure other potential benefits. Under a zero-waste future, avoided emissions from WtE electricity generation decline with diversion and source reduction due to the combustion less energy-rich material (Figure 8). The diversion of material to composting and recycling can avoid even a greater amount of emissions through carbon storage and material recovery respectively.

Figure 8 shows the impact of a zero-waste pathway on the cumulative emissions from 2020 to 2050. Under this alternative pathway, cumulative direct emissions would decline by 8 Mt CO_2e (60 percent decrease), while 17 Mt CO_2e (84 percent increase) additional avoided emissions would be realized. By disaggregating these cumulative emissions numbers by emissions classification, we can compare the overall effect of the Zero Waste Pathway on Boston's waste-related GHG emissions (Figure 8).

Figure 8. Cumulative Solid Waste GHG Emissions from 2020 to 2050

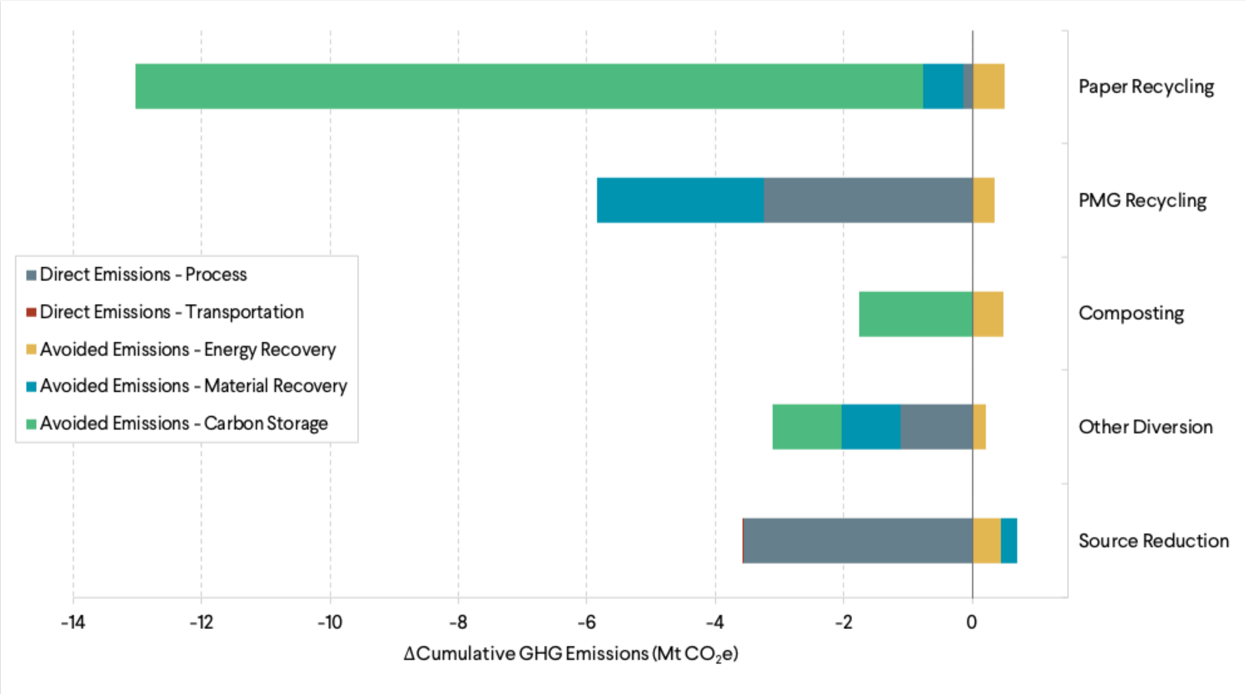
We present our results here as cumulative emissions to capture the time dynamics associated with the evolving carbon intensity of the avoided emissions from energy recovery. The benefits of energy recovery will decline as the New England grid decarbonizes. We anticipate that the emissions intensity of 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.



We deconstruct the Zero Waste Pathway to assess the impacts of each material diversion pathway by emissions classification (Figure 9). Since avoided emissions due to energy recovery are linked to MSW combustion, every diversion pathway presented below results in a loss of energy recovery benefits. In general, most of the diversion pathways result in an emissions reduction, except for composting, which is an organics diversion pathway that aims to capture a majority of Boston's organic materials (e.g., food waste, yard waste.) from the disposal stream. The composting of organics is slightly more GHG intensive than combustion since fugitive CH_4 and N_2O emissions are released directly into the atmosphere.

Figure 9. Change in Cumulative Solid Waste Emissions from 2020 to 2050 Relative to the Baseline

Negative values represent a "benefit" in the form of emissions reduction or additional avoided emissions. Positive values represent a "cost" in the form of additional direct emissions or a decrease in avoided emissions. There is substantial uncertainty associated with avoided emissions. In the case of material recovery, actual emissions are likely to be lower than calculated due to anticipated reductions in the carbon intensity of material supply chains. Likewise, avoided emissions from carbon storage likely represents a best case scenario due to WARM's approach for estimating carbon storage that is significantly higher than other studies [30]. *Source*: Institute for Sustainable Energy model calculations.



5.3.3 Final Waste Treatment Options

The goal of *zero waste* implies a future with no more burning or burying of waste material. Technical or economic limitations may make 100 percent diversion impractical. The *zero waste* framework recognizes these potential constraints and sets a 90 percent diversion target that while aspirational and impactful, would leave Boston with 133,000 short tons of waste that still needs to be sent to disposal. The diversion of organics and recoverable materials will leave a waste stream mostly comprised of treated and composite materials that are not recyclable or compostable under current technology. As the composition of the waste stream changes the relative GHG intensity of the final treatment alternatives also changes.

Under Boston's current waste stream, combustion is less GHG intensive compared to state-of-the-art methane capture landfills (Figure 10).[9] Once the Zero Waste Boston strategies are implemented, less organics and plastics will be in the disposal waste stream. 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 will likely make

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[9] Boston currently sends all its waste to municipal waste combustors, and it probably will continue to do so for the foreseeable future. Landfill disposal capacity in Massachusetts has declined markedly in the past decades as landfills close and are not replaced [32], and is expected to decline another 38 percent from 2017 to 2022 [33]. Nevertheless, it is instructive to compare GHG emissions from combustion and landfill because landfills given that they remain the two dominant forms of waste disposal.

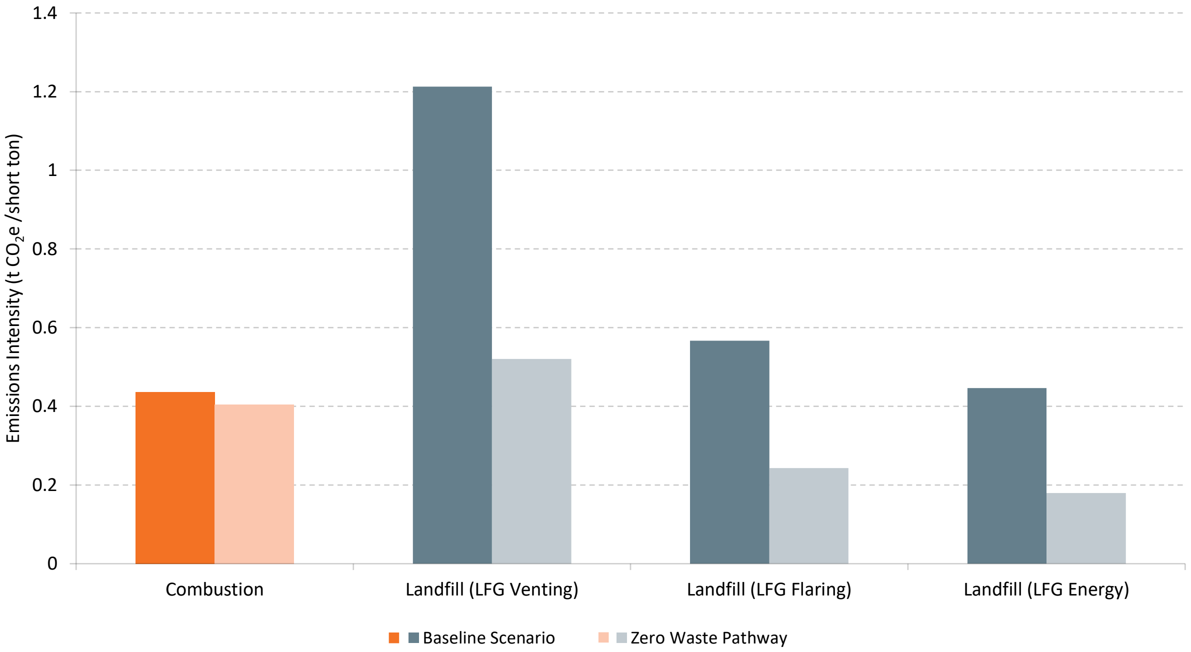
combustion a less economically favorable treatment option due to a reduction in the energetic value of the waste stream, causing less electricity to be generated per unit of waste input.

The decline in the emissions intensity for combustion is smaller in the Zero Waste Pathway because the waste stream is still largely comprised of carbon intensive materials (i.e., plastics).

Our analysis suggests that landfilling is likely to be the most suitable option from a GHG perspective for final disposition of non-divertible waste. A more detailed analysis of landfilling options and tradeoffs that consider energy recovery, location, transport distance and other factors will be necessary to maximize reduction potentials. Ultimately to process residual waste some form of offsetting would be required to achieve neutrality.

Figure 10. Emissions Intensity of Alternative Disposal Practices under Different Diversion Conditions

Source: Institute for Sustainable Energy model calculations.

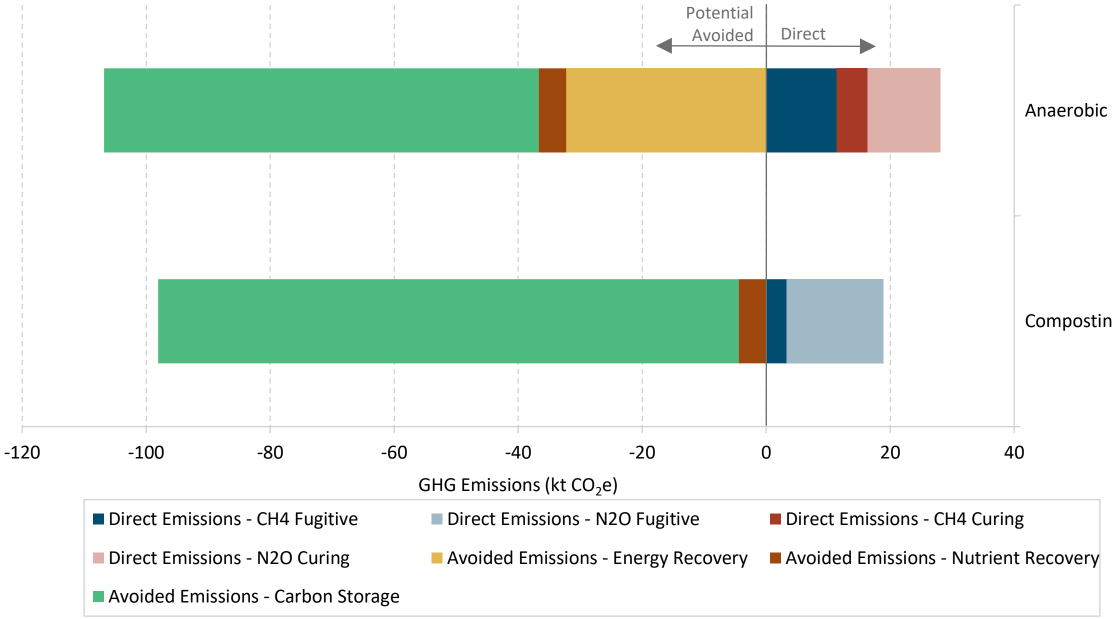


The City also needs to develop a management strategy for the organic waste stream that maximizes diversion to reach its zero waste goal. In 2050 this could amount to 444,000 short tons. The bulk of this waste could either be composted to generate a soil amendment, or anaerobically digested to generate methane and a smaller amount of soil amendment. Emerging technologies could provide other treatment options for the certain parts of the organic waste stream (e.g., fats, oils) or the entire waste stream. These include gasification or thermal treatment processes that can render synthetic fuels including liquid hydrocarbons which could be utilized in heavy equipment, aviation and backup services.

The two well established organic treatment options have similar GHG emissions profiles, mostly due to biological decomposition and methane leakage (Figure 11). Anaerobic digestion has a higher capital and operating cost than composting. Notably, the emissions associated with anaerobic digestion are largely from the curing and processing of the digestate prior to its application as a soil amendment. Biogenic methane may be an attractive energy source to replace fossil fuels, and it could help decarbonize sectors that are difficult to electrify. Approximately 574 TJ (5.4 million therms) of natural gas could be obtained from the organic fraction of Boston's 2050 waste stream if it were to be anaerobically digested. This currently represents approximately 2 percent of Boston's natural gas use, but could meet a substantial fraction of the residual natural gas following a deep electrification of buildings strategy, approximately equivalent to a district energy system.

Figure 11. Boston's Organic Waste Stream in 2050 under Different Organics Treatment Practices

Source: Institute for Sustainable Energy model calculations.



5.4 PATHWAY TO NEUTRALITY

The waste diversion strategies proposed by Zero Waste Boston would dramatically reduce the GHG emissions associated with solid waste management. From a GHG reduction perspective, there is no single policy that dominates. Instead, a broad and comprehensive waste diversion is required to achieve the GHG reductions quantified here. More detailed evaluations of the tradeoffs of different strategies are discussed in the Zero Waste Boston report. Alternatively, potential GHG emission reductions can be assessed based on different diversion pathways (Figure 12). By doing this, the City can identify which diversion pathways can provide the largest potential GHG reduction (Table 10). Specific focus should be placed on commercial waste, which makes up the majority of the city's generation and is poorly characterized in terms of quantity, composition, and disposition.

Complete elimination of GHGs from waste streams is challenging since all treatment options generate some direct emissions that are difficult to eliminate. Achieving neutrality will require the use of offsets in these categories. Waste treatment processes, particularly those that can provide carbon sequestration benefits, could be considered for offsets.

Waste planning should include ongoing monitoring of existing and emerging waste treatment systems. In particular, comprehensive, locally-relevant analyses of organic waste treatment options such as composting and anaerobic digestion will inform the tradeoffs associated with these options.

Figure 12. 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.

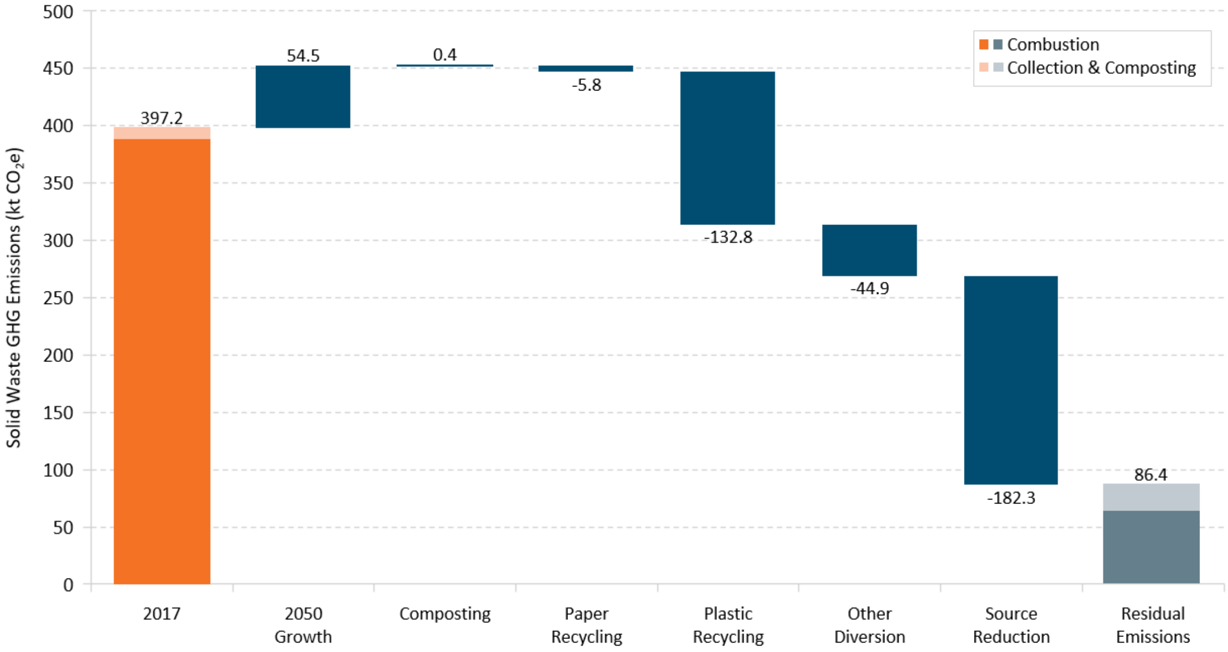


Table 10. The Impact of Different Diversion Pathways on Direct GHG Emissions in 2050

Negative values represent potential GHG emission reductions. *Source*: Institute for Sustainable Energy model calculations.

Diversion Pathways	GHG Impact (kt CO_2e)
Composting	0.4
Paper Recycling	-5.8
Plastic Recycling	-132.8
Other Diversion	-44.9
Source Reduction	-182.3
Total	**-365.3**

6 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. These services are provided by two quasi-public entities. The Boston Water and Sewer Commission (BWSC) oversees in-city water distribution and sewage collection, while 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 (DIWWTP), which is physically located in Boston.

Deer Island provides sewage treatment for 2.13 million people in eastern Massachusetts, including the residents of Boston. DIWWTP is the second largest wastewater treatment (WWT) plant in the country. The facility became fully operational in 2000 as part of a concerted effort to improve water quality in Boston Harbor that was continually at risk due to inadequacy of Boston's older treatment plants.

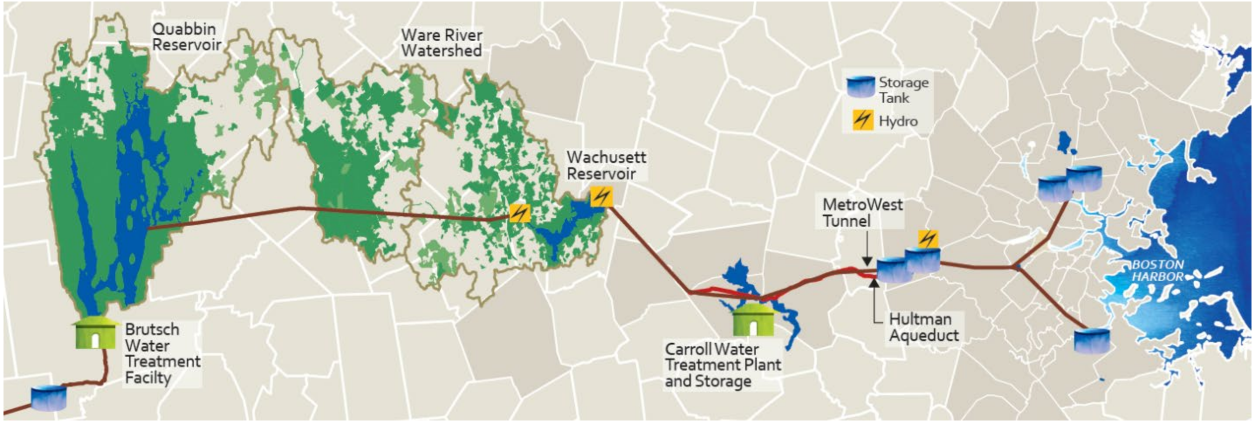
GHG emissions from water delivery and treatment are a very small fraction of the city's total emissions, but the systems are important to include in mitigation planning for several reasons. First, the BWSC and the MWRA are among the largest energy consuming entities in the city. Second, the BWSC and the MWRA have been at the leading edge of clean water delivery and the provision of sustainable wastewater treatment services. Such services are critical to public health and protecting freshwater and marine resources. Finally, technological limitations and the nature of wastewater make it very difficult to fully mitigate emissions in these sectors and thus necessitate an offset strategy.

6.1 WATER DELIVERY

Moving water uphill takes energy, moving water down can generate energy. The MWRA transports water from the Quabbin and Wachusett Reservoirs via a series of aqueducts and tunnels to lower elevations in Boston (Figure 13). On the journey, potential energy from the water is captured though a hydroelectric dams. It is treated at the John J. Carroll Water Treatment Plan in Marlborough before being sent to Boston. Most water delivery is facilitated by gravity and the hydraulic head maintained by several storage tanks. Some pumping is required for delivery to higher elevations areas by MWRA and to storage tanks in high buildings by building owners. Other energy is utilized by operations.

Figure 13. The MWRA Water Distribution System

Source: MWRA



6.2 WASTEWATER AND WASTEWATER TREATMENT

Wastewater treatment can mitigate these emissions by controlling the biological degradation process, but treatment is an energy intensive process. The pumping and transport of sewage and sewage treatment processes requires substantial electricity inputs and in some cases heat treatment from the combustion of fuels such as methane. Well-designed wastewater treatment systems can reduce some of these energy demands. For example, treated sewage sludge contains significant amounts of embodied chemical energy. The incorporation of anaerobic digestion can capture methane digestate gas (digas) and use it to generate electricity and process heat. The resultant CO_2 emissions from this digas are biogenic, making this a renewable form of energy production. Anaerobic digestion is the visibly distinguishable technology (the digester "eggs") of Deer Island, and is the largest source of renewable energy at Deer Island, and with proposed upgrades, a potential source of even more renewable energy.

6.3 SEWAGE COLLECTION IN BOSTON

The BWSC maintains and operates the city's sewer system, which is comprised of both *separated* and *combined* collection systems. The separated system is comprised of sanitary sewers and storm drains. The sanitary sewers are designed to transport sanitary waste material, while the storm drains transport stormwater flows. The older combined systems mix these services and during storm events can cause undesirable discharge of sanitary sewage into the Charles River and other water bodies. The BWSC is actively converting combined systems into separated systems in order to mitigate the discharge of sewage. Sewage is collected in a large network of pipes, screened for large debris and ultimately conveyed to the MWRA's collection system and Deer Island through a series of pumps.

6.4 TREATMENT

At Deer Island the sewage is pretreated to remove large debris and sand that is disposed of in a landfill. Primary treatment of the sewage settles out the majority of the biosolids. Secondary treatment involves the addition of oxygen to promote biological breakdown of dissolved solids and toxic components of the sewage. Following secondary treatment, the water is disinfected with bleach and then dechlorinated. At this point the water is considered effluent and is sent through a 9.5 mile outfall tunnel, 250 feet below the ocean floor, at the end of which it is diffused at water depths of 120 feet into Massachusetts Bay over the last 1.25 miles of the tunnel.

The pumping, mixing and aeration of the wastewater at various stages of wastewater treatment require significant amounts of electricity, and thus generates indirect emissions. The biological breakdown of wastes generates a substantial amount of biogenic CO_2, and significant amounts of N_2O and CH_4. Technological options for reducing these emissions are limited, especially in the case of N_2O. While, biological degradation of wastewater biosolids in the absence of oxygen can promote increased CH_4 generation, this process can be harnessed to generate renewable energy. At DIWWTP, biosolids from sludge in the primary and secondary treatment are diverted to on-site anaerobic digesters in which 55 percent of the solid portion of the sludge is broken down into methane by biological anaerobic activity. This process generates methane that is captured and used onsite to cogenerate 3.4 MW of electricity and 125 mmBTU hr^{-1} heat for building thermal loads and treatment processes. This is an essential source of energy for the facility with backup generation being supplied by fuel oil. The remaining sludge is piped to Quincy where it is dewatered, dried, pelletized and processed into fertilizer. The drying process consumes a substantial amount of fossil natural gas, however this final processing activity is out of Boston's boundary and thus out of its scope of emissions.

6.5 EMISSIONS & EMISSIONS MITIGATION POTENTIAL

The scope of our analysis focuses only on Boston-based water delivery and wastewater treatment activities. The MWRA regularly conducts and publishes a comprehensive greenhouse gas inventory [34] of their Massachusetts-wide activities. Our analysis here encompasses all MWRA activity at Deer Island Wastewater Treatment Plant except for transportation, and all MWRA and BWSC non-building energy use (e.g. pumping) in the rest of Boston. Fleet transportation and buildings are generalized and evaluated in the transportation and building chapters respectively.

Emissions in the water and wastewater treatment systems are broken down into 3 distinct categories:

i. Emissions from the consumption of electricity
ii. Emissions from onsite combustion of digester biogas and fossil fuels
iii. Emissions from wastewater

We focus on CO_2, CH_4 and N_2O emissions. MWRA's detailed analysis of fluorinated-gases used in chillers and air conditioners at Deer Island reveals that these are relatively minor emissions [34], but should be evaluated in more facility-specific future mitigations studies. Total water treatment is influenced by weather and other factors in addition to population. We make the simplifying assumption that future energy demand is fixed using an average of 2014-2016 values. We use a population forecast to estimate total protein loading for N_2O process and effluent emissions. The mitigation potential of water and wastewater systems is shown in Figure 13 and time series of the baseline scenario and a 100 percent Clean Energy scenario are shown in Figure 14.

6.5.1 Electricity Consumption

Total emissions from water and wastewater treatment in 2016 were about 75 kt CO_2e, an extremely small fraction of the city's total emissions. The largest source of emissions is electricity consumption for pumping and treatment operations. Field (non-DIWWTP) pumping of water and sewage in Boston comprises a small fraction, while Deer Island operations represents the bulk of energy and emissions for the MWRA's Boston operations. While DIWWTP consumes approximately two percent of the city's total electricity consumption, it generates a significant portion of this electricity onsite though wind, solar, hydro power and combustion of digester gas. The Renewable Energy Certificates (RECs) associated with these are sold to generate revenue, lowering costs for MWRA ratepayers.

There are few options for reducing electricity consumption at DIWWTP. Much of the electricity consumed by Boston sewer and DIWWTP is used for pumping, which is unlikely to see large efficiency gains in the foreseeable future. There is potential to generate more renewable electricity onsite by improving the efficiency of the combined heat and power system. This improvement is currently in the early stages of planning, but could potentially yield approximately 90-120 GWh of renewable electricity per year beginning sometime in the 2020's. Although a capital-intensive project, such an improvement will reduce the need to purchase electricity from the grid, deliver cost reductions for MRWA ratepayers over the long term, and add additional renewable electricity generation capacity in Boston equal to 2 percent of the city's total electricity demand.

Figure 14. 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. Unavoidable and uncertain emissions include N_2O and CH_4 emissions from biological breakdown that are difficult to mitigate. *Source*: Institute for Sustainable Energy model calculations.

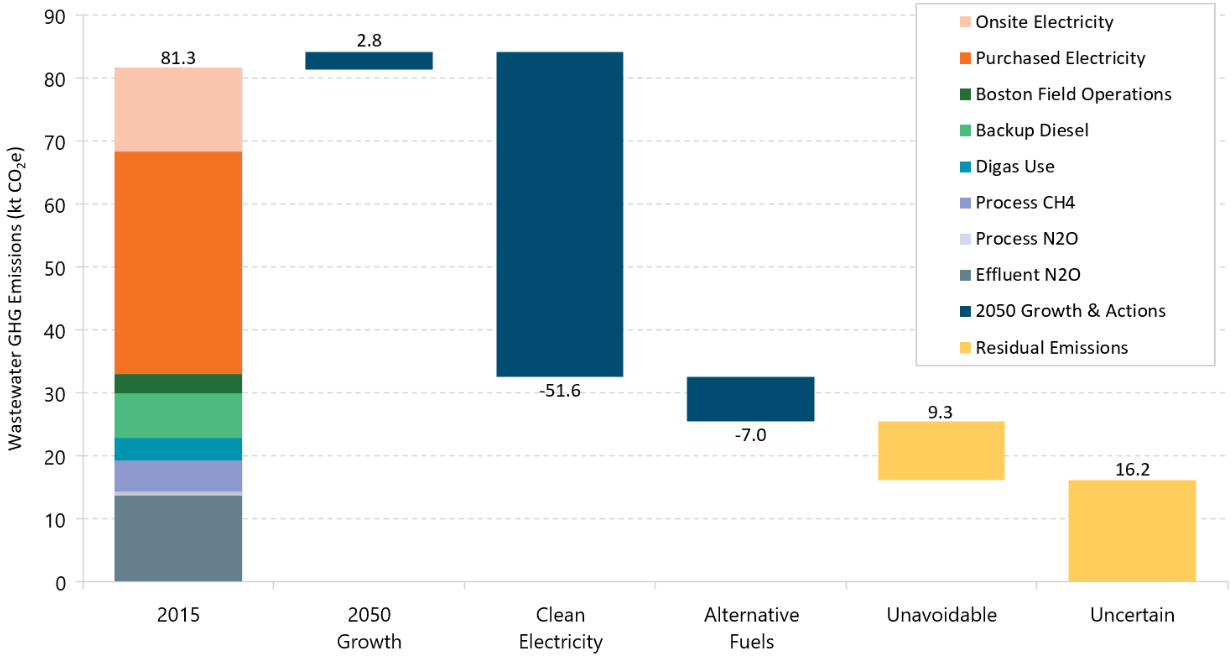
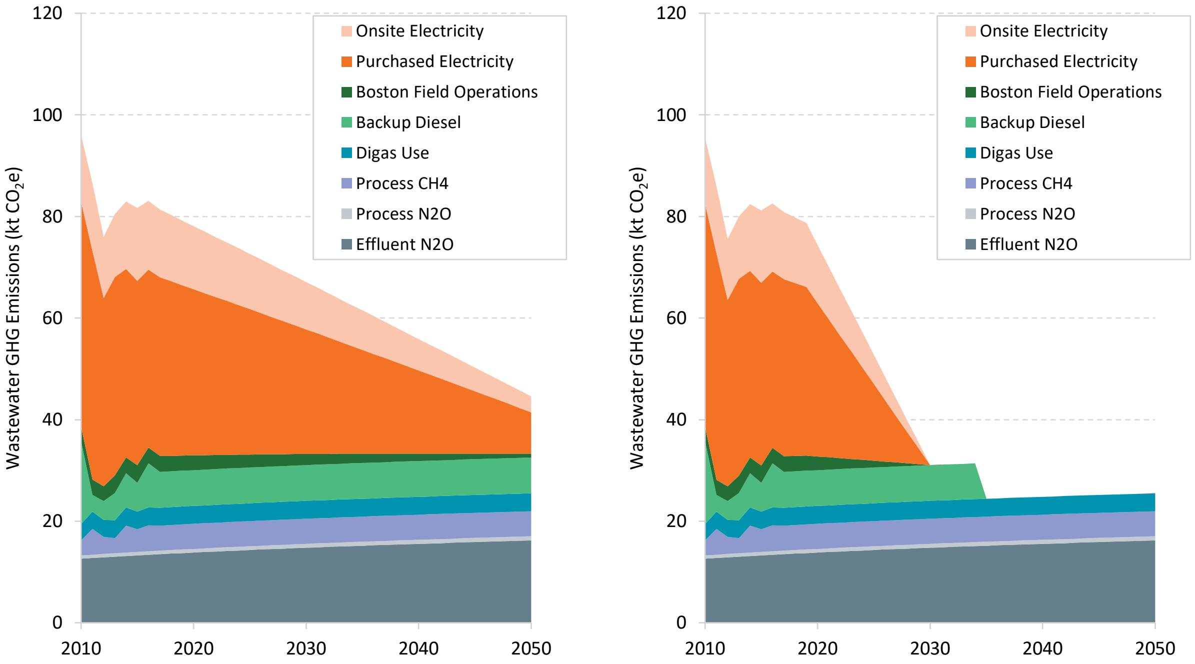


Figure 15. Boston's GHG Emissions Trajectory for Water and Wastewater Services

Baseline emissions trajectory (left) and GHG-reduction strategy (right) showing facility emissions mitigation potential under an electricity scenario that reflects the 100 percent clean electricity by 2030 and a possible renewable backup fuel target of 2030. *Source*: Institute for Sustainable Energy model calculations.



For the MWRA and Boston to claim emissions reductions from renewable generation on Deer Island, the MWRA would have to retire its RECs generated by these renewable sources instead of selling them. This would reduce revenue, but it would be a more direct and likely less costly mechanism than procuring offsite renewables as part of a city-wide strategy. In Figure 15 we assume these that RECs are retired on the same schedule as the 100 percent clean energy by 2030 strategy. Recognizing this renewable energy would result in approximately 51.6 kt CO_2e of emissions reductions. While potential revenue losses from the retirement of RECs would fall on the ratepayer, MWRA ratepayers have access to one of the most advanced, efficient and renewable wastewater treatment systems in the world.

6.5.2 Fossil Fuel Combustion

The thermal energy needs of Deer Island are met largely by the combustion of digester gas that releases biologically stored carbon. Backup and peaking service is provided by diesel fuel for boilers and an onsite combustion turbine generator that produces electricity in addition to heat. The ability to generate on-site electricity is necessary for facility operations and permitting. A small amount of propane is also used. There is no natural gas service provided to the island. The combustion of these fuels emits 7 kt CO_2e emissions annually. In principle, various alternative fuels could be used for on-site combustion to generate backup electricity and heat. These include sustainably sourced biodiesel, biomass, compressed biogenic natural gas, or hydrogen. Biodiesel may be the most technically feasible, but it would require some facility upgrades and may result in air quality tradeoffs that should be evaluated.

6.5.3 Digas Consumption

The use and incomplete combustion of the biogenic digester gas results in a small amount of CH_4 and N_2O generation. These residual emissions are characteristic of such systems that generate and utilize biogenic digester gas, and are difficult to completely mitigate. Some incremental reductions may be possible, for example Deer Island was able to eliminate vented methane emissions over the last decade. For this analysis we treat these as unavoidable emissions which would require the use of offsets.

6.5.4 Process and Biological Emissions

Small quantities of CH_4 and N_2O are released during the processing of waste. Methane is emitted during odor control, and N_2O is released from the sewage and during the treatment processes; it also can be emitted from the nitrogen load of the effluent stream. Following the GPC's approach, we estimate that CH_4 and N_2O emissions amount to 15 kt per year. This estimate is based on a model designed for surface water discharge of waste water effluent. The effluent from Deer Island is diffused 9 miles into Massachusetts Bay at a depth of 100 ft, where the potential for emissions is low. The Australian Government [35] assigns zero emissions to such ocean discharge. To address this discrepancy, we note these emissions are currently uncertain and should be further evaluated in terms of their inclusion in Boston's inventory. Non-effluent CH_4 and N_2O process emissions are considered unavoidable.

6.6 PATHWAY TO NEUTRALITY

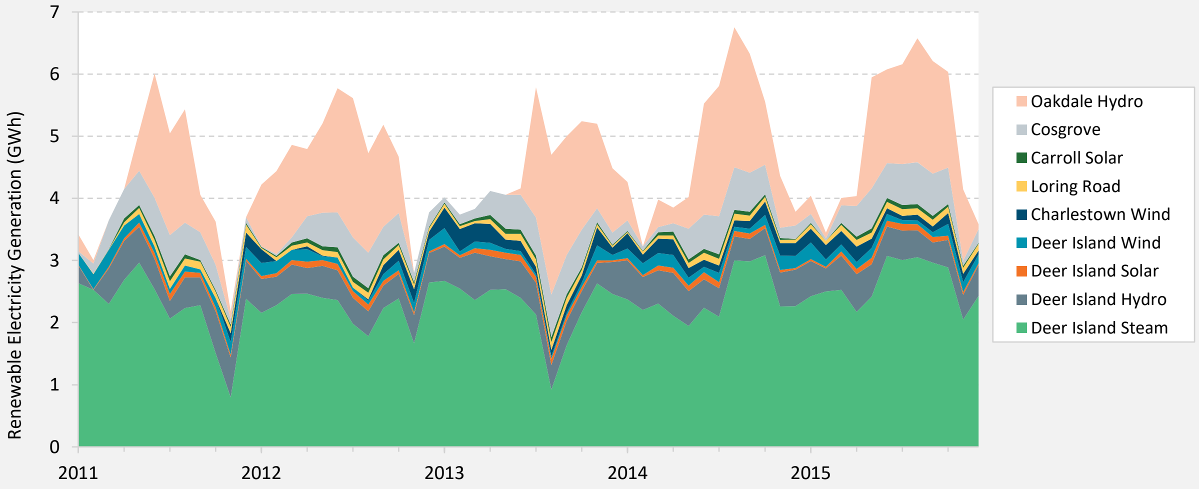
The DIWWTP is already a highly efficient wastewater treatment system with relatively lower total emissions compared to other systems and options for treating waste. Increased generation of on-site electricity and ownership of its renewable attributes, will result in a 61 percent decrease in emissions at relatively low costs. Sourcing alternative fuels will be necessary to reduce 7 kt CO_2e of GHG emissions from critical combustion services, but the alternatives will need to be further investigated. Achieving complete neutrality will likely require offsets for various unavoidable emissions (9.3 kt CO_2e) and some emissions of uncertain magnitude (16.2 kt CO_2e).

CASE STUDY: INTEGRATING CLEAN ENERGY AT DEER ISLAND AND THROUGHOUT THE MWRA

Ever wonder what that random wind turbine was doing sitting at the tip of Charlestown on the Mystic River? That 1.5 megawatt turbine is generating 2 GWh of renewable electricity per year and saving the MWRA's rate-payers $350,000 per year. The turbine sits at the DeLauri Sewer Pump Station, which delivers waste water from Somerville, Cambridge and Charlestown to a headworks facility in Chelsea before being pumped to Deer Island for treatment. The Charlestown turbine is just part of the MWRA's clean energy portfolio. The MWRA and its preceding entities have been a first mover in generating zero carbon electricity, both out of opportunity and necessity.

Figure 16. Clean Electricity Generation at MWRA Facilities

Oakdale, Cosgrove, Carroll and Loring sites are outside of Boston city limits. *Source*: Data from MWRA.



The Quabbin Reservoir lies at an elevation of 530 feet, roughly rising as far above Boston as the pinnacle of the iconic Custom House Tower. Water from the Quabbin reservoir travels through tunnel to the Wachusett Reservoir, and upon entry, generates approximately 10-12 GWh of hydroelectricity annually in West Boylston MA. An additional 4-5 GWh is generated each year as the water leaves the Wachusett and enters the Cosgrove Tunnel. Water continues through this tunnel where it reaches the Carroll Water Treatment Plant. Here the MWRA has installed a 496 kW Solar Array on unused land that generates an annual electricity savings of almost $90,000. The water supply continues towards Boston where it reaches a couple of storage facilities in Weston. Another turbine at Loring Road is able to generate approximately 1.2 GWh per year in hydroelectricity. After point, there is little opportunity to capture hydroelectricity in order to maintain enough head to ensure water delivery.

At the Deer Island Wastewater Treatment Plant the MWRA has attempted to generate every amount of renewable energy that it can while striving to go further. Deer Island is home to 736 kW of solar capacity on rooftops and an underused parking lot. These panels generate approximately 850 MWh annually. Two 600 kW 190 ft wind turbines grace the island generating about 1.6 GWh annually. Not to leave any hydraulic head unused, Deer Island generates 5.75 GWh a year in hydroelectricity from the flow of effluent into the bay. The pièce de résistance of the MWRA clean energy portfolio is the captured anaerobic digester gas and the 30 GWh of electricity generated from its combustion and avoid the purchase of heating oil for process and building heat. In total approximately 60 GWh (40 GWh in Boston) of electricity is produced annually.

7 SHAPING THE FUTURE OF BOSTON'S ZERO WASTE SYSTEM

The emergence of modern municipal waste management and wastewater treatment systems 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. This approach is unsustainable. It was unsustainable in the 1960's and 1970's, 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 impact 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 for the City and its residents and businesses 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.

It may be impossible to become 100 percent zero waste and eliminate 100 percent of emissions from the waste sector due, respectively, to problem materials and hard-to-mitigate emissions. Here, offsets will likely be needed to complement zero waste efforts to achieve carbon neutrality.

Pursuing the goal of net zero emissions though zero waste will require participation from all of Boston's constituents. The City can lead by example by implementing zero waste strategies for its 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. Most notably zero waste initiatives are relatively cheap from a carbon mitigation standpoint and are not as reliant on emerging technologies as the other sectors. Emissions mitigation through waste reduction can thus be an early point of action.

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ABBREVIATIONS

BWSC	Boston Water and Sewer Commission
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CORe	Centralized Organics Recycling
DIWWTP	Deer Island Wastewater Treatment Plant
EPA	Unites States Environmental Protection Agency
FLIGHT	EPA’s Facility Level Information on GreenHouse Gases Tool
GHG	Greenhouse Gas
GHGRP	EPA’s Greenhouse Gas Reporting Program
GPC	Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories
GWP	Global Warming Potential
LFG	Landfill Gas
MassDEP	Massachusetts Department of Environmental Protection
MOVES	Motor Vehicle Emission Simulator
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
MWRA	Massachusetts Water Resources Authority
N_2O	Nitrous Oxide
PMG	Plastic, Metal, and Glass
REC	Renewable Energy Certificate
t CO_2e	Tonne (Metric ton) of CO_2e
TPY	Short Tons Per Year
VMT	Vehicle Miles Traveled
WARM	EPA’s Waste Reduction Model
Wh	Watt-hour
WtE	Waste-to-Energy
WWT	Wastewater Treatment

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