Greenhouse Gas Emissions Inventory Update

2006-2022

Massachusetts Water Resources Authority

January 2024

This report updates the Massachusetts Water Resource Authority (MWRA) report, *Greenhouse Gas Emissions Inventory Update 2006-2019*, with the latest available data in order to present and examine MWRA greenhouse gas (GHG) emissions from 2006-2022.

Disclaimer: All calculations presented in this report are based on data collected and estimated by MWRA as well as emissions factors and global warming potentials published by the Intergovernmental Panel on Climate Change (IPCC), Environmental Protection Agency (EPA), Massachusetts Department of Environmental Protection (MassDEP), and the Australian Government Department of the Environment. Every effort has been made to ensure the accuracy of the data. This report is intended to provide a reasonable estimation of greenhouse gas emissions and provide information from which MWRA can base policy decisions.

MWRA Key Contributors:

Denise Breiteneicher – Program Manager, Energy & Environmental Management
Stephen Estes-Smargiassi – Director, Planning & Sustainability
Hillary Monahan – Senior Planner
Christian Murphy – Program Manager, Energy Management, Deer Island
Michael O'Keefe – Senior Program Manager, Planning
Kristen Patneaude – Manager, Energy
Malcolm Ragan – Environmental Planner

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Executive Summary

This report provides an updated accounting of MWRA's greenhouse gas (GHG) emissions from 2006 to 2022. The objectives of this inventory are to:

1. Present an analysis of GHG emissions to identify major sources and reveal trends
2. Highlight successes to date regarding GHG emission reductions
3. Identify emissions reduction opportunities

The Commonwealth of Massachusetts has committed to net-zero GHG emissions by 2050, with intermediate targets of 33% and 50% reductions by 2025 and 2030, respectively. The MWRA has achieved the 2025 target, reducing emissions by 41% compared to a baseline of 2006.

Wastewater collection and treatment continues to be much more energy and emissions intensive than drinking water treatment and transport, accounting for nearly 90% of MWRA's total emissions over the past 17 years. In terms of emissions sources, electricity purchases are the largest, accounting for roughly 44% of the total. Other major sources of emissions include treatment processes and fugitive gases, natural gas, and diesel and fuel oil combustion used to run standby generators and heat facilities.

Although electricity accounts for a significant portion of MWRA's emissions, it is also where there has been the greatest reductions, accounting for 84% of total progress. Electricity consumption has been reduced at many facilities through energy efficiency measures such as high efficiency lighting and controls, more efficient heating, cooling, and ventilation (HVAC) systems, building management systems, variable frequency drives (VFDs), and process optimizations. Greenhouse gas emissions from electricity are also partially offset by MWRA's use of on-site renewable energy, which includes using anaerobic digester gas to power processes at the Deer Island Treatment Plant, as well as a portfolio of hydroelectric, wind, and solar photovoltaic generation. Additional solar facilities are being considered at Deer Island, several covered water storage sites, and new construction, major facility upgrades, or roof renovations. Emissions from electricity have fallen faster than total demand because of the continued buildout of non-emitting generation sources supplying the electric grid, making the regional electricity greener over the years. This trend is expected to continue at an even faster pace as major wind and hydroelectric projects are utilized by the Commonwealth.

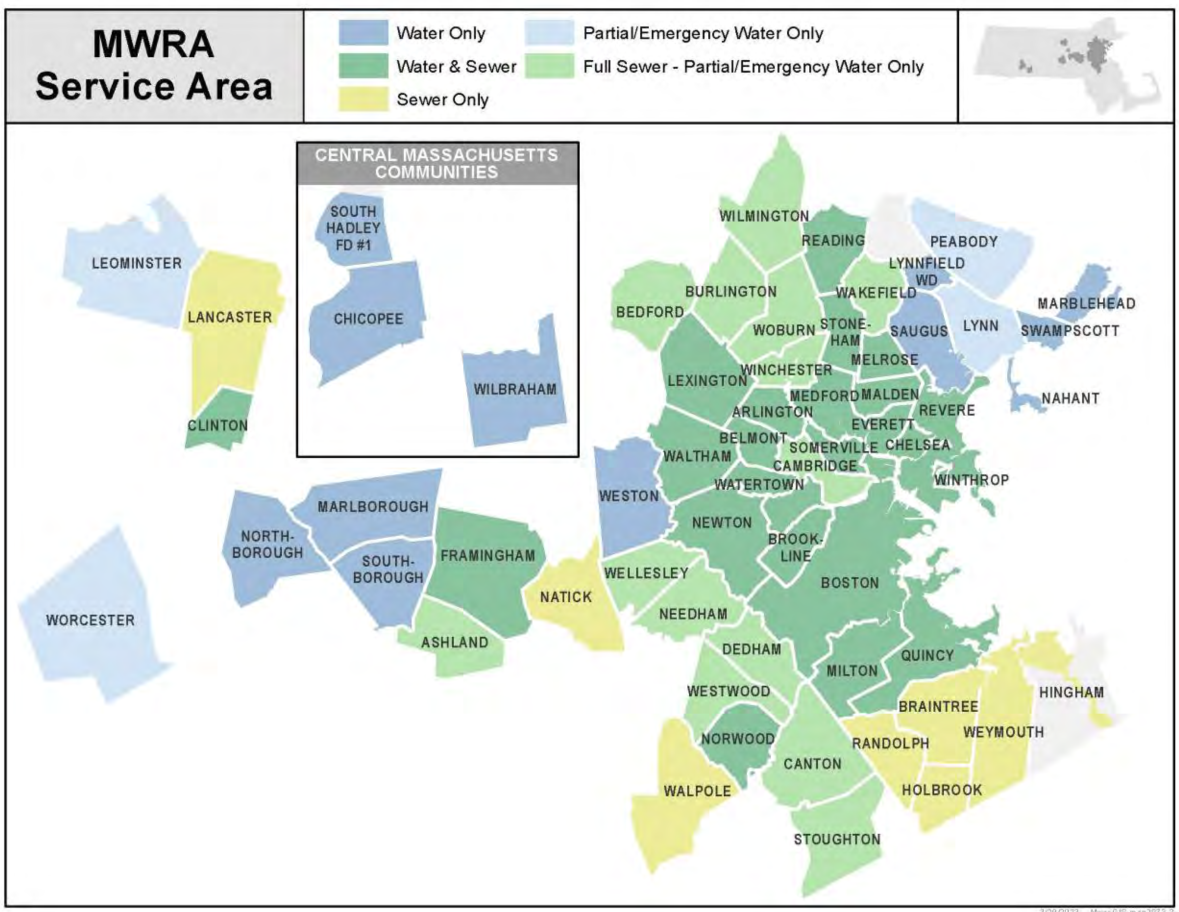
While significant progress has been made since 2006, the rate of GHG reductions has decreased in recent years. This recent slowdown reflects that many of the lower cost, readily available methods of mitigation have been implemented. Major emissions reductions are expected from the replacement of the existing combined heat and power (CHP) system at Deer Island, which is currently scheduled for completion within the next decade. MWRA will continue to pursue additional efficiency and renewable energy projects to meet future emissions targets.

1 - Introduction

Overview and Background

Massachusetts Water Resources Authority (MWRA) provides wholesale water and sewer services to over 3.1 million people and 5,500 industrial and commercial users in 61 metro Boston communities.

Figure 1: MWRA Service Area

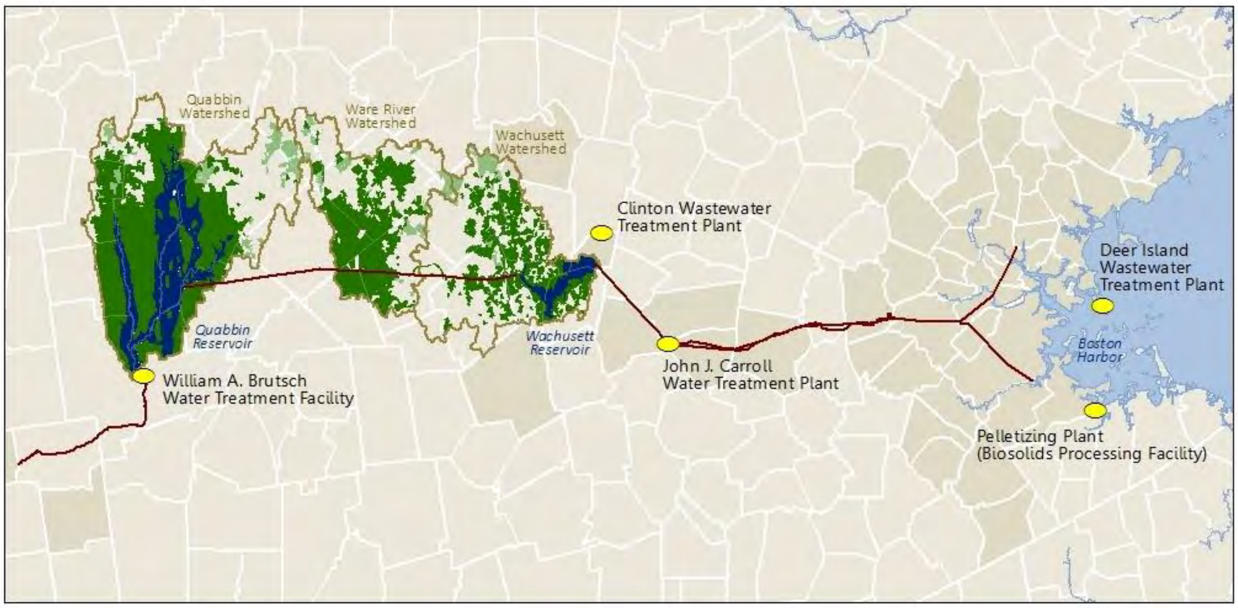


Water and wastewater trasnsport and treatment are energy intensive enterprises, and energy consumption is a significant contributor to GHG emissions. MWRA is committed to being a leader in environmental stewardship and has worked to reduce the GHG emissions required to provide safe drinking water and high quality wastewater treatement to its member communities. This commitment was recently acknowledged by the Commonwealth with MWRA's selection for the 2023 Leading by Example Award. This annual award, which MWRA also received in 2007 and 2011, recognizes outstanding efforts among Commonwealth agencies, public colleges and universities, and municipalities that have implemented policies and programs resulting in significant and measurable environmental and energy benefits.

MWRA fulfills its core mission with a variety of facilities, including:

- John J. Carroll Water Treatment Plant
- William A. Brutsch Water Treatment Facility
- 11 water pumping stations
- Deer Island Wastewater Treatment Plant
- Clinton Wastewater Treatment Plant
- Biosolids Processing Facility
- 12 wastewater pumping stations
- 4 headworks facilities
- 4 combined sewer overflow (CSO) treatment facilities
- 2 large warehouse and maintenance buildings
- Covered water storage, aqueducts, meter vaults, dams, and numerous other small facilities
- 1 administrative building

Figure 2: Major MWRA Water and Wastewater Treatment Facility Locations



Objectives

MWRA has worked to meet or exceed the goals of Massachusetts Executive Order 594, which establishes emissions reduction targets for state agencies, as well as the Clean Energy and Climate Plan, which commits the Commonwealth to net zero greenhouse gas emissions by 2050 with intermediate targets of 33% and 50% reductions by 2025 and 2030, respectively.

This report is developed to assist in tracking the progress toward meeting these goals and to inform stakeholders about MWRA's efforts to reduce emissions. The objectives of this document are:

1. Present an analysis of GHG emissions to identify major sources and reveal trends
2. Highlight successes to date regarding GHG emission reductions
3. Identify emissions reduction opportunities

By adding data from calendar years 2020 through 2022, this report serves as an update to MWRA's 2006-2019 Greenhouse Gas Emissions Inventory, and reports on MWRA's ongoing initiatives to reduce overall GHG emissions.

GHG Accounting Methodology

This inventory utilizes methods from multiple GHG reporting protocols and involves significant data collection and staff input. These reporting protocols define three different categories, or "scopes" of GHG emissions:

- *Scope 1*: Direct emissions from on-site energy use and process emissions from MWRA operations
- *Scope 2*: Indirect emissions (not on MWRA property) associated with the consumption of energy at MWRA facilities (i.e. emissions at utility plants from electricity generation)
- *Scope 3*: Indirect emissions not included in Scope 2 from facilities or operations not owned or controlled by the MWRA, such as those from employee vehicles used to commute to work and the lifecycle emissions from treatment chemicals and construction materials.[1]

Scope 3 emissions have not been included in this report. Obtaining data needed to estimate scope 3 emissions can be challenging and measurements are often less straightforward than indicators such as electricity or fuel purchased. Additionally, reporting is considered optional under the Local Government Operations Protocol (LGOP)[2] and is not mentioned in Executive Order 594.

[1] A limited analysis of Scope 3 emissions for MWRA can be found in the 2014 GHG Report.
[2] See §4.6 Scope 3 Emissions in the Local Government Operations Protocol v. 1.1.

Biogenic emissions, those resulting from processes not directly a result of human activity, are also not considered in this inventory report. The LGOP specifies that biogenic emissions should not be included in Scope 1 or Scope 2 estimates, but should be tracked separately. See Appendix A for more discussion of the accounting methodology used. Appendix C provides a limited estimate of some of MWRA's biogenic emissions.

GHG Emissions Factors

Key parameters used in the determination of GHG inventories are GHG emissions factors. These factors are multiplied by the amount of energy used in order to generate a value for the GHG emissions from an energy source consumption. An example of such a factor would be used to convert the megawatt hours of electricity consumed from the utility into the equivalent metric tons of carbon dioxide (CO_2) equivalent ($MTCO_2e$)[3].

The electricity emissions factor used in this inventory, calculated by the Massachusetts Department of Environmental Protection (MassDEP), has been reduced by roughly half since 2006. This reflects a shift away from carbon emitting generation sources toward a greater mix of renewables.

Other emissions factors, such as those for fuels combusted by the MWRA, are published and regularly updated by the US EPA. Tables with the emission factors used in this inventory can be found in Appendix B.

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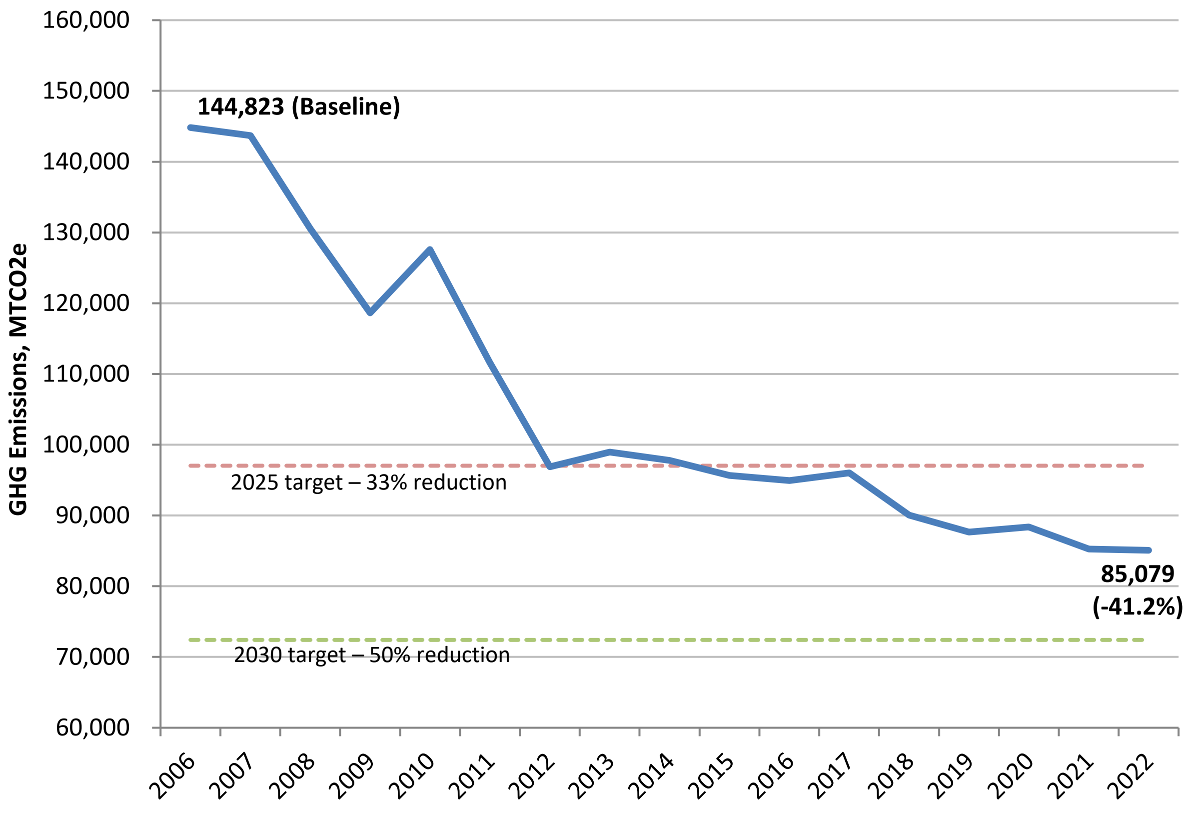
[3] CO_2e is carbon dioxide equivalent, which is a measure that allows the comparison of the emissions of other greenhouse gases, such as methane, relative to one unit of CO_2.

2 - Greenhouse Gas Emissions Summary

As shown in Figure 3, MWRA's 2022 GHG emissions are 41% lower than 2006 levels, an overall decrease of 59,744 $MTCO_2e$, comparable to taking over 13,000 passenger vehicles off the road per year. A majority of this reduction, roughly 84%, was achieved through reduced electricity purchases and a cleaner regional grid. Emissions increased slightly in 2020, mostly due to recent increases in electricity demand and the regional electric grid emissions factor. The dashed lines in Figure 3 show interim emission reduction targets as established by the Commonwealth, which calls for an 85% reduction by 2050 compared to baseline levels in order to achieve "net-zero" emissions (in combination with various carbon offsets). Note that these targets apply to total GHG emissions within the Commonwealth and not one specific sector or organization. MWRA is using these reduction goals as guidelines until specific internal emissions reductions targets out to 2050 are established.

Figure 3: MWRA GHG Emissions, Metric Tons of CO_2 Equivalents (2006 – 2022) [4]

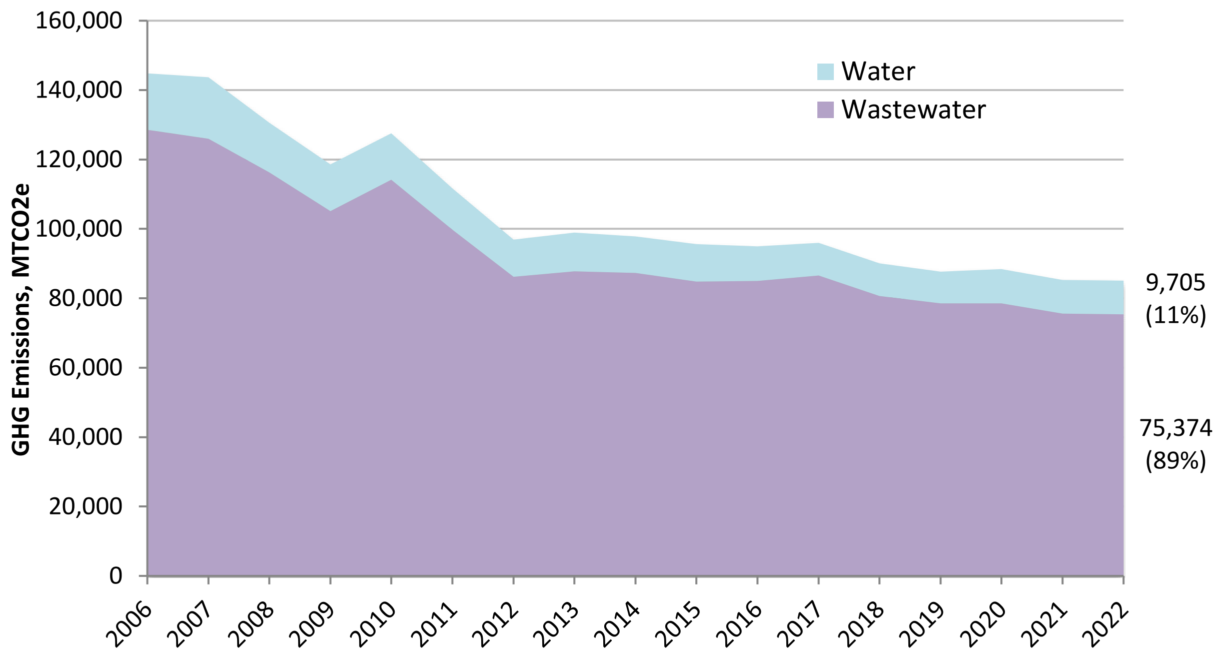


[4] The spike in emissions in 2010 was due to unusual weather patterns necessitating extended use of the backup Combustion Turbine Generators (CTGs) at the Deer Island Wastewater Treatment Plant, to ensure continuous pumping and treatment during extreme high flows which significantly increased diesel fuel usage for that year.

Comparison of Water & Wastewater GHG Emissions

As shown in Figure 4 below, the wastewater system is much more emissions intensive than the drinking water system. Every million gallons of drinking water delivered results in emissions of 133 kilograms (kg) of carbon dioxide equivalent (CO_2e), compared to 772 kg of CO_2e emitted per million gallons of wastewater treated. This is partly due to the fact that the drinking water distribution system is primarily gravity fed whereas the wastewater system is powered by pumping at Deer Island and pump stations throughout the service area. Between 2006 and 2022, the water system has accounted for an average of 11% of MWRA's total GHG emissions, while wastewater has accounted for the other 89%.

Figure 4: GHG Emissions from Water & Wastewater Sectors (2006-2022)



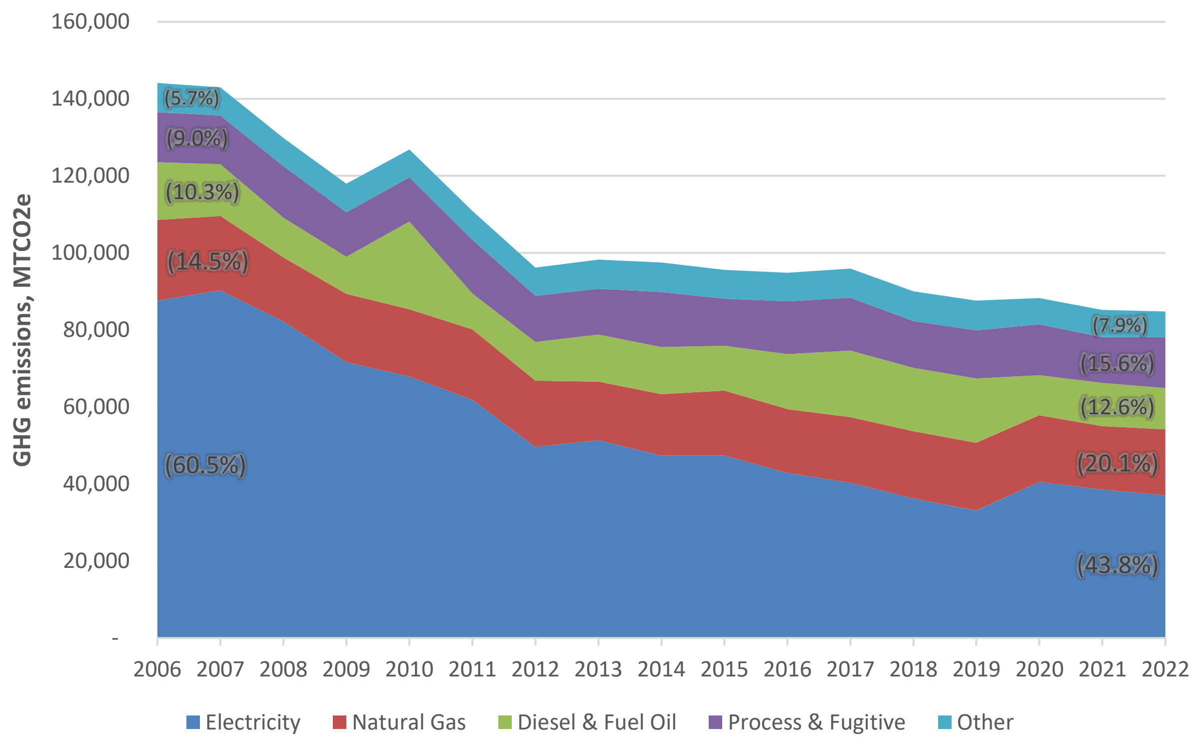
3 - GHG Emissions by Source

As shown in Figure 5 below, in 2022 the major sources of GHG emissions in the MWRA's operations (as a percent of total emissions) included:

- Electricity (includes water and wastewater treatment plants, pump stations, and headworks facilities), **43.8% (37,294 MTCO$_2$e)**
- Natural gas (dryers at the biosolids processing plant, building space heating), **20.1% (17,096 MTCO$_2$e)**

- Process and Fugitive[5] (nitrous oxide and methane emissions at wastewater treatment plants, landfills, and the sludge pelletizing plant), **15.6% (13,238 MTCO$_2$e)**
- Diesel and fuel Oil (standby generators, process and building heating), **12.6% (10,729 MTCO$_2$e)**
- Other (stationary CH_4 emissions from incomplete combustion of Digester Gas, vehicle fleet, refrigerants), **7.9% (6,732 MTCO$_2$e)**

Figure 5: MWRA GHG Emission Sources, 2006-2022



Electricity Emissions

Electricity purchases make up the majority of MWRA's utility spending and account for nearly 44% of total emissions. The energy demand that drives these emissions is influenced by many factors, including precipitation, customer demand, and evolving regulatory requirements.

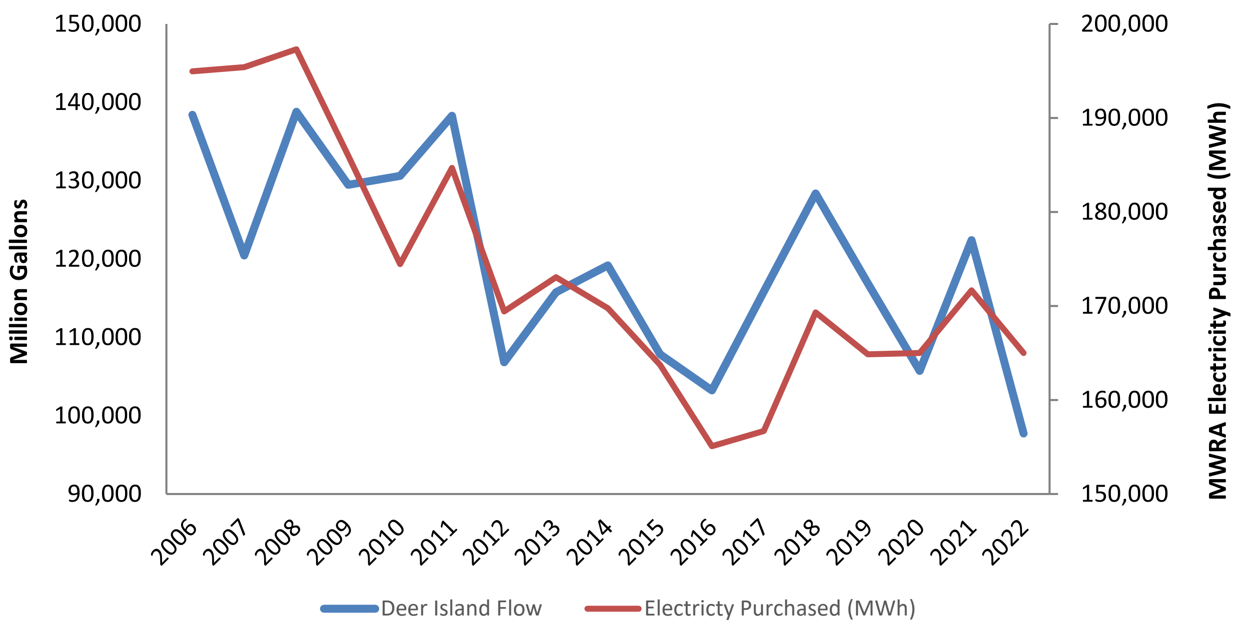
Because the Deer Island Wastewater Treatment Plant, the second largest in the United States, accounts for an average of 62% of these electricity purchases, the total electricity demand tends to vary with Deer Island wastewater flows (Figure 6). The flow through Deer Island varies with

[5] Process emissions refer to expected releases of gas during treatment processes, and fugitive emissions refer to unintended leaks of gases from a pressurized environment. Some of these emissions are not measured directly, but estimated based on activity data using formulas provided in reporting protocols.

rainfall totals in the service area, as several MWRA-served communities use combined sewer systems, accepting both wastewater and stormwater for treatment and discharge. Even many separated sewer systems convey excess groundwater or stormwater during extended wet periods, so treatment flows are expected to continue varying with precipitation totals.

Changing environmental regulations can have substantial impacts on MWRA's energy demands. In 2006, the Environmental Protection Agency (EPA) introduced the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), which required the MWRA to add an ultraviolet (UV) disinfection at its two water treatment plants. The addition of these UV systems increases energy demand at the treatment facilities.

Figure 6: Deer Island Total Flow & MWRA Annual Electricity Purchases (2006-2022)[6]

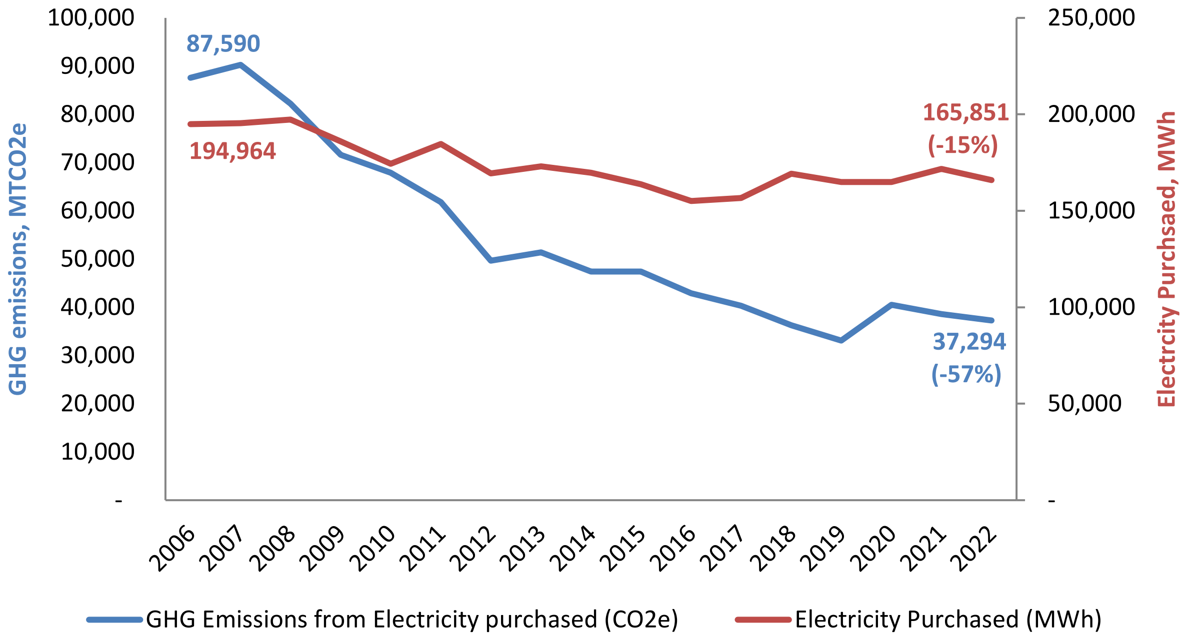


Despite these challenges, MWRA has reduced total electricity purchases by 15% and emissions from electricity by 57% between 2006 and 2022 (Figure 7). The state-wide emission factor has been falling steadily as renewable and non-emitting sources account for a larger share of total generation[7], and this has amplified the effects of MWRA's electricity saving efforts. Figure 7 shows that emissions have declined at a faster rate than electricity purchased, owing to a falling emission factor. This underscores the fact that much of MWRA's emissions reductions are the result of regional efforts to introduce lower carbon generation sources into the electric grid.

[6] Low values in 2016 and 2017 are due to the replacement of the 115 kV submerged cable that supplies power to Deer Island, during which the facility was powered entirely by standby generators. The increase in 2021 was due to high precipitation that summer, as also evident in the Deer Island Treatment Plant flow data.

[7] The increase in emissions in 2020 (seen in Figure 7) and is largely due to an increase in the emissions factor as discussed in the introduction. At time of writing, MassDEP has not yet published an emissions factor for 2022, and a 2021 value is used as a placeholder.

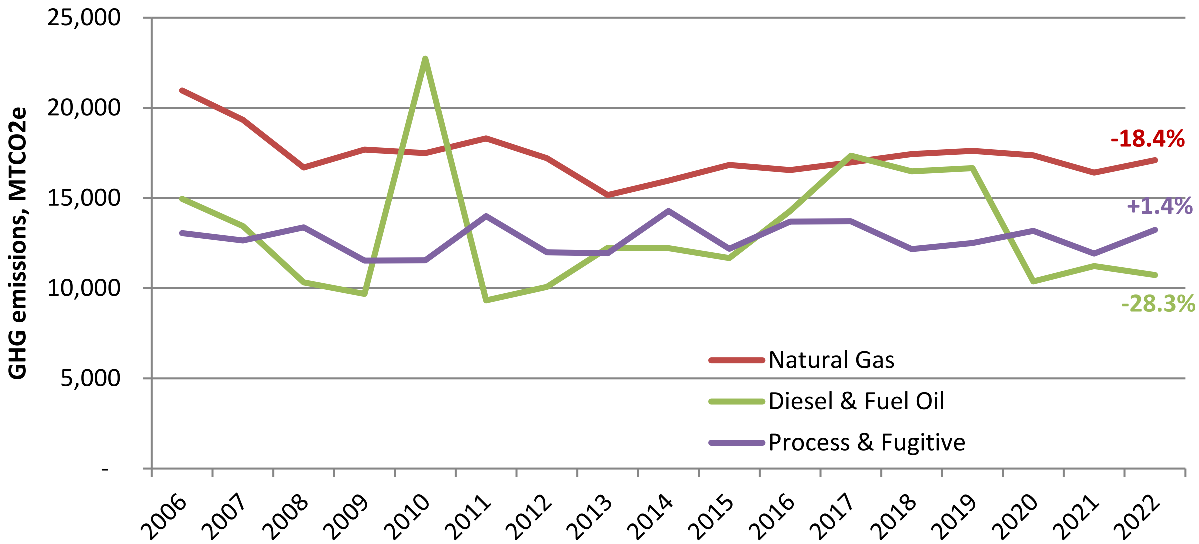
Figure 7: MWRA Electricity Purchases and Resulting Emissions ($MTCO_2e$)



Natural Gas Emissions

Natural gas is used to heat facilities throughout the MWRA system and a number of facilities have reduced their use of diesel for heating and converted to natural gas use. The most significant use of natural has is thermal drying at the Quincy pelletizing plant (biosolids processing facility), accounting for nearly 80% of MWRA's emissions from natural gas. The biosolids processing facility utilizes an energy intensive process to convert sludge (the solids that remain after the wastewater treatment process) into fertilizer pellets. Figure 8 shows that overall emissions from natural gas have decreased by 18.4% since 2006. Although natural gas demand at the biosolids processing facility has been reduced by 26% compared to 2006 levels, conversions from fuel oil to natural gas heating at facilities such as the Chelsea Headworks have partially offset this decrease. Because natural gas is a less carbon intensive energy source than fuel oil, the net effect of these conversions is a decrease in overall GHG emissions.

Figure 8: Emissions from Natural Gas, Diesel & Fuel Oil, Process & Fugitive



Diesel & Fuel Oil Emissions

Diesel and fuel oil are consumed by standby power generators at multiple MWRA facilities. Although diesel is also used by the MWRA vehicle fleet, those emissions are accounted for separately. Since 2006, emissions from diesel and fuel oil were reduced by 28%, mainly due to a decreased need to use the combustion turbine generators (CTGs) for standby power at Deer Island as a result of fewer major storms in 2022.[8] The 2010 spike in fuel oil emissions seen in Figure 8 is due to a period of extreme precipitation which required extended use of the CTGs and the spike beginning in 2017 is due to the cable that provides Deer Island electricity being temporarily taken out of service for a harbor dredging project.

Process & Fugitive Emissions

Process emissions result from biochemical reactions during wastewater treatment and discharge at Deer Island and Clinton Wastewater Treatment Plants. Process emissions include CH_4 (methane) and N_2O (nitrous oxide) emissions, whereas CO_2 (carbon dioxide) emissions are considered biogenic and accounted for separately (see Table 3 in appendix C). Fugitive emissions result from uncontrolled or unintentional releases of GHGs from pressurized environments and also result from landfill disposals. Fugitive emissions are difficult to measure directly, and values reported here reflect informed estimates based on flow data following accepted GHG reporting protocols.

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[8] During high precipitation, intense storms that cause high flows at Deer Island, MWRA operates the CTGs as a standby emergency power source to ensure continued service in the case of a power outage. Fewer major storms means less frequent operation of the CTGs and less oil used.

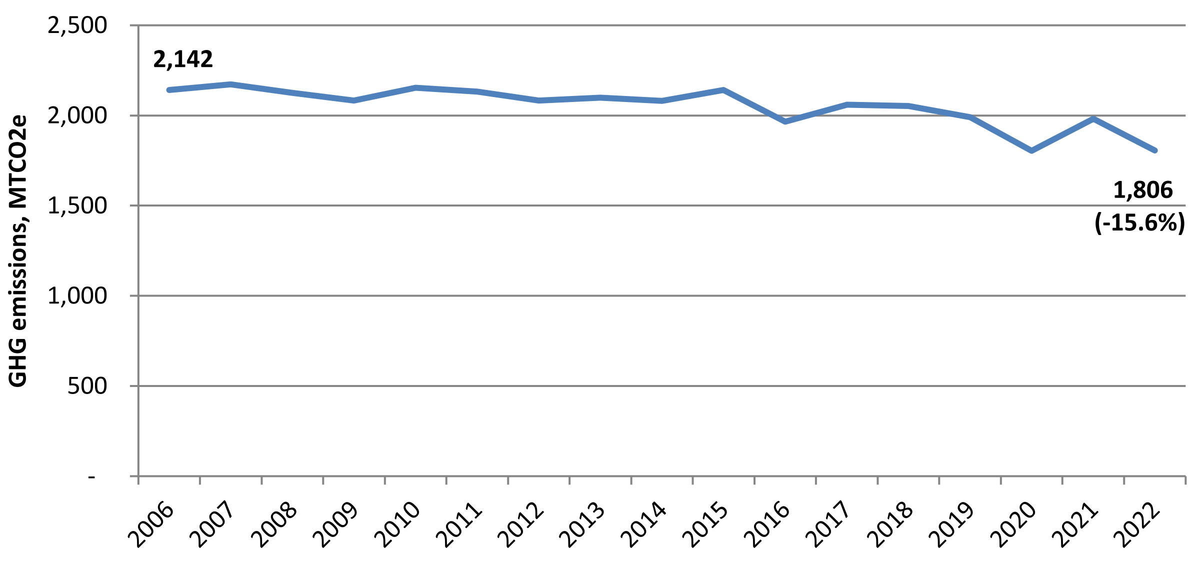
Total process and fugitive emissions are 1.4% higher than 2006 levels. However, it should be noted that methane emissions from the Deer Island odor control systems, which make up more than half of estimated process emissions, were likely undercounted prior to 2012. Increases in the service population will make methane removal from the Deer Island odor control processes challenging and available bio filtration technologies would be challenging to install and could pose operational risks. MWRA staff may assess options for greater methane removal from DITP processes as part of future emissions reduction planning.

Emissions from Other Sources

Other sources of GHG emissions include an anthropogenic component of digester gas combustion and flaring, MWRA's vehicle fleet, refrigerants, and small quantities of propane. Overall emissions from these categories have fallen 12% since 2006, to a total of 6,660 metric tons of CO2e in 2022. Recent reductions are mostly the result of reduced vehicle fleet emissions.

MWRA vehicle fleet emissions decreased by just over 15% compared to 2006 levels. This reduction was achieved by improvements in vehicle fuel efficiency and, more recently, by the adoption of hybrid and electric vehicles. Fleet emissions are expected to continue falling in coming years as the electric vehicle fleet is expanded, especially as electric versions of medium- and heavy-duty work vehicles suitable for MWRA use become readily available.

Figure 9: Emissions from MWRA Vehicle Fleet



4 - Renewable Energy and Avoided Emissions

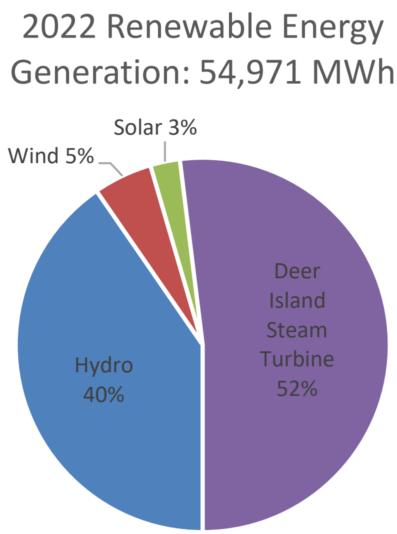
Onsite generation of renewable energy enables MWRA to decrease GHG emissions, even if total energy consumption is not reduced.[9] In addition to wind turbines, hydroelectric generators, and photovoltaic solar installations, MWRA utilizes the methane gas that is emitted during sludge digestion at Deer Island, which is then combusted in a boiler based combined heat and power (CHP) plant. This system comprises the majority of MWRA's onsite energy generation, providing the heating equivalent of over 5 million gallons of fuel oil each year and more than 28 million kilowatt-hour (kWh) of electricity. The full list of onsite renewable sources and their capacity is provided in Table 1.

Table 1: List of Renewable Electricity Generation Facilities and Rated Capacities

Facility	Rated Capacity (Megawatt (MW) or Kilowatt (kW))
Digester Gas Powered Steam	
Deer Island Steam Turbine Generator	19 MW
Hydroelectric Generators	
Oakdale	3.5 MW
Deer Island	2 @ 1 MW
Cosgrove	2 @ 1.7 MW
Loring Road	200 kW
Brutsch Treatment Facility (Hatchery)	60 kW
Wind Turbines	
Charlestown	1.5 MW
Deer Island	2 @ 600 kW[10]
Photovoltaic Solar	
Carroll Water Treatment Plant	496 kW
Four Locations at Deer Island	736 kW
Wachusett Aqueduct Pumping Station	76 kW

[9] GHG emissions figures and total electrical utility consumption already account for the electricity generated onsite with renewables.
[10] In 2023 one of the two wind turbines failed and has been deactivated while its future is determined. For the time of the data for this report, however, Deer Island had two wind turbine generators.

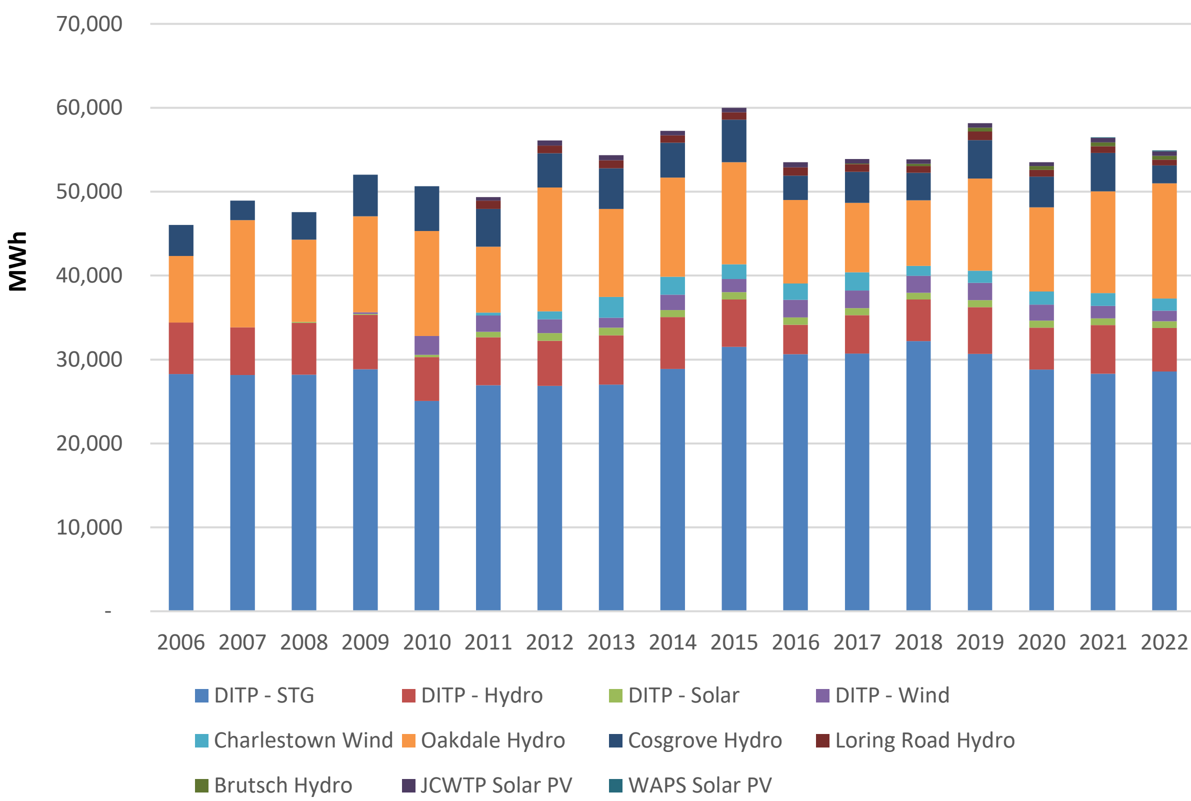
Figure 10: MWRA Renewable Energy by Source in 2022 (MWh)



In 2022, MWRA generated 54,971 megawatt-hour (MWh) from renewables (Figure 10). 36,102 MWh of this total was consumed on site, avoiding 14,820 MTCO$_2$e that otherwise would have been associated with MWRA electric grid usage. Figure 11 shows a more detailed breakdown of renewable energy generation at all of MWRA's installations since 2006.

Renewable energy sold to the grid is not counted as a direct reduction in MWRA's emissions from electricity, although providing more renewable sources to the regional generation mix contributes to the continued reduction in the grid emissions factor. All sources of renewable energy at Deer Island are consumed on site, whereas most other facilities sell power back to the regional grid.

Figure 11: Renewable Energy Generation 2006-2022 (MWh)



William A. Brutsch Hydroelectric Facility and the McLaughlin Fish Hatchery Pipeline

Since 2017, MWRA has operated a hydroelectric turbine at the Brutsch Treatment Facility in a pipeline to the Division of Fisheries and Wildlife's (DFW) McLaughlin Fish Hatchery. This successful project has multiple benefits, including, reducing MWRA's greenhouse gas emissions by generating renewable hydroelectric power, providing revenue to MWRA through energy sales to the electrical grid, reducing the hatchery's carbon footprint by eliminating electrical demand associated with pumping water from the Swift River, and delivering cold, well oxygenated water to the fish hatchery without pumping, benefiting the health and growth of the fish.

Renewable Energy Certificates

In addition to renewable energy generation, for several years MWRA was voluntarily purchasing enough renewable energy certificates (RECs) to ensure that an amount of power equivalent to MWRA's electrical utility demand is being supplied from renewable sources. A renewable energy certificate is a market-based instrument that represents the property rights to the environmental, social and other non-energy attributes of renewable electricity generation. RECs are issued when one MWh of electricity is generated and delivered to the electricity grid from a renewable energy resource. In 2022, MWRA purchased enough New England sourced "Class II" (generation facilities in operation before 1998) RECs to account for 100% of the Authority's electricity, in addition to the required RECs for any electricity supplied to Massachusetts electricity customers.[11] Although this does not technically mean that 100% of MWRA's electricity is generated from renewable sources, it does support the continued operation of that equivalent renewable capacity across the regional grid. The reporting protocol that MWRA relies on specifies that these voluntary purchases cannot be deducted from Scope 2 emissions, as doing so would constitute a double counting. This is because the renewable energy portion of each utility's energy supply is already accounted for in the statewide emissions factor that is being multiplied by MWRA's activity data.[12]

[11] Massachusetts' Renewable Energy Portfolio Standard (RPS) was one of the first programs in the nation that required a certain percentage of the state's electricity to come from renewable energy.
[12] See §6.2.4 of the Local Governments Operations Protocol v1.1.

MWRA captures value from the sale of RECs created by our own renewable electricity production for the financial benefit of our water and sewer rate payers. MWRA has generated and traded RECs since 2002. The sale of these RECs is a reliable source of revenue, generating over $16.6 million in non-rate revenue to date, at an average of approximately $750,000 annually. RECs created by the MWRA come from a variety of sources and are classified depending on the type of source and the year the system came online, and market values depending on the classification.

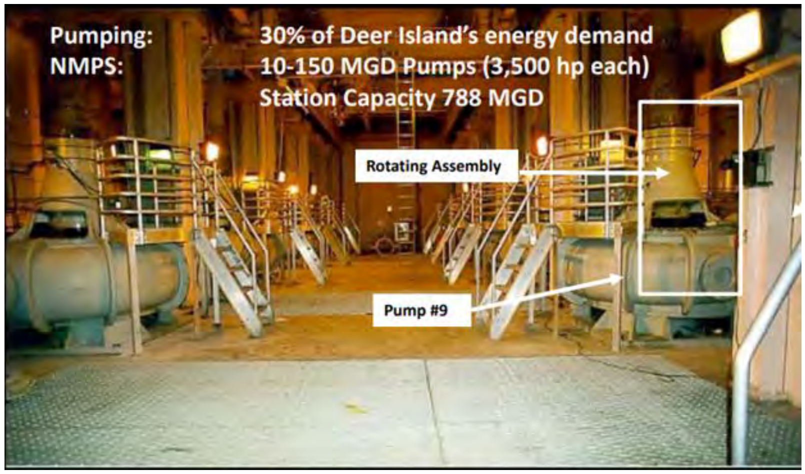
5 - GHG Emissions Reduction Successes

Reducing overall energy use by increasing efficiency continues to be MWRA's most effective strategy for reducing GHG emissions. Energy audits conducted over the last decade resulted in measures such as the installation of VFDs in pumping facilities, energy efficient lighting, more efficient heating and cooling systems, and other customized solutions. Energy Management Systems (EMS) have been installed in several MWRA buildings, providing staff the ability to actively manage HVAC energy use. Significant savings are also achieved through process changes. For example, at Deer Island in 2011, changes to secondary treatment resulting from installation of dissolved oxygen probes and control panels allowed for a reduction in blower and dissolved oxygen use, resulting in a savings of 9.2 million kWh/yr.

Several examples of completed energy efficiency initiatives are listed below. A longer list of completed efficiency projects can be found in Chapter 13 of the MWRA Wastewater Master Plan.

- Deer Island has ten raw wastewater pumps in the North Main Pump Station (NMPS). MWRA staff routinely maintain these pumps to ensure they operate at maximum efficiency. In an effort to identify opportunities for optimization of the pumping equipment for energy savings, Pump Number 9 was identified as operating below an acceptable pump efficiency level. In December 2019, Pump Number 9 was refurbished, including an epoxy resin recoating, thereby increasing energy efficiency, reliability, and extending the pump's useful life (Figure 12). This project provides an estimated 236,000 kWh savings per year.

Figure 12: DITP North Main Pump Station - Pump 9



- Wachusett Aqueduct Pumping Station (WAPS) is a critical component of MWRA's water transmission redundancy plan and a model for sustainability. Completed in 2019, WAPS includes: 1) enhanced building envelope and subgrades insulation; 2) a cold roof that was added to the project to minimize energy transfer from the sun and outside air into the building; 3) a geothermal heat pump that circulates forebay water into the building, where it interacts with a heat exchanger that is connected to a water-cooled heat pump; 4) LED lights connected to motion and daylight sensors; and 5) 76 kilowatt (kW) of roof top and ground mount solar panels.

Figure 13: WAPS Geothermal Heat Pump Installation

- Five LED lighting upgrade projects from 2020-2022 (384,633 kWh saved annually)
- Pipe insulation at four water facilities to decrease the need for dehumidification (215,170 kWh saved annually)

- Installation of VFDs on the ventilation at Union Park Combined Sewer Overflow Facility to avoid constant running at full throttle (23,400 kWh saved annually)
- Installation of VFDs on 3 pumps at Deer Island Treatment Plant in September 2021 (227,461 kWh saved annually)

To ensure that energy saving and GHG emission reducing efforts are considered as part of normal capital planning, MWRA adopted a social cost of carbon (SCC) of $125 per metric ton of CO_2 for assessments when evaluating the life cycle costs of new projects in 2022. The social cost of carbon is an estimate of the economic costs, or damages, of emitting one additional metric ton of carbon dioxide into the atmosphere.

6 - Future Emissions Reduction Opportunities

Several projects are currently in development that will support the reduction of MWRA's GHG emissions. The following are the primary methods to reduce GHG emissions:

1. Reduction of energy use or use of energy more efficiently (efficiency)
2. Installation of onsite renewable energy (renewables)
3. Transition from fossil fuel to electricity as energy source (electrification)

The following subsections discuss future projects planned in each of these areas.

Efficiency

Efficiency improvements are an effective method to reduce GHG emissions and MWRA has internal standard operating procedures to ensure that energy efficiency is considered whenever facilities are rehabilitated or newly constructed. This has resulted in efficiency improvements being incorporated into facility rehabilitations at Chelsea Creek, Nut Island, Ward Street, and Columbus Park Head Works, Braintree-Weymouth, Alewife Brook, Hingham and Hayes Pump Stations, and the Quabbin Reservoir Administration building. Improvements include LED lighting, HVAC system upgrades, and installation of energy management systems that allow for remote operation. Rehabilitations of the Chelsea Creek and Nut Island facilities alone are expected to save 1.7 million kWh annually.

Efficiency improvements can also be accomplished by extracting more utility from existing renewable energy sources. The existing CHP system at Deer Island provides thermal and electrical energy from the digester gas generated onsite as part of the treatment plant process. Through simulations it was determined significantly more energy could be extracted from this digester gas resource. MWRA is currently engaged in working towards the design and construction of a new CHP facility with construction estimated to be completed in the next decade. This project is estimated to result in the production of an additional 40 gigawatt-hour (GWh) of electricity per year; along with a reduction in fuel oil usage by roughly 300,000 gallons per year. These are expected to reduce emissions by 12,800 $MTCO_2e$/yr, a 15% decrease of MWRA total emissions compared to 2022 levels.[13] The project will potentially include development of a microgrid with a battery energy storage system designed to reduce the running time of existing backup generators and coordinate the different energy sources at Deer Island with the potential to further decrease GHG emissions from Deer Island.

Expansion of Renewables

MWRA is committed to siting new renewable energy projects at as many facilities as economically feasible and continues to aggressively seek out any available grant and loan funds to improve project paybacks.

Additional solar photovoltaic capacity is in the early stages of development at several MWRA facilities. At Deer Island, a 2 MW parking lot canopy system is targeted for operation in 2026. Scopes of work are also being developed for a 5 MW array at the Norumbega covered storage facility, a 1.5 MW array at the Loring Road covered storage, and a 300 kW array at the Arlington covered storage. Several upcoming roof replacement projects will also assess the viability of rooftop solar on a case-by-case basis.

Electrification

Electrification converts an energy source from one that uses fossil fuels locally to one that uses electricity. This will obviously increase the electricity consumption, but as the electrical grid is supplied by more renewable energy (or onsite renewable resources are expanded) the GHG emissions of those facilities will be reduced.

Though they contribute only a small portion of the total MWRA GHG emissions, the vehicle fleet is also being electrified. The installation of an additional 60 electric vehicle charging ports at major facilities is planned over the next several years. These will support the continued expansion of the number of electric vehicles in the MWRA fleet. Up to this point electric vehicle purchases have focused on passenger vehicles, but with the production of electric light-duty pickups beginning in 2023, MWRA will target the replacement of the existing light-duty pickup trucks beginning in 2024. Further opportunities for fleet electrification will be assessed as more manufacturers and vehicles enter the market. MWRA will continue to lead by example and work toward the Commonwealth’s goal of 100% zero emission vehicles by 2050.

Heat pumps can be installed to either replace or augment the operation of fossil fuel fired boilers for space heating needs. The thermal source for these heat pumps can be either air or water. MWRA is evaluating use of air source heat pumps as well as water/wastewater source heat pumps at drinking water and wastewater pump stations. Major rehabilitation projects at the Ward

[13] This value was calculated using the GHG emissions factor for this analysis. Previous values for the new CHP were calculated with the supplier-specific emission factor reported for the Deer Island account, which is nearly 50% higher than the regional estimate provided by MASSDEP. As a result, this GHG emissions reduction contribution is lower than reported elsewhere.

Street and Columbus Park headworks, currently in the design phase, are also evaluating the feasibility of heat pumps.

7 - Conclusion

As this report shows, the MWRA has been successful at reducing GHG emissions from the base year of 2006 – having already met the state's 2025 target of a 33% reduction in emissions. GHG emissions have been reduced roughly 41% compared to 2006 baseline levels. This reduction was accomplished through projects and practices to reduce energy use and install renewables, and further aided by a falling regional electric grid emissions factor.

As many of the low cost and easy to implement tasks have been accomplished, it could become more difficult to locate additional opportunities. However, a major overhaul of the CHP system at Deer Island and further expansion of onsite renewable energy, plus many other smaller projects, will build on past successes. The further buildout of renewable energy in New England, especially once additional hydro power from Canada and offshore wind power are interconnected with the regional grid, will mean the electricity MWRA must consume to fulfill its critical mission will be cleaner and more sustainable.

Appendices

Appendix A: Methodology

The approach to building the MWRA GHG inventory is consistent with international and national standards and best practices. Both the Greenhouse Gas Protocols - Corporate Accounting and Reporting Standard[i], and the Local Government Operations Protocol (LGOP), version 1.1[ii], were used as the core guiding documents. The U.S. Environmental Protection Agency (EPA) Climate Leadership for Greenhouse Gas Inventories[iii] was used to identify emissions factors and the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report[iv] was referenced for global warming potentials. Although the IPCC has since published new editions of the Assessment Report, EPA will continue to use global warming potentials from the Fourth edition until 2024. The Australian National Greenhouse and Energy Reporting[v] (NGER) protocol was used to estimate nitrogen emissions from wastewater treatment plant (WWTP) effluent to receiving bodies of water. Massachusetts Department of Environmental Protection (MassDEP) emission factors were used to estimate emissions from electricity purchases. In previous GHG inventories, supplier specific emissions factors were used to try to more accurately estimate MWRA's emissions. However, following recommendations by the MassDEP and Executive Office of Energy & Environmental Affairs (EOEEA), the latest inventory instead employs a consumer-level (i.e., accounting for losses during transmission and distribution) statewide emission factor.

There are seven major greenhouse gases included in the GHG Protocol, however the five listed below are the only ones that MWRA's operations contribute to:

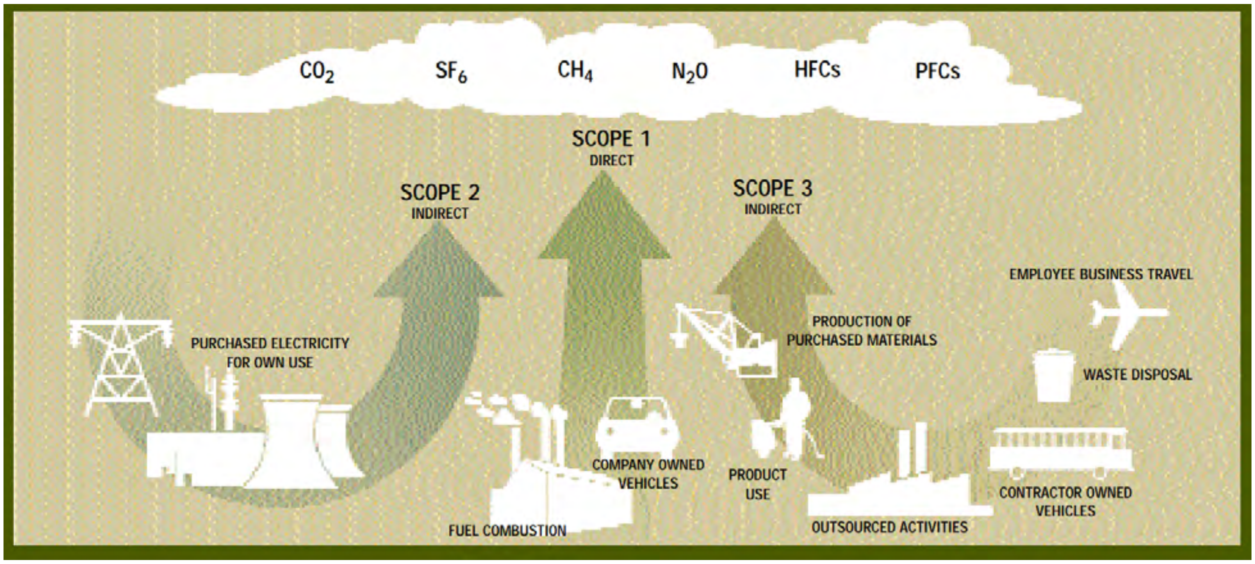
- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Hydrofluorocarbons (HFCs) (minor contribution)
- Sulphur hexafluoride (SF_6) (minor contribution)

MWRA operations are not believed to emit perfluorocarbons (PCFs) or nitrogen trifluoride.

The base year for this greenhouse gas inventory is 2006 because it is the earliest year with consistent and reliable data for all emissions sources.

<u>Operational Boundaries</u>

In order to categorize direct and indirect emissions, to improve transparency, to standardize accounting practices, and to identify different types of climate policies and goals, emissions are reported within the bucket of one of three Scopes:



Source: GHG Protocol

Scope 1 emissions include stationary combustion to produce power at a fixed location, mobile combustion of fuels in fleet transportation sources, and process and fugitive emissions.

Process emissions include:

- Process CH_4 from WWTP
- Process N_2O from WWTP without nitrification
- Process N_2O from WWTP with nitrification
- Process N_2O from effluent discharge to receiving aquatic environments

Fugitive emissions include:

- CH_4 from incomplete combustion of digester gas
- CH_4 emissions from venting digester gas
- CH_4 fugitive emissions from distribution
- CO_2 fugitive emissions from dry tonnage sludge
- CH_4 from landfill without LFG collection

Scope 2 emissions include:

- Emissions from electricity purchased estimated with MassDEP and supplier-based emission factors

Biogenic emissions were also accounted for, but not included in the inventory (aggregate emissions) per standard practices and guidance from the GHG Protocol and LGOP (See Appendix C).

Biogenic emissions include:

- Digester gas combustion and flaring (CO_2)
- Process CO_2 from digester gas
- Biogenic emissions from electricity purchases
- Mobile emissions from biodiesel and ethanol

Biogenic vs. Anthropogenic Emissions[vi]

The combustion of biomass and biomass-based fuels (such as wood, wood waste, landfill gas, ethanol, etc.) emit CO_2 emissions, but these CO_2 emissions are distinct from Scope 1 emissions generated by combusting fossil fuels. The CO_2 emissions from biomass combustion are tracked separately because the carbon in biomass is of a biogenic origin—meaning that it was recently contained in living organic matter—while the carbon in fossil fuels has been trapped in geologic formations for millennia. Because of this biogenic origin, the IPCC Guidelines for National Greenhouse Gas Inventories requires that CO_2 emissions from biomass combustion be reported separately.[vii]

Not included in the MWRA GHG inventory:

Scope 1

- Refrigerants from field operations (Deer Island and Biosolids Processing Facility refrigerants are included)
- CH_4 and N_2O emissions from operating field equipment

Scope 3

- Grit & screenings disposed of in landfills by MWRA contractor
- Life cycle emissions of chemicals used (including liquid oxygen and soda ash)
- Contracted transportation
- Energy extraction/production/transportation
- Contracting construction and new projects
- Life cycle emissions of goods and services procured
- Waste emissions

Rationale for exclusion of certain emissions sources

Per the guidelines set forth in the LGOP, the water and wastewater systems at MWRA were studied and interviews conducted with facilities managers and engineers in order to identify any additional potential emissions sources.

Emissions from refrigerants were only accounted for at the Deer Island and Biosolids Processing facilities because emissions from refrigerants in field operations are considered insignificant, and data is difficult or impossible to source outside these large facilities.

Several Scope 3 emissions sources, which are optional to report, were excluded from this inventory. Future updates may be expanded to include Scope 3 emissions from sources such as contracted transportation (trucks, trains, barges), life cycle of chemicals (especially liquid oxygen and soda ash), and energy extraction and distribution. Scope 3 emissions, despite being indirect, often provide important and actionable information. For this reason, MWRA conducted an authority-wide Employee Commuter Survey in 2014 to assess Scope 3 emissions associated with employee commuting. Post COVID-19 pandemic, most MWRA office staff are splitting their time between remote work and a consolidated office at the Chelsea facility, so a new survey of employee commuting patterns is needed.

Calculation methods:

Activity data[viii] are the relevant measurement of energy use or other GHG generating processes. Examples of activity data referenced in this Protocol include fuel consumption by fuel type, metered energy consumption, and vehicle mileage by vehicle type. Activity data are used in conjunction with an emission factor (see Appendix B) to determine emissions using the following generalized equation:

$$Emissions = Activity\ Data \times Emission\ Factor$$

Appendix B: Emission Factors and Global Warming Potentials

Emission factors[ix] are calculated ratios relating GHG emissions to a proxy measure of activity at an emissions source. Emission factors are used to convert activity data, like energy usage, into the associated GHG emissions and thus are central to creating an emissions inventory. Emissions factors are usually expressed in terms of emissions per unit of energy used (e.g., lbs. of CO_2 per kWh).

Emission factors are determined by means of direct measurement, laboratory analyses or calculations based on representative heat content and carbon content. The Local Government Operations Protocol (LGOP) provides default emission factors for most calculation methodologies.

Massachusetts-based (MassDEP) approach reflects the average emissions of electricity generation for all energy that is consumed by the state. [x]

In previous inventories for electricity use, MWRA used a combination of supplier specific, EPA eGRID, and MassDEP emissions factors to estimate emissions. The current inventory update uses only a MassDEP non-biogenic statewide emission factor, which has been applied to all years of available data. MassDEP generally publishes these statewide values with a lag of about 3 years, so a 2021 value is being used to estimate 2022 emissions. The estimate of 2022 emissions from electricity may change when an updated factor becomes available, and will be reflected in a later emissions inventory update.

Stationary Scope 1 Emissions Factors
(Source: EPA Climate Leaders Emission Factors, updated April 2023)

Natural Gas	CO2	CH4	N2O
	kg CO2/mmBtu	g CH4 / mmBtu	g N2O / mmBtu
	53.06	1	0.1
	kg CO2/mmBtu	kg CH4 / mmBtu	kg N2O / mmBtu
	53.06	0.001	0.0001

Digester Gas	CO2	CH4	N2O
	kg CO2 / MMBtu	kg CH4 / mmBtu	kg N2O / mmBtu
	52.07	0.0032	0.00063

Diesel Fuel (Mobile)	CO2	CH4	N2O
	kg CO2 / gallon	kg CH4 / gallon	kg N2O / gallon
	10.21	0.00041	0.00008

Diesel (Stationary) - Distillate Fuel #2	CO_2	CH_4	N_2O
	kg CO_2 / MMBtu	kg CH_4 / mmBtu	kg N_2O / mmBtu
	73.96	0.003	0.0006

Propane	CO_2	CH_4	N_2O
	kg CO_2/mmBtu	g CH_4 / mmBtu	g N_2O / mmBtu
	62.87	3	0.6
	kg CO_2/mmBtu	kg CH_4 / mmBtu	kg N_2O / mmBtu
	62.87	0.003	0.0006

Mobile Emissions Factors
(Source: EPA Climate Leaders Emission Factors, updated April 2023)

Vehicle Fuel Use	CO_2
Mobile Combustion CO_2	kg CO_2 / gallon
Motor Gasoline	8.78
Diesel Fuel	10.21
Ethanol	5.75
Biodiesel	9.45

Vehicle Mileage			
		CH4	N2O
Vehicle Type	**Vehicle Year**	**kg/mile**	**kg/mile**
Diesel Heavy-Duty Vehicle	1960-present	0.0000051	0.0000048
Diesel Light-Duty Truck	1983-1995	0.0000005	0.000001
Diesel Light-Duty Truck	1996-present	0.0000005	0.000001
CNG Light-Duty Truck	All	0.000737	0.00005
Gasoline Heavy-Duty Vehicle	1990-1995	0.0003246	0.0001142
Gasoline Heavy-Duty Vehicle	1997	0.0000924	0.0001726
Gasoline Heavy-Duty Vehicle	1998	0.0000641	0.0001693
Gasoline Heavy-Duty Vehicle	1999	0.0000578	0.0001435
Gasoline Heavy-Duty Vehicle	2000	0.0000493	0.0001092
Gasoline Heavy-Duty Vehicle	2001	0.0000528	0.0001235
Gasoline Light-Duty Truck	1987-1993	0.0000813	0.0001035
Gasoline Light-Duty Truck	1994	0.0000646	0.0000982
Gasoline Light-Duty Truck	1995	0.0000517	0.0000908
Gasoline Light-Duty Truck	1996	0.0000452	0.0000871
Gasoline Light-Duty Truck	1997	0.0000452	0.0000871
Gasoline Light-Duty Truck	1998	0.0000391	0.0000728
Gasoline Light-Duty Truck	1999	0.0000321	0.0000564
Gasoline Light-Duty Truck	2000	0.0000346	0.0000621
Gasoline Light-Duty Truck	2001	0.0000151	0.0000164
Gasoline Light-Duty Truck	2002	0.0000178	0.0000228
Gasoline Light-Duty Truck	2003	0.0000155	0.0000114
Gasoline Light-Duty Truck	2004	0.0000152	0.0000132
Gasoline Light-Duty Truck	2005	0.0000157	0.0000101
Gasoline Light-Duty Truck	2006	0.0000159	0.0000089
Gasoline Light-Duty Truck	2007	0.0000161	0.0000079
Gasoline Light-Duty Truck	2008-present	0.0000163	0.0000066
Gasoline Passenger Car	1992	0.0000704	0.0000647
Gasoline Passenger Car	1995	0.0000358	0.0000473
Gasoline Passenger Car	1996	0.0000272	0.0000426
Gasoline Passenger Car	1998	0.0000249	0.0000393
Gasoline Passenger Car	2000	0.0000178	0.0000273
Gasoline Passenger Car	2002	0.0000107	0.0000153
Gasoline Passenger Car	2003	0.0000114	0.0000135
Gasoline Passenger Car	2009-present	0.0000173	0.0000036

Process and Fugitive Emissions Factors

Emission factor for a WWTP without nitrification/ denitrification (g N2O/person/year)	**3.2**
Emission factor for a WWTP with nitrification/denitrification (g N2O/person/year)	**7**
Emission factor [kg N2O-N/kg sewage-N produced]	**0.005**
Natural Gas Fugitve Emissions from Distribution: Simplified Estimation Method: Emissions Factor (mt CH4/mile of pipe)	**1.611**

Source: LGOP v1.1 & GRP electric power sector, ST-07

Electricity Emissions Factors

MA DEP Non-Biogenic Emission Factor** (lbs. CO2e / kWh)	
2006	0.990
2007	1.019
2008	0.918
2009	0.849
2010	0.858
2011	0.738
2012	0.646
2013	0.655
2014	0.616
2015	0.638
2016	0.610
2017	0.567
2018	0.472
2019	0.443
2020	0.541
2021	0.496
2022**	0.496

Source: MassDEP

*The number above represent the MA-based non-biogenic emissions factor with transmission loss of 5-7% applied.
** No value has been published for 2022 at time of writing. 2021 value used as placeholder

EPA eGRID Renewable and Avoided Emission Factor (lbs. / kWh)			
	CO2	CH4	N2O
2006	1.315	7.7E-05	1.6E-05
2007	1.205	6.1E-05	1.3E-05
2008	1.205	6.1E-05	1.3E-05
2009	1.157	6.2E-05	1.4E-05
2010	1.107	6.2E-05	1.2E-05
2011	1.107	6.2E-05	1.2E-05
2012	1.080	6.8E-05	1.3E-05
2013	1.080	6.8E-05	1.3E-05
2014	1.066	1.1E-04	1.5E-05
2015	1.066	1.1E-04	1.5E-05
2016	0.975	8.6E-05	1.1E-05
2017	0.975	8.6E-05	1.1E-05
2018	0.931	8.6E-05	1.1E-05
2019	0.840	8.9E-05	1.2E-05
2020	0.883	7.0E-05	9.0E-06
2021	0.900	7.3E-05	9.0E-06
2022*	0.900	7.3E-05	9.0E-06

Source: EPA, Northeast Power Coordinating Council (NPCC) New England Emission factors used for calculating avoided emissions from renewables use “Annual Non-Baseload Output Emissions Rates”. See p. 18.

* No value has been published for 2022 at time of writing. 2021 value used as placeholder

Global Warming Potentials (GWP) are conversion factors used to compare all greenhouse gas emissions to carbon dioxide equivalent units. The GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation. All calculations presented in this report are based on global warming potentials published by the IPCC Fourth Assessment Report[xi].

Global Warming Potentials	
CO2	1
CH4	25
N2O	298

Source: IPCC, AR4

Refrigerants

Global Warming Potentials	
R-134a	1,430
R-404A	3,922
R-407C	1,774
R-410A	2,088

Source: IPCC, AR4

Appendix C: Emissions Tables (including Biogenic)

MWRA's greenhouse gas emissions in metric tons of CO_2e by scope and year since 2006 are shown in Table 3 below. Net reductions in emissions are primarily due to reductions from purchased electricity, while other categories are relatively stable over this period. Reductions in electricity emissions are due to efficiency gains and deployment of on-site renewable energy that have reduced overall demand, as well as continued deployment across the regional electric grid that has reduced the amount of emissions per unit of purchased power.

Table 2 shows that indirect energy consumption is the largest single source of emissions. These emissions were calculated using Mass DEP's non-biogenic electricity emission factors. Losses during transmission and distribution, which are estimated at 5.7-7% depending on year, are accounted for in these emission factors. Statewide as opposed to supplier specific factors have been used to provide a consistent and conservative estimate of emissions that recognizes the interconnectedness of the regional power grid.

Large contributors to direct energy consumption associated GHG emissions include natural gas use - primarily by the heaters and dryers at the Biosolids Processing Facility, and diesel use - most significantly by the backup generators at DITP, and in the MWRA's vehicle fleet. Scope 3 emissions, which are considered optional to report under the LGOP standards, have not been reported. Lifecycle emissions from treatment chemicals and construction materials are likely the largest sources of scope 3 emissions, and these have not yet been estimated. We hope to begin estimating these values in annual reporting from 2023 onwards. While some scope 3 emissions from employee commutes have been estimated, these are based on a 2014 survey of commuting patterns that are no longer considered relevant, especially given MWRA's office space and major expansion of remote work.

Table 3 below includes estimated biogenic emissions from MWRA's use of digester gas to produce heat at Deer Island. The LGOP specifies that biogenic CO_2 emissions from combustion of biomass should be quantified and reported, but should not be included in scope 1 emissions. [xii] These values should not be considered a complete estimate of biogenic emissions at the MWRA.

Table 2: GHG Emissions by Scope – CY 2006 through 2022

Metric tons CO2e by type	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Scope 1 (direct)																	
Stationary	36,483	33,317	27,556	27,896	40,739	28,161	27,756	27,925	28,734	29,041	31,350	34,865	34,511	34,871	28,264	28,134	28,328
Mobile	2,142	2,173	2,125	2,082	2,155	2,131	2,083	2,099	2,081	2,142	1,966	2,060	2,052	1,990	1,804	1,981	1,805
Process	6,726	6,655	7,498	5,263	5,599	7,777	6,082	5,780	8,115	7,253	7,877	7,511	6,796	6,815	8,103	6,663	8,001
Fugitive	11,883	11,265	11,185	11,756	11,199	11,752	11,318	11,765	11,458	9,836	10,850	11,259	10,464	10,883	9,676	9,871	9,650
Total Scope 1	57,234	53,409	48,364	46,997	59,692	49,821	47,239	47,568	50,388	48,271	52,043	55,695	53,824	54,559	47,846	46,649	47,784
Scope 2 (indirect)																	
Electricity (MassDEP Emission Factor)	87,590	90,270	82,183	71,641	67,893	61,807	49,643	51,379	47,403	47,387	42,892	40,327	36,243	33,094	40,529	38,600	37,294
Total (metric tons CO2e) Scope 1 & 2	**144,823**	**143,679**	**130,547**	**118,637**	**127,585**	**111,628**	**96,882**	**98,947**	**97,791**	**95,657**	**94,935**	**96,022**	**90,066**	**87,653**	**88,375**	**85,249**	**85,079**

Table 3: MWRA Biogenic Emissions – CY 2006 through 2022

tCO2e by type	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Biogenic Biogas Combustion CO2	51,526	49,342	49,798	51,816	48,774	52,296	50,612	53,003	53,382	50,194	53,474	54,599	54,982	55,248	49,437	49,227	47,190
Biogenic Biogas Flaring CO2	2,191	1,311	1,025	947	1,854	1,202	1,414	1,324	1,689	998	1,560	1,065	637	1,710	885	1,149	928
Biogenic Ethanol CO2	57	82	76	70	64	62	61	60	60	57	57	58	57	52	53	50	47
Biogenic Biodiesel CO2	48	50	51	54	61	62	60	62	60	66	57	61	61	62	51	62	56
Digester Gas Process CO2	32,875	31,693	31,693	33,311	30,480	33,754	33,039	32,435	32,613	33,276	32,215	33,240	34,222	34,632	31,531	31,919	32,050
Biogenic Emissions	**86,697**	**82,477**	**82,644**	**86,197**	**81,233**	**87,375**	**85,187**	**86,883**	**87,805**	**84,590**	**87,363**	**89,023**	**89,959**	**91,703**	**81,958**	**82,407**	**80,271**

Appendix D: Endnotes

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i https://ghgprotocol.org/corporate-standard

ii https://ww2.arb.ca.gov/sites/default/files/classic/cc/protocols/lgo_protocol_v1_1_2010-05-03.pdf

iii https://www.epa.gov/climateleadership/ghg-emission-factors-hub

iv https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html

v See Division 5.3.5 of the National Greenhouse and Energy Reporting (Measurement) Determination 2008
https://www.legislation.gov.au/Details/F2022C00737/Html/Text#_Toc107314679

vi See EPA Accounting Framework for Biogenic CO2 Emissions from Stationary Sources:
http://www.epa.gov/climatechange/Downloads/ghgemissions/Biogenic-CO2-Accounting-Framework-Report-Sept-2011.pdf

vii See the LGOP v1.1, http://www.arb.ca.gov/cc/protocols/localgov/localgov.htm

viii See the LGOP v1.1, http://www.arb.ca.gov/cc/protocols/localgov/localgov.htm

ix See the LGOP v1.1, http://www.arb.ca.gov/cc/protocols/localgov/localgov.htm

x Technical Support Document: GHG Emission Factors:
https://www.mass.gov/lists/massachusetts-greenhouse-gas-ghg-reporting-program-data

xi https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html

xii See the LGOP v1.1, http://www.arb.ca.gov/cc/protocols/localgov/localgov.htm