LETTER

Reduction in urban water use leads to less wastewater and fewer emissions: analysis of three representative U.S. cities

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Keywords: greenhouse gas emissions, energy from digester biogas, wastewater treatment, urban water use

Supplementary material for this article is available online

Abstract
Electricity consumption and greenhouse gas (GHG) emissions associated with wastewater flows from residential and commercial water use in three major cities of the United States are analyzed and compared for the period 2010–2018. Contributions of unit wastewater treatment processes and electricity sources to the overall emissions are considered. Tucson (Arizona), Denver (Colorado), and Washington, DC were chosen for their distinct locations, climatic conditions, raw water sources, wastewater treatment technologies, and electric power mixes. Denver experienced a 20% reduction in treated wastewater volumes per person despite a 16% increase in population. In Washington, DC, the reduction was 19%, corresponding to a 16% increase in population, and in Tucson 14% despite a population growth of 3%. The electricity intensity per volume of treated wastewater was higher in Tucson (0.8 kWh m$^{-3}$) than in Washington, DC (0.7 kWh m$^{-3}$) or Denver (0.5 kWh m$^{-3}$). Tucson's GHG emissions per person were about six times higher compared to Denver and four times higher compared to Washington, DC. Wastewater treatment facilities in Denver and Washington, DC generated a quarter to third of their electricity needs from onsite biogas and lowered their GHG emissions by offsetting purchases from the grid, including coal-generated electricity. The higher GHG emission intensity in Tucson is a reflection of coal majority in the electricity mix in the period, gradually replaced with natural gas, solar, and biogas. In 2018, the GHG reduction was 20% when the share of solar electricity increased to 14% from zero in 2016. In the analysis period, reduced wastewater volumes relative to the 2010 baseline saved Denver 44 000 MWh, Washington, DC 11 000 MWh and Tucson 7000 MWh of electricity. As a result, Washington, DC managed to forgo 21 000 metric tons of CO$_2$-eq and Denver 34 000 metric tons, while Tucson's cumulative emissions increased by 22 000 metric tons of CO$_2$-eq. This study highlights the variability observed in water systems and the opportunities that exist with water savings to allow for wastewater generation reduction, recovering energy from onsite biogas, and using energy-efficient wastewater treatment technologies.

1. Introduction

The water sector is responsible for about 4% of global electricity consumption. About 40% goes to water withdrawal, 25% to wastewater treatment (WWT), and 20% to water distribution [1]. By 2030, the International Energy Agency [2] anticipates a 50% increase in the amount of energy consumed by the water sector due to increased reliance on desalination, large-scale water transfer via pumping, and increased collection of wastewater.

In addition to increased wastewater generation, evolving effluent quality standards contribute to the WWT sector's increasing share of energy consumption and greenhouse gas (GHG) emissions. GHG emissions from wastewater treatment plants (WWTP) are mainly comprised of methane (CH$_4$), carbon dioxide (CO$_2$) and nitrous oxide (N$_2$O), which account for 3% of the global carbon dioxide equivalent (CO$_2$-eq) emissions [3]. Apart from the contribution of GHG emissions from energy use, 98% of the total methane from the WWTPs is emitted
directly from the anaerobic digestion stage of the WWT processes [4]. Process-related N₂O emissions are responsible for about 26% of the total GHGs emitted from the water sector [5].

The United States consumes more electricity in the water sector than any other country or region in the world, though the much more populous China is not far behind [1]. The U.S. water-related energy is estimated to account for about 4% of the nation’s electricity use, roughly 40% of which goes to wastewater treatment [6].

On the other hand, U.S. per-capita water use has been declining on the national level since the 1980s, mostly due to efficiency improvements [7], but local and regional trends may vary. We have validated this decreasing trend in three major U.S. cities, Denver, Colorado, Tucson, Arizona, and Washington, DC for the years 2011–2016 [8], and have found that savings in water use reduced energy consumption and GHG emissions, but to varying degrees in the different cities.

Reduced potable water consumption often results in reduced wastewater flows (but does not have to as, for example, reduced irrigation may not have wastewater implications), which could save energy and emissions. Therefore, it is essential to understand the combined system-wide impacts of urban water and wastewater flows to help identify potential areas for energy savings and GHG and other emissions reductions. A life-cycle assessment (LCA) approach can evaluate the entire urban system comprehensively, taking into account a range of conditions for water and wastewater treatment processes [9–12].

The environmental impacts of urban water and wastewater systems have been analyzed in various geographic regions: Sydney (Australia) [13], the Walloon Region (Belgium) [14], Aveiro (Portugal) [15], Durban (South Africa) [16], Tarragona (Spain) [17], Trondheim (Norway) [18], and various regions and cities in California and the United States [19–22]. A study [23] assessed not only environmental, but also some social impacts of the water system in Mexico City. Of these studies, some analyzed the system-wide and complementary energy and emissions impacts of urban water and wastewater systems, such as [13, 15, 18, 24]. Two recent U.S. studies analyzed urban water systems in the Greater Cincinnati region [24] and in Atlanta [25], and described what parts of the system contributed the most to each environmental impact category.

However, most of the literature has analyzed the water system separately from wastewater or focused on one or a few components of the urban water system [12, 26–32]. At a smaller scale, several studies have estimated the energy and carbon footprint of a limited segment of the WWT system on the basis of the studies’ objectives of cost, technology, and effluent quality [33–36]. A few other articles have compared not only the energy implications but also the environmental impacts, such as global warming potential (GWP), eutrophication potential, acidification potential, human toxicity of conventional and advanced WWT processes in different regional settings [36–39]. Most of the studies had applied simulation models to estimate WWT energy use instead of using actual plant data. One study [40] predicted electricity demand using a statistical model that accounts for economies of scale. Beneficial consequences of energy recovery from anaerobic digestion processes have also been studied using LCA of biosolids management technologies [41–45].

Our study compares energy demand of and GHG emissions from wastewater systems linked to urban water consumption over multiple years (2010–2018) in several large and representative U.S. cities (Tucson, Denver, and Washington, DC) with varying climatic and hydrologic characteristics that use different raw water sources (groundwater, large multistate river water, regional river water, and snow melt). We used actual water consumption and population data in addition to actual operational electricity and treatment technology information obtained from WWTPs in the three cities. This study is particularly different from other urban water analyses in three major ways. First, it calculated and compared electricity and GHG implications of WWT technologies at process level over multiple years, taking into consideration population growth (or decline) and technological changes, including the closure and opening of new WWTPs within the service area. Second, it evaluated the impact of a population’s water consumption habits over multiple years on wastewater flows and assessed the associated electricity demand and GHG emissions of WWTPs. Using water consumption data, the forgone wastewater (the amount of wastewater not generated relative to an earlier baseline) and corresponding forgone electricity and GHG emissions were calculated. Third, the GHG footprint of grid electricity purchased by the WWTPs was contrasted to the onsite electricity generation utilizing biogas. To calculate avoided GHG emissions from onsite electricity generation from biogas, an approach on the basis of GHG mass-balance variations was used. This approach consists of a series of equations based on the net emissions of biogas released in the ecosphere, which is the difference between CO₂ generated and CH₄ combusted.

Urban water consumption trends, their consequences on variations of wastewater volume treated, and associated electricity use and GHG emissions were evaluated. We analyzed the contributions of unit treatment processes and technological advancements on the overall life-cycle energy impacts to address the limitations of existing studies. Representing a large country with varying precipitation patterns, population densities, sources of electricity mixes, water consumption trends, influent/effluent wastewater flow characteristics, regulations, and
numerous possibilities of treatment technologies with a limited sample size is very challenging. However, selecting these case study cities with distinctive geographical (West Coast, Rocky Mountains, East Coast), climatic, and technological conditions can be informative of U.S. WWT practices. Tucson, Denver, and Washington, DC use different raw water sources, WWT technologies, and electric power mixes relative to one another.

The main purpose of our study is to determine the extent to which the population’s water usage reductions lead to reductions in wastewater generation and associated energy use and GHG emissions in three representative U.S. cities. We wanted to provide a methodological approach to estimating the scale of the energy recovered from biogas from anaerobic digestion, and determine the extent to which WWTPs can offset grid-sourced electricity and related GHG emissions. This study highlights the significance of renewable sources in the electricity mix to achieving reductions in GHG emissions of WWT. Three case study cities present examples to other cities worldwide how to improve the energy and GHG performance of urban water systems.

2. Scope, methodology, and data sources

2.1. Scope of the study
Located in the semi-arid Southwest, Tucson has the lowest precipitation rate among the three cities. The Pima County Regional Wastewater Reclamation Department (RWRD) provides wastewater collection and treatment services to Tucson Water customers [46]. In 2018, the RWRD treated about 74 million cubic meters (Mm³) of wastewater from 0.74 million people within the service area [47]. In the same year, DC Water’s WWTP treated 401 Mm³ of wastewater from 2.5 million people in Washington, DC (0.70 million people) and Montgomery and Prince George’s counties in Maryland and Loudoun and Fairfax counties in Virginia (1.8 million people) [48, 49]. Also in 2018, Denver’s Metro Wastewater Reclamation Facilities (WRF) treated 186 Mm³ of wastewater from about 1.3 million people in Denver, and 0.5 million in Arvada, Aurora, Brighton, Lakewood, Thornton, and Westminster [50].

The boundary of the analyzed systems is depicted in figure 1. After wastewater from urban water users is transferred to a WWTP, it undergoes a series of treatment stages and the effluent is discharged into a water body. Biogas (mainly methane) is generated as a byproduct of anaerobic digestion onsite. Electricity use and GHG emissions are estimated for the operational steps necessary for the proper treatment of wastewater and biosolids as well as associated with buildings and other facilities. Life-cycle GHG emissions from fuels used as sources of electricity purchased from the electric power utilities are also estimated. The energy and GHG emissions from the production and transportation of treatment chemicals, plant construction and capital equipment manufacturing, company fleet vehicle fuel consumption, as well as life-cycle impacts from treatment and transportation of solid waste are excluded from the analysis due to lack of data. The distribution of recycled wastewater to the urban customers is also out of scope. Supplementary data section S.3.1 (available online at stacks.iop.org/ERL/15/084024/mmedia) describes major WWT processes within liquid and solids treatment systems, and section S.3.2 provides energy intensity of commonly used secondary treatment and biological nutrient removal (BNR) technologies.

Biogas (also known as anaerobic digester gas, ADG) can be captured and combusted through combined heat and power (CHP) recovery. In the United States today, there are over 14,000 municipal WWTPs, but only 1286 have anaerobic digesters that produce ADG [51], and of those only 184 (generally large WWTPs) currently utilize their biogas for CHP [52]. Around one-third of the facilities utilize their gas for electricity, while the remaining use their ADG to heat the digester tanks. WWTPs require a substantial amount of electric power, and anaerobic digesters need a constant heat source to maintain internal temperatures. Although CHP installations at U.S. WWTPs have been increasing in recent years, there is still a large unexploited capacity for the addition of CHP systems [51]. The avoided GHG emissions from digester biogas (mainly methane) captured during anaerobic digestion are estimated via emission factors and high heating values defined for biogas as a source of energy in the Code of Federal Regulations [53]. Supplementary data section S.5.3 discusses the dynamics of GHG emissions associated with the onsite electricity generation from biogas in figure 5.8. The methodology involves equations S.4 through S.8 to estimate the emission factor for the avoided GHG emissions.

All WWTPs in Tucson, Denver, and Washington, DC generate onsite electricity from ADG. The avoided grid-purchased electricity for WWTP operation is accounted for herein. Based on the U.S. Environmental Protection Agency’s Mandatory GHG Reporting Rule e-CFR Title 40 [53], when calculating the GHG emissions from biogas usage for electricity and heating needs, only CH₄ and N₂O emissions should be considered and CO₂ emissions from biogas are considered biogenic.

Supplementary data tables S.7 and S.8 in sections S.4.4 and S.5 provide further details about the treatment processes and technologies that are specific to each WWTP.

2.2. Methodology
The impacts of technological, demographic, and geographical changes with respect to electricity use and
GHG emissions from WWT are discussed in the following sections.

We conducted a systematic approach to determine the extent to which the population’s water usage reductions lead to drop in wastewater generation and associated energy consumption and GHG emissions. However, we only had data about how much total wastewater (including industry, services, households, and commercial operations) the WWTPs treated in each year of the study period, so the per-person wastewater generation had to be estimated.

Population and per-person water usage data for the water service areas are presented in figures S.1 and S.2 in supplementary data section S.1. A decreasing trend in water demand was observed over the period. (Unfortunately, the data we worked with did not come with an explanation why the drop in water consumption had occurred.)

Wastewater flow ($Q$, m$^3$/year) from water consumption data is calculated as:

$$Q = R \cdot D$$  \hspace{1cm} (1)

$R$ = ratio of wastewater collected to water demand (0.8 for Denver, 0.9 for Washington, DC, and 0.6 for Tucson, generally 0.5–0.9 in the United States; see supplementary data, section S.1.1)

$D$ = water consumption per year (m$^3$/year)

Thus, a customer in Tucson generated 90 m$^3$/person of wastewater in 2010 and 77 m$^3$/person in 2018, larger volumes than in Denver (66 and 53 m$^3$/person/year), and Washington, DC (59 and 48 m$^3$/person/year) (figure 2). Denver treated 20% less wastewater per person despite a 16% increase in population in the period. For Washington, DC, the reduction was 19%, with a 16% increase in population. For Tucson, the reduction of 14% came at a population growth rate of 3%.

Electricity use attributed to wastewater treatment depends on the population’s water consumption and WWT processes. From 2010 to 2018, Tucson was the most electricity intensive (figure 3), with a peak reaching about 1 kWh m$^{-3}$ due to technological changes at the WWTP that required more electricity and a capacity increase to treat more wastewater from increased water consumption. Washington, DC observed the highest electricity intensity of 0.7 kWh m$^{-3}$, while Denver’s was steadily lower (0.5 kWh m$^{-3}$) despite the utilization of energy-intensive nitrification and denitrification processes. Electricity use in Denver and Tucson was calculated using the treatment technology descriptions obtained from WWTPs and energy...
intensity-by-technology data (supplementary data figure S.6) that were compiled from literature analysis (section S.3.2). For Washington, DC, we obtained the data directly from DC Water [48]. Biogas from anaerobic digesters was used to generate electricity onsite, thus forgoing purchases from the grid. Tucson’s biogas-derived electricity served only 5% of the WWTP’s electricity needs in 2018, while for Washington, DC and Denver the numbers were 24% and 33%, respectively. The addition of a new WRF in Tucson in 2014, after the retirement of an older one, caused the energy intensity to further increase. The new facility utilizes an energy-intensive modified 5-stage Bardenpho process, while the older facility was using conventional activated sludge [47]. Moreover, following the retirement of the facility which had CHP, biogas utilization was postponed until 2017.

Figure 4 breaks down the electricity intensities of WWTPs by process step in 2018. For all three cities, electricity consumption by biological nutrient removal (BNR) treatment was the highest, followed by secondary treatment and biosolids treatment. BNR treatment removes total nitrogen and total phosphorus from wastewater through the use of chemicals and microorganisms [54].

Tucson needed the most electricity per person to treat wastewater (supplementary data figure S.7). In 2018, it was almost three times higher compared to the other two cities.

Electricity consumption of WWTPs in Denver, Tucson, and Washington, DC is disaggregated by electricity mixes in figure 5. The percentage of coal decreased in the period by 33% in Denver, 40% in Washington, DC, and 30% in Tucson. The share of natural gas increased by 31% in Denver, 150% in Washington, DC, and 170% in Tucson. The share of renewables (solar, wind, and onsite biogas) also increased, especially in the last two years, but was still modest, except in Denver.

Forgone wastewater reflects the amount of wastewater not produced each year due to the population’s water reduction. Wastewater is estimated on the basis of forgone water, which is defined as the amount of water saved each year due to the average per-person water consumption reduction. Equations S.1, S.2, and S.3 in the supplementary data section S.5.2 calculate the forgone wastewater, electricity, and GHG emissions.

The life-cycle inventory of GHG emissions includes the emissions from electricity purchased from electric power companies and electricity generated from biogas onsite (figure 1). The electricity providers are Tucson Electric Power Co., Xcel Energy in Denver, and Pepco Inc. in Washington, DC. The energy sources for the electricity mixes are provided by Tucson Electric Power Co. and Xcel annually and by Pepco every other year. The electricity fuel mix details for each provider are presented in the supplementary data section S.2.1, figures S.3 to S.5.

The required data for estimating the life-cycle GHG emissions of electricity generated from fossil fuels were sourced from the Emissions and Generation Resource Integrated Database (eGRID) reports for the period years (supplementary data section S.2.2). Data, shown in table S.2, from a California Energy Commission report [55] were used for the fuel life-cycle stages upstream of the power plants. Electricity emission factors are presented in supplementary data, section 2.2, in table S.3 for Denver, table S.4 for Tucson, and table S.5 for Washington, DC.

The avoided GHG emissions from digester biogas (mainly methane) captured during anaerobic digestion are estimated via emission factors and high heating values defined for biogas as a source of energy in the Code of Federal Regulations [53]. Supplementary
data section S.5.3 discusses the dynamics of GHG emissions associated with the onsite electricity generation from biogas in figure S.8. The methodology involves equations S.4 through S.8 to estimate the emission factor for the avoided GHG emissions.

3. Electricity use and GHG emissions results

The WWT trends in Denver, Tucson, and Washington, DC are shown in figure 6 along with bars of forgone wastewater volumes. The annual volume of treated wastewater (markers) shows fluctuations since 2010, but indicates an overall declining trend. Denver had forgone the largest volume. As the average per-person wastewater generation volume had been declining, the impacts from population growth in all three cities from 2010 to 2018 had been offset.

Figure 7 shows the electricity consumption (markers) and the forgone electricity (bars), calculated using equation S.2 from supplementary data section S.5.2. (figure S.9 in section S.5.4 magnifies the
Forgone bar chart in figure 7 with more precision.) Tucson’s forgone electricity was negative in 2014 because the technological changes at the WWTPs were energy intensive: Due to the closure of the CHP facility in a retired plant and a capacity increase at the current WWTP, the electricity consumption increased by 12% in parallel with the increase in volume of wastewater treated. Although the newly opened facility in Tucson has higher electricity intensity (0.8 kWh m$^{-3}$) compared to the retired facility (0.7 kWh m$^{-3}$), total electricity consumed by these two facilities remained at almost the same levels. The new facility uses energy-intensive BNR technology to meet effluent requirements. The reason for Tucson’s forgone electricity to turn positive in 2015 was a 6% decrease in wastewater volume. Therefore, the capacity increase at WWTPs as well as the energy-consuming technological upgrades were mainly responsible for the diminishing forgone electricity despite the increased volume of the wastewater saved.

**Figure 5.** Electricity consumption of WWTPs in Denver, Tucson, and Washington, DC disaggregated by source of electricity (ADG: anaerobic digester gas).

**Figure 6.** Annual volume of wastewater treated (markers) and forgone wastewater (bars) with respect to base year 2010.
in 2014 with respect to 2010. Similarly, with increasing water consumption in 2012, Denver experienced a larger demand for electricity, but over the course of the subsequent years variations in forgone electricity were smaller compared to the other two cities. Denver had forgone the largest amount of electricity in the period (7 and 4 times larger compared to Tucson and Washington, DC, respectively). Washington, DC experienced a drop in electricity use in 2016 following a reduction in the volume of wastewater treated.

Annual GHG emissions per person from electricity use at the WWTPs are presented in figure 8. In 2018, Tucson’s were about 6 times higher than Denver’s and 4 times higher than Washington, DC’s. The higher GHG emission intensity is a reflection of more wastewater treated per person and higher percentages of coal in the electricity mix. Tucson’s electricity mix was comprised mainly of coal, while Denver’s and Washington, DC’s had more natural gas, renewables, and ADG. A general downward trend is observed between the beginning and the end of the period.

Figure 9 provides details about GHG emissions by electricity source. Denver’s grid mix composition also changed from 2010 to 2018. Coal was replaced with natural gas, but this change was not reflected much in the forgone emissions as the WWT facility in Denver was already using biogas to provide about a third of the facility’s electricity requirements. In 2018, electricity generation from biogas avoided grid-electricity purchases as well as around 19 000 mt CO$_2$-eq per year compared to a scenario when biogas would escape into the atmosphere.

In Washington, DC, the share of coal in electricity grid decreased from 2010 to 2018 and was replaced with natural gas and renewable sources. In 2017, the WWTP added a CHP facility fueled by ADG. About 30% of the ADG was utilized in electricity generation, which reduced grid-electricity purchases and the plant’s GHG emissions by about a quarter.
Figure 9. Greenhouse gas emissions from electricity demand of wastewater treatment by source of electricity (from the grid and the onsite anaerobic digester gas-based combined heat and power generation).

Figure 10. GHG emissions from electricity use in wastewater treatment (markers) and cumulative forgone GHG emissions with respect to base year 2010 (bars).

Figure 10 reflects the GHG emissions implications of changes in wastewater volume, treatment technologies, capacity changes, electricity generation technologies, and fuel mixes. (Supplementary data, figure S.10 shows the forgone bar chart in figure 10 with more precision.) Forgone GHG emissions were calculated using equation S.3 from supplementary data section S.5.2. From 2010 to 2014, GHG emissions in Tucson gradually increased, attributed to the ongoing reduction in the capacity of the onsite CHP facility and an increase in energy need despite a slight growth in natural gas and a decrease in coal as fuel sources in the electricity mix. In 2015, Tucson started to experience a reduction in GHG emissions after a reduction in electricity demand coupled with increased share of natural gas in the electricity mix replacing coal. Further reduction in 2017 occurred following the introduction of solar energy (11%) in the electricity mix and the utilization of biogas for onsite electricity use, indicated by the negative forgone bars changing direction from 2017 to 2018 and moving upward in the positive direction, resulting in GHG savings for two years in a row.
GHG emissions from electricity use in Denver and Washington, DC were significantly smaller than in Tucson, due in Denver to higher percentage of electricity generated from biogas (figure 9) and in Washington, DC to lower wastewater volumes (figure 6). The avoided emissions depend on the electricity mix the biomass replaces. In the case of Denver and Washington, DC, the electricity from ADG replaces the electricity grid mix comprised mostly of coal and natural gas, with very small percentages of renewable energy sources such as solar, wind, and hydroelectricity. GHG emissions could be further lowered with increased onsite biogas utilization for electricity as well as renewable sources. Therefore, when analyzing energy use and GHG impacts from WWTPs, both facility-specific technologies and location-specific fuel sources of electricity mix play an important role. Technological investments in treatment processes, biosolids digesters, and biogas capture (for onsite electricity generation) in Tucson could lead to higher
emissions savings than similar efforts in Denver and Washington, DC in the near future.

4. Discussion

The interconnectedness of water systems is manifested in the examples of the three cities as reduced potable water consumption resulted in reduced wastewater flows. Each WWTP employs a different set of technologies based on the influent composition and effluent requirements, and uses location-specific electricity mixes. We find that the electricity intensity and GHG emissions per volume of treated wastewater differ between the cities.

Figure 11 shows the combined energy consumption and figure 12 the combined GHG emissions of the water and wastewater treatment systems in the three cities. (As described earlier, the water analysis for 2011–2016 is from another paper from us [8]. Supplementary data section S.1 provides details about the estimation of water consumption data used in wastewater calculations for the other years.) Reductions in water consumption led to less wastewater generation, but in the case of Tucson, wastewater-related GHG emissions increased despite the decreasing water-related emissions from 2010 to 2014 and in 2016. Tucson started to experience a reduction in GHG emissions with increased share of natural gas from 2011 to 2016 and solar energy from 2016 to 2018 in the electricity mix, replacing coal (figure 5). Further reduction in 2017 occurred following the reintroduction of biogas-based electricity coupled with the introduction of solar electricity. By 2018, Tucson had seen a 16% reduction in GHG emissions compared to 2016. Therefore, when analyzing wastewater-related GHG impact, not only water consumption trends but also factors such as changes in wastewater treatment technologies and electricity mixes should be considered.

Another important observation from this work is the extreme variability between the GHG emissions associated with water consumption versus wastewater treatment processes from one city to another. Local and regional analyses in this sector are necessary [20, 56]. Tucson’s potable water production was the most GHG intensive, possibly (given uncertainties) exceeding the combined emissions of Denver’s and Washington, DC’s entire water and wastewater systems. In Tucson, water is first pumped from a ground source and the remaining demand is imported from the Colorado River (hundreds of kilometers away) to replenish the groundwater. Additionally, the electricity grid mix with fossil fuel sources contributed to Tucson’s high GHG emissions. Denver’s water treatment processes resulted in about two times more GHG emissions (at about the same level of energy demand) compared to wastewater-related GHG emissions, explained in part by the benefits of onsite electricity generation from wastewater-derived biogas. Wastewater facilities in Washington, DC emitted up to 1.5 times more GHGs compared to water-related emissions from 2010 to 2016. In 2017, this ratio went down to 1.0 with the addition of a CHP facility.

From 2010 to 2018, forgone wastewater treatment (due to the amount of wastewater not generated relative to the baseline year of 2010) saved Denver a cumulative amount of about 44 000 MWh, Washington, DC 11 000 MWh, and Tucson 7000 MWh of electricity. If an average coal-fired power plant (400 MW nameplate capacity, operating 365 d with 38% efficiency [57]) generates 1.33 million MWh per year, the three cities together avoided about 0.6% of electricity generation over the 8-year period just through their water and wastewater systems while seeing their populations increase. In terms of GHG emissions, Denver and Washington, DC have forgone 34 000 mt and 21 000 mt CO₂-eq, respectively, whereas the cumulative emissions were 22 000 mt CO₂-eq in Tucson.

Our results show that WWTPs that use anaerobic digestion can support onsite CHP generation and lower their GHG emissions, thus helping transform wastewater treatment into a resource-recovery system.

Acknowledgments

This material is based upon work supported by the U.S. Department of Energy’s U.S.-China Clean Energy Research Center for Water-Energy Technologies (https://cerc-wet.berkeley.edu/) and the National Science Foundation under Grant No. 1444758 (UWIN, a Sustainability Research Network). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agencies.

Data Availability Statement

Any data that support the findings of this study are included within the article and the Supplementary Data.

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