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Insights from Global Cities

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Toward Carbon-Neutral Water Systems: Insights from Global Cities

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ABSTRACT

Many cities have pledged to achieve carbon neutrality. The urban water industry can also contribute its share to a carbon-neutral future. Using a multi-city time-series analysis approach, this study aims to assess the progress and lessons learned from the greenhouse gas (GHG) emissions management of urban water systems in four global cities: Amsterdam, Melbourne, New York City, and Tokyo. These cities are advanced in setting GHG emissions reduction targets and reporting GHG emissions in their water industries. All four cities have reduced the GHG emissions in their water industries, compared with those from more than a decade ago (i.e., the latest three-year moving averages are 13%–32% lower), although the emissions have "rebounded" multiple times over the years. The emissions reductions were mainly due to various engineering opportunities such as solar and mini-hydro power generation, biogas valorization, sludge digestion and incineration optimization, and aeration system optimization. These cities have recognized the many challenges in reaching carbon-neutrality goals, which include fluctuating water demand and rainfall, more carbon-intensive flood-prevention and water-supply strategies, meeting new air and water quality standards, and revising GHG emissions accounting methods. This study has also shown that it is difficult for the water industry to achieve carbon neutrality on its own. A collaborative approach with other sectors is needed when aiming toward the city's carbon-neutrality goal. Such an approach involves expanding the usual system boundary of the water industry to externally tap into both engineering and non-engineering opportunities.

1. Introduction

Cities have been recognized as central in fast-tracking and transformative action for global climate change mitigation [1], and many cities have pledged to achieve carbon neutrality [2]. The urban water industry can contribute its share to a carbon-neutral future by, for example, improving its energy efficiency, reducing direct emissions from wastewater treatment, improving water end-use efficiency, and recovering energy and nutrients [3,4]. Of the greenhouse gas (GHG) emissions from urban water systems, a significant portion is associated with energy use [5]. A large body of literature has assessed these energy-related GHG emissions [6]. In the water industry, improving energy efficiency is often one of the easiest ways to reduce GHG emissions [7]; moreover, there has been an increasing adoption of renewable energy sources [8,9] and anaerobic digestion of sewage sludge [10,11]. Many studies have evaluated the potential of achieving energy-neutral (or even energy-exporting) municipal wastewater treatment [12–15]. Energy-neutral operation can avoid energy-related GHG emissions, while energy-exporting operation can offset direct GHG emissions from wastewater treatment.

In addition to the energy-related Scope 2 GHG emissions (which mostly involve purchased electricity), Scope 1 direct GHG emissions (e.g., fuel combustion, nitrous oxide (N_2O) emissions, and methane emissions) are of concern for wastewater treatment [16,17]. A great deal of technical research has been conducted to understand the mechanism of N_2O emissions [18,19], to measure and model N_2O in full-scale treatment plants [20,21], and to develop control strategies for reducing N_2O emissions [22]. A body of literature has also assessed Scope 3 indirect GHG emissions (e.g., chemical and material supply), typically using life cycle assessment and carbon footprint analysis of urban water infrastructure

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[23–25]. Beyond emissions from urban water infrastructure, few studies advocate for a broader system boundary that encompasses water-related GHG emissions management in water end use [26,27].

Although a great deal of research on water-related GHG management (i.e., energy use, direct emissions, and Scope 3 emissions accounting) has been conducted, city-scale analyses for understanding the system-wide management of water-related GHGs remain limited. Furthermore, most city-scale studies on the GHG emissions of urban water systems are conducted for a single city or a snapshot of a year (e.g., Wu et al. [23], and Zhou et al. [28]). Few studies have taken a multi-city analysis approach or a time-series analysis approach to assess GHG emissions in urban water systems.

In this study, therefore, we draw on historical time-series GHG emissions inventory and information from multiple cities to gain insights into the GHG emissions management of urban water systems. A multi-city analysis can promote inter-city learning [29], support performance benchmarking [30], and offer insight into the impacts of geospatial characteristics [31]. Venkatesh et al. [31] evaluated the GHG emissions associated with the energy use of the urban water infrastructure in four cities: Nantes, Oslo, Turin, and Toronto. Mo et al. [32] quantified the GHG emissions impacts through 2030 of using different types of water supply sources in Tampa Bay and San Diego.

Time-series GHG emissions analysis is useful for identifying trends, patterns, and potential drivers [33,34]. Van der Hoek et al. [35] explained that energy savings, process optimizations, and the use of renewable energy led to the reduction of GHG emissions between 1990 and 2013 for the urban water system of Amsterdam. Zhang et al. [24] reported on the increased GHG emissions from water utilities in Chinese cities between 2006 and 2012.

This study aims to assess the progress and lessons learned from the GHG emissions management of urban water systems in four global cities: Amsterdam, New York City, Melbourne, and Tokyo. These cities were chosen because they have ① city-wide GHG emissions reduction targets, ② routine reporting on the GHG emissions of their water industries, and ③ time-series data beginning at least in the early 2000s. In this study, we do not aim to directly compare these four cities. Instead, our focus is on the development within each city's water industry.

2. Case study cities

2.1. Amsterdam

Amsterdam's climate goals include a 55% reduction in GHG emissions by 2030 and a 95% reduction in GHG emissions by 2050, compared with 1990 [36]. Waternet, the public water utility for Amsterdam and surroundings, is responsible for all water-related activities, including the drinking water supply, sewerage, wastewater treatment, surface water management, groundwater management, flood protection, and control of the canals in Amsterdam [35]. It serves approximately 1.2 million people and is owned by the City of Amsterdam and the Regional Water Authority Amstel, Gooi and Vecht.

2.2. New York City

New York City's target is carbon neutrality by 2050 [37]. The New York City Department of Environmental Protection manages the city's water supply, sewer, and wastewater treatment, serving approximately 8.5 million people. Water is supplied by reservoirs from a watershed, mostly by gravity. Unlike the other three cities, New York City's GHG emissions inventory for water supply and wastewater treatment is reported collectively with all other urban sectors (e.g., building, transportation, and solid waste) by the city government, instead of being reported by the water industry.

2.3. Melbourne

The state of Victoria, which has Melbourne as its state capital, has legislated a target of net-zero GHG emissions by 2050 in accordance with the Climate Change Act 2017 [38]. Melbourne Water is the state-owned utility for water supply catchments management, bulk water supply, and wastewater treatment in Melbourne. Water is distributed by three water retailers that serve approximately five million people. Melbourne Water has pledged to halve its emissions by 2025 and achieve net zero by 2030. The city of Melbourne has an interconnected system of reservoirs that supplies water mostly by gravity. An inter-basin water transfer pipeline and a seawater desalination plant were built in response to a decade-long drought in recent years [39]. Both have a high energy consumption when operating during dry years.

2.4. Tokyo

Tokyo's climate goals include a 30% reduction in GHG emissions by 2030, compared with 2000, and zero GHG emissions by 2050 [40]. The Tokyo Metropolitan Government Bureau of Waterworks supplies water to approximately 13.6 million people, while the Bureau of Sewerage manages sewer and wastewater treatment. The Bureau of Sewerage's target is a 30% reduction in GHG emissions by 2030, compared with 2020 [41].

3. Material and methods

3.1. Overview

Time-series annual GHG emissions data of the water industries in these four cities were first collected and compiled (included in the Appendix A). In the analysis, we first discuss the progress of these cities toward carbon-neutral urban water systems, with reference to the GHG emissions reduction opportunities each city has implemented. We then discuss the lessons learned from the GHG emissions management of urban water systems in these four cities, and how these insights are relevant to other cities across the world that are aiming toward carbon-neutral water systems.

3.2. Data collection and compilation

We collected time-series annual GHG emissions data for the water industries in Amsterdam, Melbourne, New York City, and Tokyo. Each city has a different time-series range. A breakdown of GHG emissions by scope was compiled, where available. We used the data (i.e., when examining historical changes) as they were reported historically, except for those for New York City. Most of the water industries in these cities have not recalculated the GHG emissions figures reported in earlier years, when the accounting methods for GHG emissions were revised. Table 1 gives an overview of the four cities, including their GHG emissions data.

The system boundary of each urban water system follows that of the local water industry. We consider only the GHG emissions associated with the water industries in these cities (i.e., those from operating the water infrastructure). While we recognize the significant water-related GHG emissions from water end use [27], we do not include this fraction of emissions in our study due to a lack of data and of robust methods to estimate these emissions.

The Greenhouse Gas Protocol Corporate Accounting and Reporting Standard defines three scopes of GHG emissions for an

Table 1
Overview of the four cities.

City	Years	Scope of emissions	GHG data sources[d]	Population served in 2019	Volume of water supplied in 2019	Volume of wastewater collected and treated in 2019
Amsterdam	1990, 2004, 2007–2020	Scopes 1, 2, and 3[a]	Internal data from Waternet	1.1 million	95 GL	125 GL
Melbourne	2001–2020	Scopes 1 and 2[b]	Annual reports from Melbourne Water	5.1 million	449 GL	347 GL
New York City	2006–2019	Scopes 1 and 2	New York City GHG Inventory from the City of New York	8.4 million	1638 GL	2158 GL
Tokyo	2000, 2008–2019	Scopes 1, 2, and 3[c]	Annual environmental reports from the Bureau of Waterworks, and Bureau of Sewerage, Tokyo Metropolitan Government	13.6 million	1543 GL	1710 GL

[a] For Amsterdam, Scope 3 emissions include residual materials transport and processing, chemicals production and transport, building materials and piping materials, sludge transport, and business travel.
[b] For Melbourne, the data only include that of Melbourne Water, the bulk water supply and wastewater treatment utility. The GHG emissions from the three local water retailers are not included because of data gaps and relatively small emissions.
[c] For Tokyo, the inventory does not explicitly distinguish between Scope 1 and Scope 2 emissions for some of the activities.
[d] See Appendix A for the list of data sources.

organization [42]. Scope 1 emissions comprise direct GHG emissions from sources controlled by the organization. Scope 2 emissions refer to indirect GHG emissions associated with the organization's use of purchased electricity, steam, heat, and cooling. These emissions occur externally at utilities that generate and supply these energy commodities. Scope 3 emissions include all other indirect GHG emissions as a consequence of the activities of the organization. These emissions occur from sources not owned or controlled by the organization. For the urban water industry, for example, Scope 1 emissions include methane and nitrous oxide emissions at wastewater treatment facilities, Scope 2 emissions include process electricity use, and Scope 3 emissions include chemical use and building materials.

3.3. Multi-city analysis

In addition to compiling each city's GHG emissions inventory, we reviewed the GHG emissions management plans from the water industries in these cities. In particular, we reviewed the GHG emissions reduction opportunities (both engineering and non-engineering) that have been implemented or are planned to be implemented. In combination with the historical time-series GHG emissions trends, these form the basis for discussing ① the lessons learned from the water industries of these four cities on managing water-related GHG emissions, and ② how these insights are relevant to other cities around the world that are aiming toward carbon-neutral water systems.

4. Results and discussion

4.1. GHG emissions trend of the water industries in global cities

Fig. 1 shows the time-series GHG emissions trend of the water industries in the four global cities. All four cities show a reduction in the GHG emissions of their water industry compared with their first reported years, although the emissions appear to "rebound" multiple times over the years (mainly due to revised accounting methods or actual increased electricity use). The latest three-year moving averages are as follows: a 32% reduction for Amsterdam, 17% for Melbourne, 18% for New York City, and 13% for Tokyo. The difference in the magnitude of GHG emissions across these four cities is mainly due to differences in population size, water supply mix, and the scope of GHG emissions being accounted for. There are large variations in GHG emissions in Amsterdam, Melbourne, and New York City over the years.

Amsterdam (2016), Melbourne (2016), and Tokyo (2015) have a step increase in one year of their time-series. For Amsterdam, this was mainly due to a change in the method for estimating direct emissions from sewer and wastewater treatment plants (WWTPs) (i.e., Scope 1 emissions). For Melbourne, the National Greenhouse and Energy Reporting (NGER) system in Australia changed the guidelines for estimating emissions from wastewater treatment (i.e., Scope 1 emissions). For Tokyo, it was due to an increase in the GHG emissions factor of grid electricity (as a result of the reduced use of nuclear power), which is not being updated every year (i.e., Scope 2 emissions). In the cases of Amsterdam and Melbourne, even with the revised GHG emissions accounting method, the cities did not recalculate their historical values.

Offsets are important instruments to reduce net GHG emissions. In this context, an offset is a reduction of GHG emissions achieved elsewhere (outside the three scopes of emissions by the water industry) to compensate for the emissions of the water industry. Different types of offsets were accounted for in three of the cities, such as upgraded biogas exporting (Amsterdam), exporting heat from sludge incineration (Amsterdam), purchase of Renewable Energy Certificates/Greenhouse Gas Abatement Certificates (Melbourne), and catchment forest management (Tokyo).

In Amsterdam, the increased Scope 1 emissions were driven by an underestimation of direct emissions from sewer and wastewater treatment plants (CH_4 and N_2O) in earlier years. Scope 2 emissions have been minimized in recent years by sourcing electricity generated from renewable sources (i.e., directly included in Scope 2 emissions, instead of showing as an offset). Scope 3 emissions include residual materials transport and processing, chemicals production and transport, building materials and piping materials, sludge transport, and business travel. In terms of the contributions from individual system components, sewer and wastewater treatment respectively contributed 4% and 93% of the total Scope 1 emissions in 2020, while wastewater treatment contributed 100% of the total Scope 2 emissions. The major offset opportunities include heat export from waste sludge incineration, electricity export from solar energy generation, energy export from biogas generation, and the use of recovered materials (e.g., calcite, struvite, and reed) from water systems.

For Melbourne, the breakdown of the time-series GHG inventory is presented by system component. In 2020, Scopes 1 and 2 emissions respectively accounted for 48.9% and 51.1% of the total emissions, while Scope 3 emissions were not included [43]. The energy use (and associated GHG emissions) of the water supply depends on the mix of water sources used, as the mix of gravity-fed surface water, desalinated water, and inter-basin transferred

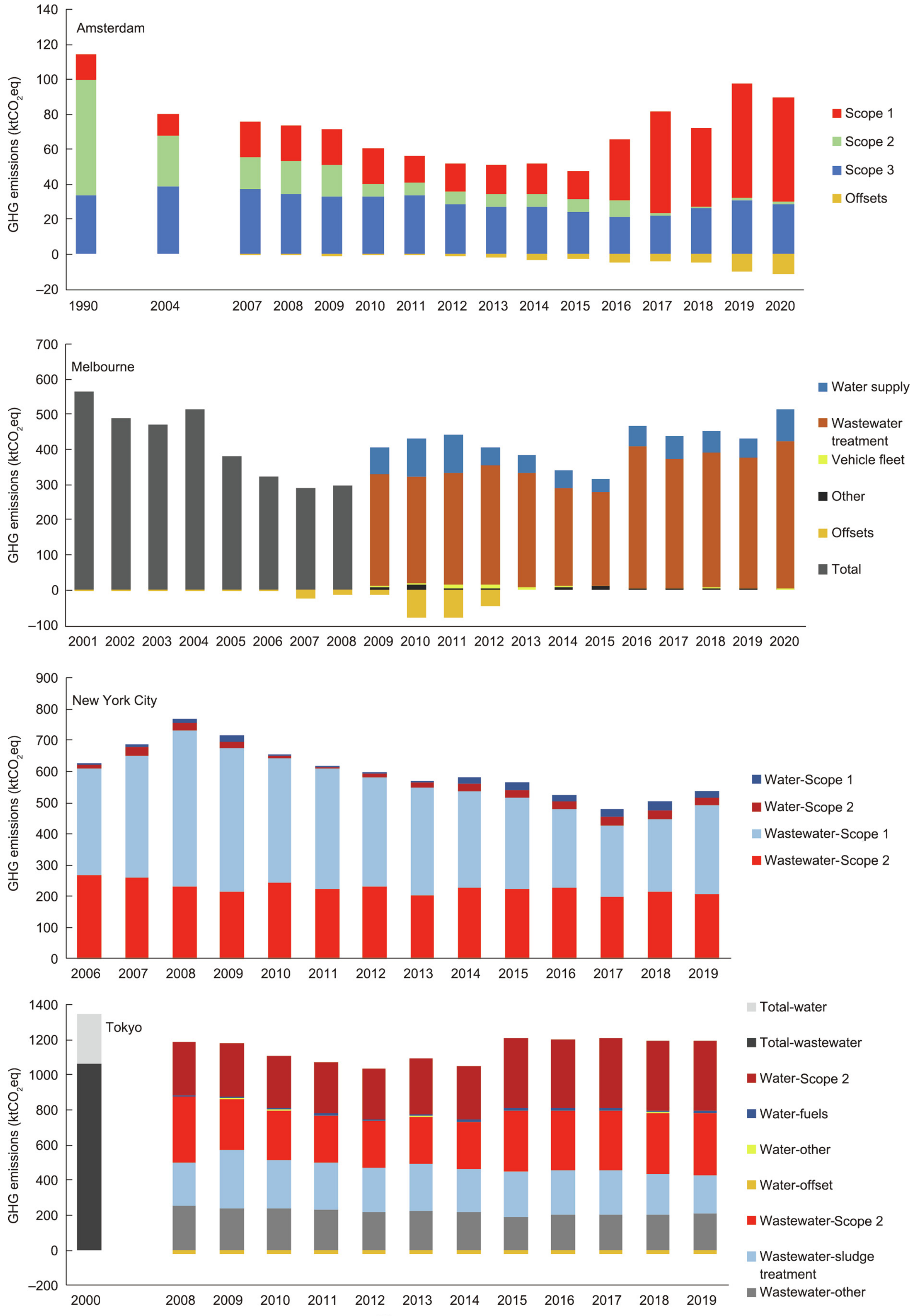

Fig. 1. Annual GHG emissions (broken down by scope and component) of the respective water industries in Amsterdam, Melbourne, New York City, and Tokyo. $ktCO_2eq$: 1000 tonnes CO_2 equivalent.

water varies considerably between wet and dry years [39]. In addition, the GHG emissions of wastewater treatment depend on the annual rainfall because of significant stormwater infiltration (i.e., more rainfall in 2020 than in 2019). Moreover, carbon offsets have not been purchased since 2013, which could be related to the carbon pricing scheme in Australia being scrapped.

In New York City, there has been a long-term reduction of GHG emissions, especially from wastewater treatment facilities. The lower carbon intensity of grid electricity (i.e., a shift from coal to natural gas for electricity generation and the building of new, more efficient gas power plants) has contributed to this reduction, as has the reduction of fugitive and process emissions of nitrous oxide and methane from wastewater treatment [44]. Between 2008 and 2019, nitrous oxide and methane emissions decreased by 13% and 58%, respectively [37]. Similar to Melbourne, the gravity-fed water supply system in New York City is characterized by low Scope 2 emissions.

In Tokyo, no reduction in GHG emissions can be seen between the first year and the last year of the time-series, although the relative contributions of different emission scopes have changed. Scope 2 emissions from electricity consumption have remained the main contributor. The positive impact of energy efficiency improvement has been cancelled out by the increased emissions intensity of grid electricity [45].

4.2. Insights from global cities

4.2.1. Role of engineering opportunities

All four cities have implemented or planned to implement engineering opportunities to different extents in order to reduce the GHG emissions of their water systems. Here, "engineering opportunities" are opportunities that involve physical or operational changes to the water systems. These opportunities can be categorized as energy conservation, renewable energy generation, heat recovery, process optimization to reduce direct emissions, and fugitive emissions reduction. Local circumstances (e.g., climate for cold recovery to provide cooling in Amsterdam and a gravity-fed system for mini-hydropower in Melbourne) influence the opportunities each city has implemented.

In Amsterdam, the water industry has aimed for a 50 000 tonnes CO_2 equivalent (tCO_2eq) GHG emissions reduction target through a portfolio of engineering and non-engineering opportunities (Fig. 2). Engineering opportunities include, for example, the optimization of sludge digestion at the wastewater treatment plant (WWTP) Amsterdam West, the installation of solar panels, more energy-efficient pumps in WWTPs and wastewater pumping stations, and exporting upgraded biogas. Collectively, these engineering opportunities contribute the majority of reductions toward the total reduction target.

In Melbourne, biogas capture from the wastewater treatment process for electricity generation has been able to meet electricity needs for its two main WWTPs 80% of the Western Treatment Plant and 30% of the Eastern Treatment Plant [46]. Melbourne's gravity-fed water supply system also enables a high uptake of mini-hydropower generation [47].

In New York City, the management of fugitive methane and nitrous oxide emissions contributed to a net reduction in GHG emissions for wastewater treatment [44] (Fig. 3). A decomposition of the drivers behind the net reduction between 2006 and 2015 reveals that the efficiency of grid electricity generation (i.e., an external factor) actually made the greatest contribution to emission reduction, by switching the fuel source for electricity generation from coal to natural gas and by the construction of higher efficiency natural gas power plants. These findings illustrate that the water industry does not have full control over its Scope 2 emissions, unless the electricity grid enables "green power" purchase or the water industry generates its own electricity.

In Tokyo, engineering opportunities for reducing GHG emissions for water supply and wastewater treatment include: upgrading sludge incineration to reduce nitrous oxide emissions; renewable energy generation (i.e., mini-hydropower and solar

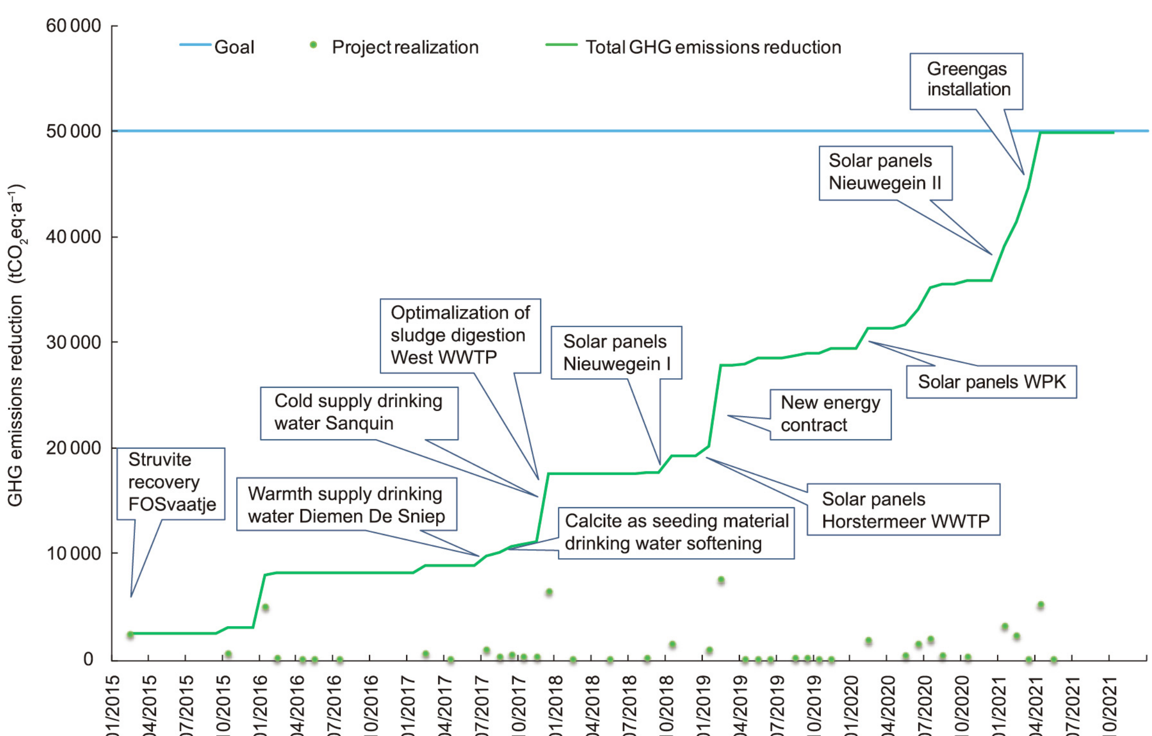

Fig 2. A portfolio of opportunities toward a 50 000 tCO_2eq GHG reduction target in Amsterdam. WWTP: wastewater treatment plants; WPK: Weesperkarspel.

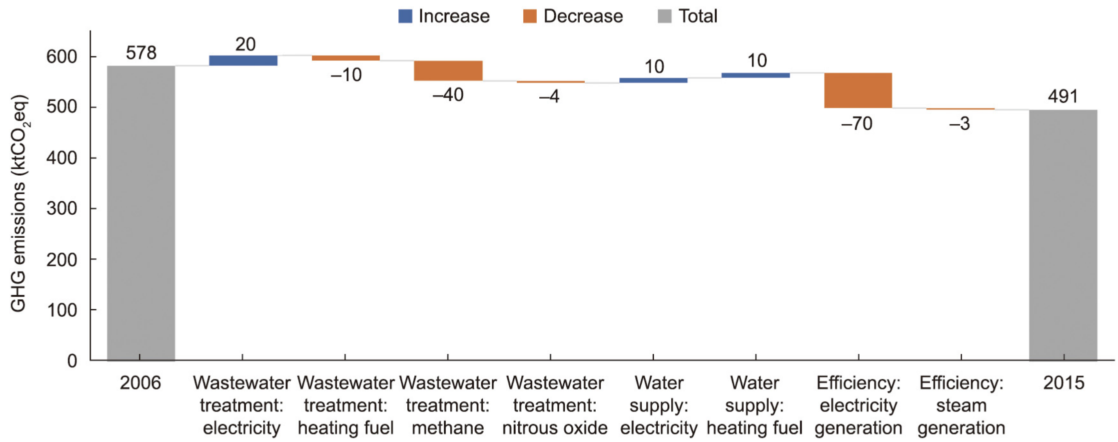

Fig. 3. Drivers of changes in wastewater treatment GHG emissions in New York City between 2006 and 2015 [44].

photovoltaic); the installation of energy-efficient diffusers, pumps, and sludge dehydrators; waste heat utilization; aeration system optimization; and sludge carbonization [40,41,48].

While many engineering opportunities are available, the water industry needs to select those that are cost effective [49] in order to minimize the impact on water customer bills [50]. However, the water industry is unlikely to have sufficient cost-effective engineering opportunities within its jurisdiction to achieve carbon neutrality. Supporting Scope 3 engineering opportunities to generate offset credits (e.g., thermal energy recovery and supply, water-efficient devices, and the co-digestion of sludge and food waste for biogas valorization) can be a viable pathway toward carbon-neutral urban water systems. Although it may be easier to quantify the credits for generating and exporting excess renewable energy from the water industry to the electricity or gas grid, it is challenging to credit some other opportunities (e.g., electrifying hot water systems and installing water-efficient devices).

4.2.2. Expanding the system boundary for GHG emissions reduction opportunities

An important issue is where the water industry should draw the system boundary for managing water-related GHG emissions. Some types of water-related GHG emissions, such as reservoir methane emissions [51], surface water/peatland emissions [52], and water end-use emissions [5], can be more significant than emissions from the assets of the water industry. Although the water industry mostly does not have the statutory responsibility for managing these types of water-related GHG emissions, it is the entity with the most influence on and knowledge of managing these types of emissions. Thus, the water industry is the most suitable entity to play the role of filling these gaps in water-related GHG emissions management.

The analysis of these four cities shows that, when the water industry expands its system boundary beyond water supply and wastewater treatment service providers, many "external" engineering opportunities can favorably contribute to a city's carbon-neutrality goal. For example, Amsterdam has demonstrated that cold recovery from drinking water can provide cooling capacity at a blood bank, which can then reduce the blood bank's energy use and associated GHG emissions [53]. New York City has been exploring water end-use opportunities, such as low-flow water fixtures, utility-controllable electric hot water heaters for reducing peak demand, and electrified domestic hot water systems [37]. These opportunities would require mechanisms to generate offsets credit [54].

To expand the system boundary, it is necessary to embrace a systems approach for water-related GHG emissions management. Many engineering opportunities have wider systemic impacts. Therefore, it is preferable to assess opportunities based on their life-cycle impacts in order to avoid unintended GHG emissions consequences and better value these opportunities. For example, centralized softening of drinking water can reduce the GHG emissions of the water end user [55].

4.2.3. GHG emissions accounting

Revising the GHG emissions accounting method or the estimated GHG emissions reduction potential of opportunities (as new knowledge develops) can pose a challenge to achieving carbon neutrality within the originally planned timeframe. The reference baseline or business-as-usual baseline essentially "moves" when GHG emissions accounting methods are revised. This has been the case for Amsterdam, New York City, and Melbourne, particularly in quantifying Scope 1 direct emissions from sewer and wastewater treatment.

Another important issue concerning GHG emissions accounting is whether the water industry should account for Scope 3 emissions or not (also see the discussion in Section 4.2.2). In the GHG protocol, Scope 3 emissions are "optional." If every organization were able to achieve zero emissions for Scopes 1 and 2, then Scope 3 emissions would also be neutral. Nevertheless, including Scope 3 emissions does help the water industry to reduce its emissions more effectively by tapping into "external" opportunities (as discussed in Section 4.2.2); it also stimulates other organizations to reduce emissions.

4.2.4. A collaborative approach toward carbon-neutral cities

It is difficult for the urban water industry to achieve carbon neutrality on its own. To reach the city's carbon-neutrality goal at the scale and pace that climate science demands, the water industry must collaborate with other sectors, such as the energy sector [56], agricultural sector [52], and food processing sector [47]. In the case of Amsterdam, the city's water industry has partnered with business sectors, who are the "end users" of recovered resources; for example, it provides cooling capacity (from drinking water) to a blood bank [53] and sells recovered raw materials (from drinking water and wastewater) and their derived products [57]. This collaborative approach has contributed more than half of the GHG emissions reductions made toward meeting the reduction target of the water industry (Fig. 2). In the case of New York City, the city's water industry has partnered with National Grid (an investor-owned electricity and gas utility company) to produce pipeline-quality biomethane from the anaerobic digestion of sewage sludge and food wastes diverted from landfills [37]. This partnership enables the city to grant National Grid a concession license to clean and sell biomethane as a regulated natural gas utility [56].

4.3. Implications for water-related GHG emissions management globally

The water industries in all four cities and beyond have recognized the many challenges in reaching carbon-neutrality goals. These challenges include fluctuating water demand and rainfall [40,43], the need to implement more carbon-intensive flood-prevention strategies [41], the need to utilize more energy-intensive water supply sources during dry years [58], meeting new air and water quality standards [44], regulatory barriers for implementing distributed energy sources [56], and revising GHG emissions accounting methods (Section 4.2.3). Other cities will also need to overcome some of these challenges on their pathways toward carbon-neutral water systems.

Cities around the world can build up their capacity to manage water-related GHG emissions. First, it is essential for any city to quantify a reference or business-as-usual baseline of water-related GHG emissions. A robust baseline is needed in order for carbon neutrality to have a real target. Second, countries can establish national accounting, benchmarking, and reporting systems that enable annual reporting of GHG emissions by the water industry, such as the National Performance Report in Australia [59]. Intra-annual data can be particularly informative and actionable [60]. Third, official up-to-date emission factors for local grid electricity must be provided to the water industry (and to any other urban sectors) to allow them to accurately track their Scope 2 emissions, which are significant in all four cities and beyond. Fourth, the significance of Scope 2 emissions implies that the water industry must invest in renewable energy sources or purchase Renewable Energy Certificates in order to reduce its Scope 2 emissions more proactively, considering the likely slow decarbonization progress of the whole electric system. Fifth, a collaborative approach (Section 4.2.4) is needed to identify more optimized opportunities for each city as a whole, rather than only for its water industry.

Many local contexts can influence an urban water system's pathway toward carbon neutrality. For example, biogas recovery from the anaerobic digestion of sewage sludge or co-digestion with organic feedstock is a significant engineering opportunity, but its success is dependent on many local factors. The economic feasibility of utilizing biogas is generally limited by the size of WWTPs [47]. In European countries, banning organic waste in landfills has been perceived as an important influencing policy to develop a biogas market [9]. In China, low organic content in waste sewage sludge makes anaerobic digestion for biogas valorization unfavorable [61].

Another example of local context concerns the decentralized components of urban water systems. In Australia, household rainwater tanks have gained popularity through the Millennium Drought. The water supplied by these tanks can be more energy intensive than centralized water sources, yet this energy use and related GHG emissions are not accounted for by the water industry [62]. In China, booster pumps are commonly used for the water supply in high-rise buildings [63] and could be responsible for a large portion of the energy used for the urban water supply. In Tokyo, the water industry promotes "direct water supply" for high-rise buildings, in which drinking water is supplied to residents directly from water distribution networks (booster pumps may be needed) instead of from rooftop tanks (which are being phased out) [40].

As shown in the progress of the four cities analyzed here, engineering opportunities alone (especially when limited to within the water industry) are unlikely to effectively guide urban water systems toward carbon neutrality. Non-engineering opportunities can be as important as engineering ones, and these cities have explored many non-engineering opportunities. In Amsterdam, the water industry used a CO_2 shadow price to assess GHG emissions reduction opportunities, in line with the price of the municipality of Amsterdam [64]. In Melbourne, it has been shown that water demand-side management can provide GHG emissions reduction potential [39,65]. This approach better values all GHG emissions reduction opportunities.

5. Conclusions

We conducted a time-series analysis of the GHG emissions management of urban water systems in four global cities: Amsterdam, Melbourne, New York City, and Tokyo. These cities are relatively advanced in setting GHG emissions reduction targets. This city-scale analysis can complement existing research on the energy and GHG management of specific water and wastewater infrastructure. The key insights of our analysis are as follows:

- All four cities have reduced the GHG emissions in their water industry, compared with more than a decade ago, and their latest three-year moving averages are 13%–32% lower. The emissions appear to "rebound" multiple times over the years due to revised accounting methods or actual increased electricity use.
- The majority of the GHG emissions reduction in the four cities was contributed by various engineering opportunities such as solar and mini-hydropower generation, biogas valorization, sludge digestion and incineration optimization, and aeration system optimization.
- The four cities have recognized the many challenges in reaching carbon-neutrality goals, which include fluctuating water demand and rainfall, more carbon-intensive flood-prevention and water-supply strategies, meeting new air and water quality standards, and revising GHG emissions accounting methods.
- Cities around the world can build up their capacity to manage water-related GHG emissions by, for example, quantifying a business-as-usual baseline of water-related GHG emissions in order to set a reduction target and establishing national accounting, benchmarking, and reporting systems to enable annual reporting of GHG emissions by the water industry.
- It is difficult for the urban water industry to achieve carbon neutrality on its own with engineering opportunities that are limited to its system boundary. The industry must collaborate with other sectors to tap into external engineering and non-engineering opportunities.
- Future research can ① review the GHG emissions accounting frameworks used in the water industries around the world, ② develop an inventory of engineering and non-engineering GHG emissions reduction opportunities for the water industry, and ③ investigate how to establish an enabling environment for the water industry to support the management of "unaccounted-for" water-related emissions such as reservoir methane emissions, surface water/peatland emissions, and water end-use emissions.

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Compliance with ethics guidelines

Ka Leung Lam, Gang Liu, Anne Marieke Motelica-Wagenaar, and Jan Peter van der Hoek declare that they have no conflicts of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2022.04.012.

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