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Air Emission Reduction Benefits of Biogas Electricity Generation at Municipal Wastewater Treatment Plants

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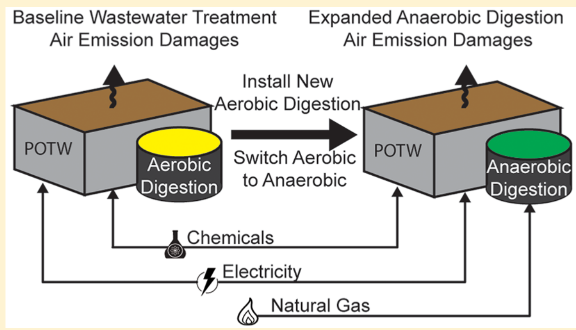
Supporting Information

ABSTRACT: Conventional processes for municipal wastewater treatment facilities are energy and materially intensive. This work quantifies the air emission implications of energy consumption, chemical use, and direct pollutant release at municipal wastewater treatment facilities across the U.S. and assesses the potential to avoid these damages by generating electricity and heat from the combustion of biogas produced during anaerobic sludge digestion. We find that embedded and on-site air emissions from municipal wastewater treatment imposed human health, environmental, and climate (HEC) damages on the order of \$1.63 billion USD in 2012, with 85% of these damages attributed to the estimated consumption of 19 500 GWh of electricity by treatment processes annually, or 0.53% of the US electricity demand. An additional 11.8 million tons of biogenic CO_2 are directly emitted by wastewater treatment and sludge digestion processes currently installed at plants. Retrofitting existing wastewater treatment facilities with anaerobic sludge digestion for biogas production and biogas-fueled heat and electricity generation has the potential to reduce HEC damages by up to 24.9% relative to baseline emissions. Retrofitting only large plants (>5 MGD), where biogas generation is more likely to be economically viable, would generate HEC benefits of \$254 annually. These findings reinforce the importance of accounting for use-phase embedded air emissions and spatially resolved marginal damage estimates when designing sustainable infrastructure systems.



INTRODUCTION

Aging systems, tightening regulatory standards, and expanding demand are driving significant investments in publicly operated treatment works (POTWs) in the U.S.[1] These facilities are likely to operate for several decades, through sweeping changes in the U.S. electricity sector. While next generation wastewater treatment trains must continue to meet standards for pathogen and nutrient control,[2,3] these treatment trains also provide an opportunity to improve nutrient recovery,[4−9] minimize electricity demand, buffer against intermittency in electricity supply, and reduce direct and embedded air emissions from the treatment process.

Biological wastewater treatment generates direct emissions of volatile organic compounds (VOCs) and greenhouse gases (GHGs), including CO_2, CH_4, and N_2O. These emissions stem from the biodegradation of organics in secondary treatment processes.[10−21] Past efforts to quantify these emissions through direct monitoring[10,17,22−24] or modeling[11,15,19,25] have been limited to individual plants. As a result, we lack a spatially resolved national emissions inventory of GHGs from POTWs that is critical to informing climate policy. We also lack tools for valuing the broader human health, environmental, and climate (HEC) damages that result from VOC and GHG emissions. Indeed, previous assessments of VOC emission damages have focused exclusively on health impacts to workers.[23,26]

In addition to direct emissions from biological wastewater treatment, there are embedded air emissions from electricity and chemicals consumed in the treatment process.[27−33] The consumption of electricity and chemicals has been evaluated for both conventional and emerging treatment processes, including small scale systems for decentralized wastewater treatment.[29,30,32−37] Studies that translate these electricity and chemical inputs into criteria air pollutant (CAP) emissions use national grid average emission factors,[5] and thus do not account for the marginal or regional variability in the emissions intensity of the grid. Finally, there are no studies that monetize the air emission damages from wastewater treatment, which stymies the inclusion of air emission damages in benefit-cost analyses used in regulatory and planning processes.[3]

Despite limited quantitative information on direct or embedded emissions from U.S. POTWs and their associated damages, energy recovery, and emissions reductions from wastewater treatment is a priority for many states.[38,39] Anaerobic sludge digestion for biogas generation is a particularly cost-effective approach to energy recovery, as it

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does not require modification of the primary or secondary treatment processes.[40−42] The biogas production rate is approximately 0.07 m^3 per m^3 of wastewater,[43] and the recovered biogas can be combusted to help meet the thermal and electrical energy requirements at the POTW. The life cycle air emissions reduction benefits of displacing electricity consumption are likely to be highest in regions with a coal-dependent grid, high population density, or high background concentrations of CAPs.

This paper quantifies the air emission reduction benefits of anaerobic sludge digestion at municipal POTWs. We begin by modeling the energy and chemical consumption of the unit processes currently installed at POTWs across the continental U.S. We also evaluate the potential for biogas generation and utilization as heat and electricity sources to power these unit processes. Next, we model the CAP and GHG emissions associated with operating these unit processes and assess the magnitude of HEC damages using AP2[44] and the social cost of carbon.[45] Finally, we assess the potential of biogas-fueled heat and electricity to reduce emissions relative to local grid supplied electricity and natural gas combustion.

■ MATERIALS AND METHODS

Wastewater Treatment System Data. We use the Clean Watershed Needs Survey (CWNS) to identify the (1) state and county, (2) average daily treatment flow rates, and (3) installed unit processes at continental U.S. POTWs in 2012 (Supporting Information (SI) Section 1.0, Tables S1 and S2, and Figures S1 and S2). The 2012 CWNS reports location and treatment flow for all 14 693 POTWs. Data on installed unit processes was reported annually through the 2004 survey. For the 2008 and 2012 Surveys, however, states reported installed unit processes only for the POTWs that upgraded their treatment trains between surveys. Thus, unit process data for POTWs in 2012 was obtained by merging the 2004,[46] 2008,[47] and 2012[48] CWNS data sets. We do this by starting with the 2012 CWNS data and identifying POTWs that do not report any installed unit processes. For these POTWs, we add unit processes reported in the 2008 CWNS responses. We repeat this merging process with the 2004 CWNS data. The final data set includes 49 634 unit processes at 12 277 POTWs. The 2416 plants missing unit processes are dropped from this analysis, resulting in coverage of 83.6% of U.S. POTWs and 95.7% of the total volume of treated wastewater in 2012.

Electricity and Heat Consumption at POTWs. Publicly operated treatment works consume electrical and thermal energy to drive wastewater treatment processes. We calculate electricity demand at POTW i, E_i in [kWh/yr], by multiplying the annual volume of wastewater treated, $\forall_{i,\mathrm{influent}}$ in [m^3/yr], by the sum of unit electricity consumption for treatment processes g installed at POTW i, W_g^{Elec} in [kWh/m^3], as shown in eq 1.

$$E_i = \forall_{i,\mathrm{influent}} \sum_g W_g^{\mathrm{Elec}} \tag{1}$$

The treatment technologies included in our analysis and the range of reported electricity consumption for these technologies are reported in SI Section 1.4. Facilities with anaerobic digestion, Q_i in [J/yr], require thermal energy to heat the digester. This thermal energy demand (eq 2) is the product of the volume of sludge digested annually, $\forall_{i,\mathrm{sludge}}$ in [m^3/yr], the sludge density, ρ in [g/m^3], which we assume to be 10^6 g/m^3,[43] the sludge heat capacity, c_P in [J/g·°C], which we assume to be 4.18 J/g·°C,[43] and the temperature difference between the average temperature in an activated sludge processes of 30 °C and the optimal anaerobic sludge digester temperature of 38 °C.[43]

$$Q_i = \forall_{i,\mathrm{sludge}} \rho c_P \Delta T \tag{2}$$

Note that we do not calculate heat demand elsewhere at the POTW (e.g., aerobic digester heating or space heating), due to a lack of available data.

Biogas Electricity and Heat Production Potential. We estimate the electricity generation and heat production from biogas combustion in a combined heat and power (CHP) system characteristic of those installed at POTWs (SI Section 2.0 and Figure S3).[49−52] Here, biogas is combusted to heat air and the hot air spins the turbine blades (in microturbine systems)[49] or moves the pistons (in reciprocating engines)[50] that generate electricity. Residual heat is then recovered from the exhaust gas and used to heat water or generate low pressure steam. We assume this heat is utilized solely by the anaerobic digester, but we also quantify the excess heat that would be available to offset other on-site heating needs such as space heat and heating of the activated sludge processes.

We estimate the electricity generation potential in a biogas CHP system, $E_{\mathrm{biogas},i}$ [kWh/yr], at facilities with anaerobic digestion using eq 3.[49,50,53] Biogas-fueled electricity generation is estimated using a biogas electricity factor, BEF [kWh/m^3], and the influent wastewater flow rate, $\forall_{i,\mathrm{influent}}$ [m^3/yr]. The BEF is the amount of electricity that can be generated in a CHP system as a function of treated wastewater volume. We select a BEF of 0.113 kWh/m^3, consistent with a review performed by the Electric Power Research Institute for CHP systems.[54] We also perform sensitivity analysis on the BEF by using a high (0.139 kWh/m^3) and low (0.0925 kWh/m^3) BEFs.[53]

$$E_{\mathrm{biogas},i} = BEF \times \forall_{i,\mathrm{influent}} \tag{3}$$

We calculate the electricity self-sufficiency, $R_{\mathrm{electricity},i}$, and net electricity demand, $E_{\mathrm{net},i}$, using eqs 4 and 5.

$$R_{\mathrm{electricity},i} = \frac{E_{\mathrm{biogas},i}}{E_i} \tag{4}$$

$$E_{\mathrm{net},i} = E_i - E_{\mathrm{biogas},i} \tag{5}$$

We estimate heat production in a CHP system, Q_{biogas} [MJ/yr], using eq 6. We multiply the influent wastewater, $\forall_{i,\mathrm{influent}}$ [m^3/yr], by the average biogas production rate, P [m^3-biogas/m^3-influent wastewater], and the recovered heat production value of biogas in CHP systems, H_{biogas} [MJ/m^3-biogas].[43] We select an average H_{biogas} ratio of 9.54 MJ/m^3-biogas,[51] for a CHP power to heat ratio of 0.607 at the average BEF. We also perform sensitivity analysis by modeling high (10.2 MJ/m^3-biogas at a power to heat ratio of 0.467) and low (8.75 MJ/m^3-biogas at a power to heat ratio of 0.817) biogas heat production values corresponding to the low and high BEFs, respectively (SI Section 2.0 and Table S4).[51]

$$Q_{\mathrm{biogas}} = \forall_{i,\mathrm{influent}} \times P \times H_{\mathrm{biogas}} \tag{6}$$

We also calculate a thermal energy self-sufficiency ratio, $R_{\mathrm{thermal},i}$ and net thermal energy demand, $Q_{\mathrm{net,I}}$ [J/yr] using eqs 7 and 8.

$$R_{\mathrm{thermal},i} = \frac{Q_{\mathrm{biogas}}}{Q_i} \tag{7}$$

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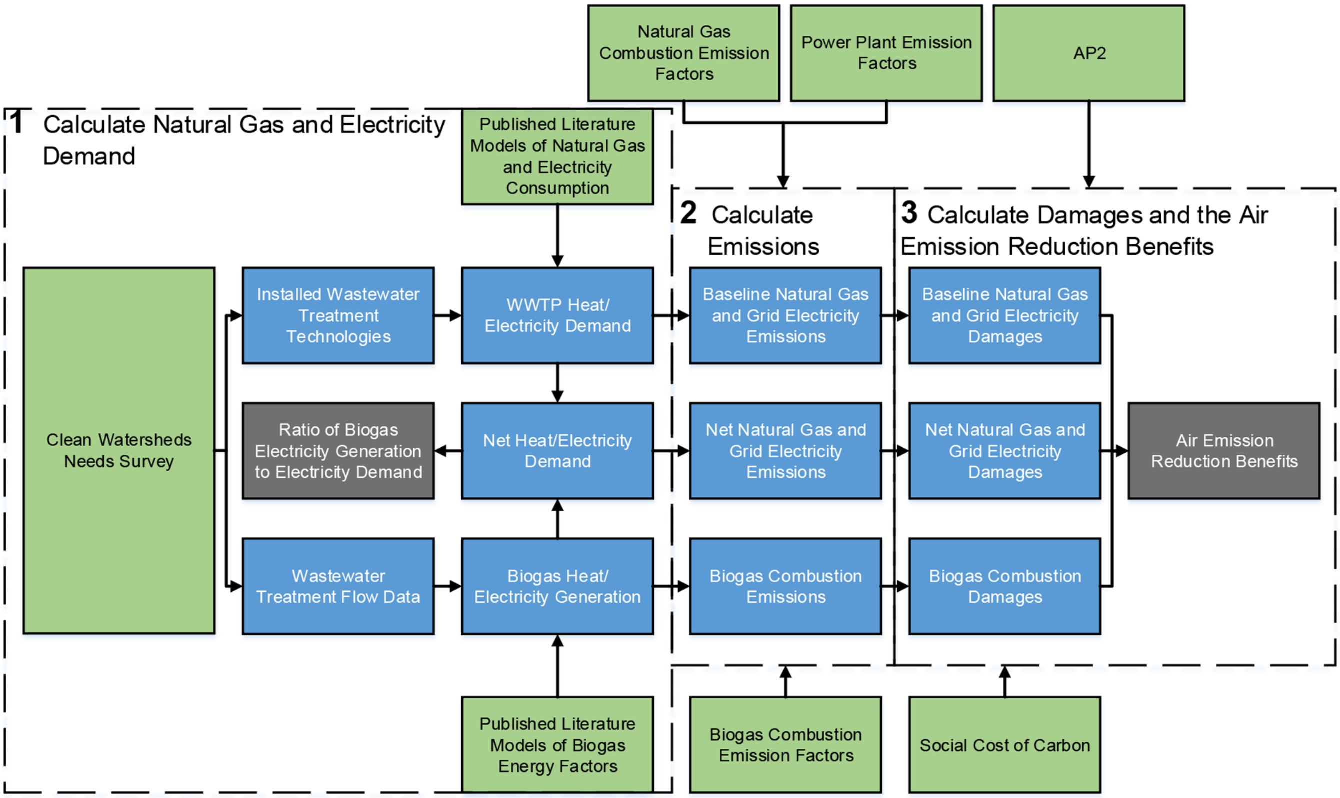

Figure 1. Methods for calculating the air emission reduction benefits of biogas-fueled electricity and heat generation. There are three primary steps in this analysis. The first step is calculating plant-level electricity and thermal energy demand using survey data on installed treatment technologies, published models on the heat and electricity consumption for wastewater treatment processes, and estimates of biogas energy factors for electricity and thermal energy production. The second step is to use grid electricity, natural gas combustion, and biogas combustion emission factors to calculate emissions in a baseline scenario (grid electricity and natural gas) and a full biogas generation and use scenario (biogas electricity and heat with grid electricity and natural gas to meet remaining demand). We also account for emissions associated with biogas combustion in the biogas use scenario. In the third step, we calculate the damages in the baseline scenario and the biogas use scenario using AP2 and the social cost of carbon. The difference in damages yields the air emission reduction benefits.

$$Q_{\text{net},i} = Q_i - Q_{\text{biogas}} \tag{8}$$

We define two energy consumption scenarios for our analysis, a *base case* and an *upgrade scenario* (Figure 1). The base case refers to the 2012 consumption of grid electricity and natural gas at all POTWs, and biogas consumption only for those facilities that report biogas utilization in the CWNS data set. For facilities in the base case that report biogas utilization, we account for the possibility that biogas does not fully meet the heat and electricity needs of the POTW by calculating demands for supplemental natural gas and grid electricity. In the upgrade scenario, we revise the 2012 estimates of energy consumption under the hypothetical scenario in which all facilities adopt anaerobic digestion and all facilities utilize their biogas to offset heat and electricity demands at the plant. This scenario accounts for the additional energy demands associated with anaerobic digestion. In addition to the base case and upgrade scenarios, we evaluate a partial upgrade scenario in which only large facilities (>5 MGD) are upgraded with anaerobic digestion and biogas utilization.

Air Emissions from Municipal Wastewater Treatment and Sludge Digestion. *Air Emissions in the Base Case.* We evaluate the emissions of four CAPs (SO_2, NO_x, $PM_{2.5}$, and VOCs), and three GHGs (CO_2, CH_4, and N_2O) from wastewater treatment processes. On-site emissions of pollutant j at facility i include direct emissions from secondary treatment processes and aerobic sludge digestion, $M_{i,j}^{\text{Aer}}$, emissions from biogas combustion at facilities with anaerobic digestion and biogas combustion, $M_{i,j}^{\text{Comb}}$, fugitive emissions of biogas at facilities with anaerobic digestion but no biogas combustion, $M_{i,j}^{\text{Fugitive}}$, and emissions from natural gas combustion to supplement biogas combustion heating of the anaerobic digester, $M_{i,j}^{\text{NG}}$.

For each wastewater treatment facility with activated sludge processes or aerobic digestion installed, we calculate the direct emissions of VOCs and GHGs resulting from secondary wastewater treatment and aerobic sludge digestion processes, $M_{i,j}^{\text{Aer}}$ [g/yr], using eq 9.

$$M_{i,j}^{\text{Aer}} = \varPsi_{i,\text{influent}} e_{\text{treat},j}^{\text{Aer}} \tag{9}$$

Emissions are the product of water treated, $\varPsi_{i,\text{influent}}$ [m^3/yr], and the average literature reported emissions per cubic meter, $e_{\text{treat},j}^{\text{Aer}}$ [g/m^3],[55−61] listed in SI Table S7.

For the 16% of facilities that report anaerobic sludge digestion, we assume that the biogas is either captured and combusted or released to the atmosphere as fugitive biogas. For facilities with anaerobic sludge digestion and that report combusting biogas, we calculate combustion emissions, $M_{i,j}^{\text{Comb}}$ [g/yr], using eq 10. We assume that 99% of biogas is combusted with the remaining 1% released to the environment, and we scale the emissions factors listed in SI Table S7 accordingly to calculate the biogas combustion emission factor,

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Table 1. Uncertain Parameters, Values, And Ranges Used in Air Emissions and Damages Calculations

variable	value in main text	uncertainty analysis ranges	sensitivity analysis method[a]	SI section for sensitivity analysis results
Uncertainty in Air Emission and Damage Calculations				
marginal emissions factors for grid electricity	Siler-Evans et al.[64]	Graff Zivin et al.[65]	P	S6.2
electricity consumption for unit processes	literature-based averages	literature minimums and maximums (listed in SI Section 1.4)	MC, P	S6.3
chemical consumption for unit processes	literature-based averages	literature minimums and maximums (listed in SI Section 1.4)	MC, P	S6.3
influent flow	CWNS average flow	CWNS design flow	MC, P	S6.4
biogas flaring at facilities that produce but do not utilize biogas	82% flare/18% emit[52]	100% flare/0% emit	P	S6.5
		0% flare/100% emit		
chemical manufacturing location	revenue distribution of chemical manufacturing sector	(a) in-state	P	S7.0
		(b) evenly distributed		
		(c) in lowest damage state		
		(d) in highest damage state		
		(e) off-shore		
Value of a Statistical Life	\$8.6 M (2012 USD)[67]	\$2 M-\$10 M	P	manuscript
Social Cost of Carbon	\$43/short ton $CO_{2,eq}$[45]	\$20-\$60/short ton	P	manuscript
Uncertainty in Biogas-Fueled Heat and Electricity Generation				
influent flow	CWNS average flow	CWNS design flow	MC, P	S9.0
biogas electricity factors	0.113 kWh/m^3	0.0925 kWh/m^3 (low)	P	manuscript
		0.139 kWh/m^3 (high)		
biogas heat production value	9.54 MJ/m^3	7.55 MJ/m^3 (low)	P	manuscript
		12.0 MJ/m^3 (high)		
electricity consumption for unit processes	literature-based averages	literature minimums and maximums (listed in SI Section 1.4)	MC, P	S9.0

[a]MC = Monte Carlo Analysis, *P* = parametric.

e_j^{Comb} [g/m^3]. We multiply the resulting emission factors by the volume of influent wastewater, $V_{i,\mathrm{influent}}$ [m^3/yr].

$$M_{i,j}^{\mathrm{Comb}} = V_{i,\mathrm{influent}} e_j^{\mathrm{Comb}} \tag{10}$$

For the 92% of facilities with anaerobic sludge digestion that do not report biogas utilization, we assume that 82% of facilities flare without on-site use and the remaining 18% of facilities release biogas as fugitive emissions.[52] As shown in eq 11, we calculate fugitive emissions, $M_{i,j}^{\mathrm{Fugitive}}$ [g/yr], by multiplying influent wastewater volume, $V_{i,\mathrm{influent}}$ [m^3/yr], and we scale the emissions factors listed in SI Table S7 accordingly to calculate the fugitive biogas emissions factor, e_j^{Fugitive} [g/m^3], listed in SI Table S7.

$$M_{i,j}^{\mathrm{Fugitive}} = V_{i,\mathrm{influent}} e_j^{\mathrm{Fugitive}} \tag{11}$$

For those facilities with an anaerobic digester but either insufficient biogas production or no biogas utilization, we calculate emissions from natural gas combustion for anaerobic digester heating. We calculate emissions of pollutant j resulting from natural gas combustion, $M_{i,j}^{\mathrm{NG}}$ [g/yr], using eq 12. We divide $Q_{\mathrm{Net},i}$ by the higher heating value of natural gas, $\mathrm{HHV_{NG}}$ [J/m^3-natural gas],[62] and multiply by the emissions factor for pollutant j for natural gas combustion in an industrial boiler, $e_{\mathrm{NG},j}$ [g/m^3] (eq 12).[63]

$$M_{i,j}^{\mathrm{NG}} = e_{\mathrm{NG},j}\left(\frac{Q_{\mathrm{Net},i}}{HHV_{\mathrm{NG}}}\right) \tag{12}$$

Finally, we calculate the embedded emissions from off-site electricity generation, $M_{i,j}^{\mathrm{Elec}}$ [g/yr], and chemical manufacturing, $M_{i,j}^{\mathrm{Chem}}$ [g/yr], as shown in our previous work[27,28] with the methods and data used to calculate these emissions summarized in SI Sections 3.0 and 4.0 and Tables S5 and S6. In the main manuscript we use marginal emissions factors from the year 2012, calculated using methods used by Siler-Evans et al.,[64] consistent with our previous work.[27,28] We perform sensitivity analyses on the marginal emissions factors by repeating our analysis using an alternative set of emissions factors from Graff Zivin et al.[65]

Air Emissions in the Upgrade Scenario. We model four changes to air emissions that result from upgrading POTWs to utilize biogas from anaerobic digestion. First, we use eq 10 to calculate the increase in emissions from biogas combustion at upgraded facilities, $M_{\mathrm{upgraded},i,j}^{\mathrm{Comb}}$ [g/yr]. Second, we use eq 13 to calculate the effect of controlling fugitive air emissions at the estimated 18% of facilities that report biogas utilization but currently do not utilize or flare their produced biogas, $M_{\mathrm{upgraded},i,j}^{\mathrm{fugitive}}$ [g/yr].[52] These emissions changes are calculated by multiplying the wastewater influent flow rate, $V_{i,\mathrm{influent}}$ [m^3/yr], by the difference in emissions factors between the fugitive emissions factor, e_j^{fugitive} [g/m^3] and the combustion emissions factor, e_j^{Comb} [g/m^3].

$$M_{\mathrm{upgraded},i,j}^{\mathrm{fugitive}} = V_{i,\mathrm{influent}}(e_j^{\mathrm{fugitive}} - e_j^{\mathrm{Comb}}) \tag{13}$$

We calculate the air emission reductions from decreased natural gas combustion for anaerobic digester heating at upgraded facilities, $M_{\mathrm{upgraded},i,j}^{\mathrm{NG}}$ [g/yr], using eq 12. Finally, we calculate the emissions reduction associated with decreased consumption of grid electricity, $M_{\mathrm{upgraded},i,j}^{\mathrm{Elec}}$ [g/yr], by multiplying the difference in grid electricity demand between the baseline, $E_{\mathrm{baseline},i}$ [kWh/yr], and upgrade, $E_{\mathrm{net},i}$ [kWh/yr],

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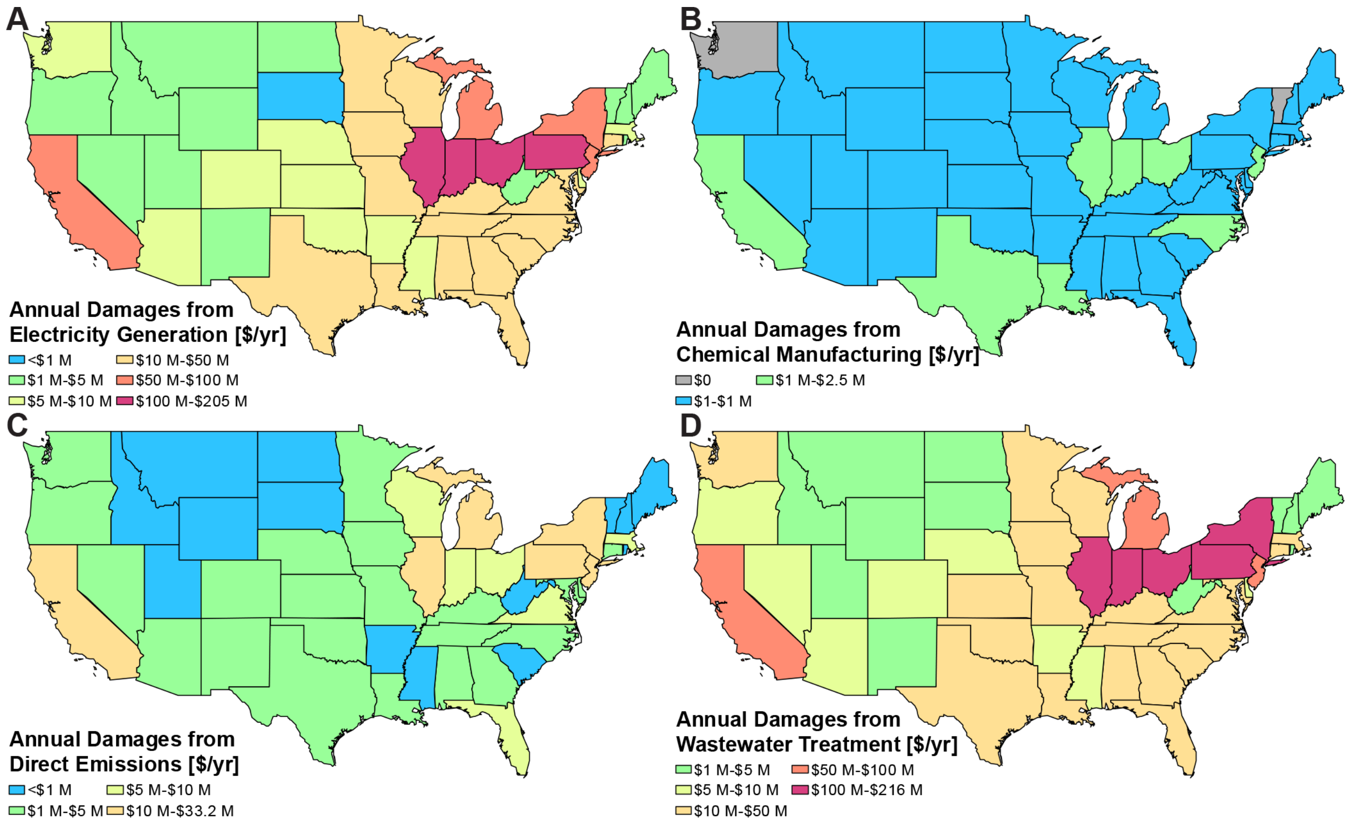

Figure 2. Air emission damages in 2012 from installed wastewater treatment and sludge digestion processes due to (A) electricity generation ($1.38 billion in 2012 USD), (B) chemical manufacturing ($18.5 million in 2012 USD), (C) direct emissions ($224 million in 2012 USD), and (D) total damages ($1.63 billion in 2012 USD). N.B. Damages from on-site emissions of biogenic CO_2 are not shown in Panel C, and would add an additional $515 million (in 2012 USD) if valued at a social cost of carbon of $43/short ton $CO_{2,eq}$ (in 2012 USD).

scenarios by the electricity emissions factor for pollutant j, $e_{\mathrm{mf},j,l}$ [g/kWh], in state l.[64−66]

$$M^{\mathrm{Elec}}_{\mathrm{upgraded},i,j} = e_{\mathrm{mf},j,l}(E_{\mathrm{baseline},i} - E_{\mathrm{net},i}) \tag{14}$$

Air Emission Damages from Municipal Wastewater Treatment and Sludge Digestion. We use a social cost of carbon[45] (SCC) of $43/short ton $CO_{2,eq}$ to estimate the damages from GHG emissions and county-level marginal damages from AP2[44] to estimate damages from CAP emissions. AP2 utilizes a value of a statistical life of (VSL) $8.6 M (in 2012 USD), the same value used by the EPA in their economic analyses.[67] We report all damages at the state-level. For consistency with the IPCC's classification of CO_2 emissions from wastewater treatment as biogenic in origin, we report CO_2 emissions associated with biodegradation at the POTW separately from damages associated with VOC, CH_4, and N_2O emissions and exclude them from total damage results.

Using eqs 15−19, we calculate the air emission damages from both the base case and the upgrade scenario at the facility level, and then aggregate these damages to the state level. Damages in state l include damages from secondary treatment processes and aerobic sludge digestion, D_l^{Aer} [$/yr]; biogas combustion, D_l^{Comb} [$/yr]; fugitive emissions, D_l^{Fugitive} [$/yr]; natural gas combustion, D_l^{NG} [$/yr]; electricity consumption, D_l^{Elec} [$/yr]; and chemical manufacturing, D_l^{Chem} [$/yr]. The damages are the product of damages per marginal gram of emissions from county k, $d_{j,k}$ [$/g], and the emissions from secondary treatment processes and aerobic sludge digestion, $M_{i,j}^{\mathrm{Aer}}$ [g/yr]; biogas combustion, $M_{i,j}^{\mathrm{Comb}}$ [g/yr]; fugitive emissions, $M_{i,j}^{\mathrm{Fugitive}}$ [g/yr]; natural gas combustion, $M_{i,j}^{\mathrm{NG}}$ [g/yr]; and electricity consumption, $M_{i,j}^{\mathrm{Elec}}$ [g/yr].

$$D_l^{\mathrm{Aer}} = \sum_i \sum_j d_{j,k} M_{i,j}^{\mathrm{Aer}} \tag{15}$$

$$D_l^{\mathrm{Comb}} = \sum_i \sum_j d_{j,k} M_{i,j}^{\mathrm{Comb}} \tag{16}$$

$$D_l^{\mathrm{Fugitive}} = \sum_i \sum_j d_{j,k} M_{i,j}^{\mathrm{Fugitive}} \tag{17}$$

$$D_l^{\mathrm{NG}} = \sum_i \sum_j d_{j,k} M_{i,j}^{\mathrm{NG}} \tag{18}$$

$$D_l^{\mathrm{Elec}} = \sum_i \sum_j d_{j,k} M_{i,j}^{\mathrm{Elec}} \tag{19}$$

Damages from chemical manufacturing in state l, D_l^{Chem} [$/yr], are calculated at the state level using SI eq S3.

Total air emission damages for the base case in state l, D_l [$/yr], are calculated using eq 20. The net benefits of the upgrade scenario, B_l [$/yr], are calculated using eq 21.

$$D_l = D_l^{\mathrm{Chem}} + D_l^{\mathrm{Aer}} + D_l^{\mathrm{Comb}} + D_l^{\mathrm{Fugitive}} + D_l^{\mathrm{NG}} + D_l^{\mathrm{Elec}} \tag{20}$$

$$B_l = \sum_i [(D_{i,\mathrm{baseline}}^{\mathrm{Elec}} - D_{i,\mathrm{net}}^{\mathrm{Elec}}) + D_{\mathrm{upgraded},i}^{\mathrm{Fugitive}} - D_{\mathrm{upgraded},i}^{\mathrm{Comb}} - D_{\mathrm{upgraded},i}^{\mathrm{NG}}] \tag{21}$$

Uncertainty Analysis. There are several uncertain parameters in our analysis (Table 1). These include uncertainty

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around emissions factors, wastewater flow, electricity consumption, chemical consumption, current biogas generation and utilization, and differences in VSL and SCC. These uncertainties impact our calculation of air emissions, damages, and benefits of biogas-fueled heat and electricity generation. For the results presented in the main manuscript, we rely on average values based on literature sources and data. We treat estimates of marginal electricity emissions factors parametrically by comparing the HEC damage results using values estimated by both Siler-Evans et al.[64] and Graff Zivin et al.[65] For the remaining sensitivity analyses, we run a Monte Carlo analysis or perform parametric analysis on the total damages resulting from electricity generation, chemical manufacturing, and on-site emissions. The probability distributions for flow rate, electricity consumption, and chemical dosage, as well as the results of the Monte Carlo Analysis, are reported in SI Section 6.1 and Table S12. We calculate the minimum and maximum air emission damages in a series of one-at-a-time parametric analyses by recalculating eqs 1−21 and SI eqs S1−S3 using the minimum and maximum value for each uncertain variable identified in Table 1 and SI Table S3 in SI Section 1.4. Results of the parametric uncertainty analyses are reported in the SI sections listed in Table 1.

There is also uncertainty in the location of chemical manufacturing. In the main manuscript, we assume that chemical manufacturing follows the national distribution of revenue from chemical manufacturing based on the Annual Survey of Manufacturers data set.[68] This is the same assumption we made in our previous work.[27,28] We also perform sensitivity analyses based on several alternative chemical manufacturing distributions in SI Section 7.0.

Finally, we perform sensitivity analyses on the heat and electricity self-sufficiency of biogas-fueled CHP systems. We calculate thermal energy self-sufficiency by recalculating eqs 6−8 for the high and low biogas heat production values reported in Table 1. For electricity, we calculate a minimum and maximum self-sufficiency scenario using eq 4. The minimum self-sufficiency scenario is a scenario with the low BEF value and the maximum electricity consumption for treatment processes. The maximum self-sufficiency scenario is a scenario with the high BEF value and the minimum electricity consumption for treatment processes.

■ RESULTS

Damages from Municipal Wastewater Treatment. We use treated wastewater volume from the 2012 CWNS to estimate the air emission damages associated with operating installed wastewater treatment processes. As such, all damage values are specific to 2012 and reported in 2012 USD.[69] In 2012, wastewater treatment generated air emission damages of $1,624 million. The geographic distributions of damages associated with electricity generation, chemical manufacturing, and direct emissions are shown in Figure 2. Generating the 19 500 GWh used in wastewater treatment (0.53% of U.S. electricity demand) accounts for 85%, or $1.38 billion, of these air emission damages. Damages from electricity generation using the Graff Zivin et al.[65] marginal emissions factors are 37−47% higher due to the higher fraction of coal combusted in the years of their analysis (SI Section 6.2 and Tables S13 and S14).

On-site emissions contribute an additional $224 million annually (14% of total damages). The largest drivers of these direct damages include VOCs released during secondary treatment ($83.7 million annually) and $91.6 million in fugitive methane emissions from facilities with existing anaerobic digesters but without gas capture or flaring. Damages from chemical manufacturing contribute $18.5 million. Air emissions and damages from wastewater treatment are tabulated in SI Section 5.0 and Tables S8 and S9.

Energy Self-Sufficiency of POTWs. Anaerobic sludge digestion and biogas combustion have the potential to offset a meaningful fraction of the air emission damages from electricity consumption at wastewater treatment facilities. Nationwide, we estimate the upper limit for electricity generation from biogas in the upgrade scenario to be 4360 GWh (3530−5170 GWh) annually (Figure 3A). If anaerobic sludge digestion and biogas utilization was fully deployed at US POTWs, 18.1−26.4% of the 19 500 GWh/yr of electricity consumed in operating wastewater treatment facilities could be met through biogas-fueled electricity generation. For the 29% of POTWs where biogas driven CHP completely meets electricity needs, there is a theoretical excess of 638 GWh of electricity that could be produced annually and allocated for nontreatment needs on-site or sold to the grid.

While the potential for biogas-fueled electricity generation is significant, the technical potential for biogas-fueled electricity generation to displace grid-sourced electricity depends upon the energy intensity of the installed treatment processes. The maximum potential electricity demand met by biogas-fueled generation potential is plotted in Figure 3B, with the numbered regions generally corresponding to different wastewater treatment process intensity. Region 1 includes facilities operating energy intensive processes including primary treatment for solids removal, activated sludge, disinfection, and tertiary treatment for nitrogen or phosphorus removal. POTWs in Region 2 are more likely to use trickling biofilters in place of energy intensive activated sludge processes, and are less likely to employ tertiary treatment technologies. Regions 3 and 4 have either a lagoon plus disinfection (Region 3) or primary treatment, aeration, and disinfection (Region 4). Finally, Region 5 contains POTWs with only solids removal and disinfection processes installed.

At all plants (Regions 1−5), the heat generated by CHP systems operated at the average power to heat ratio of 0.607[51] exceeds the thermal needs of anaerobic digestion. This enables heat allocation to other on-site needs (e.g., space heating) on the order of 17 million GJ across the POTWs considered in this study. Absent these other on-site heat needs, it may be advantageous to increase the power to heat ratio and generate additional electricity (SI Section 2). Our conclusion that biogas utilization, under the power to heat ratio range (0.467−0.817) evaluated in this paper, allows POTWs to completely meet the thermal energy needs of anaerobic digestion is robust over a range of biogas heat production values. Indeed, annual heat production in excess of anaerobic digester heating needs ranges from 14 to 19 million GJ.

In addition to issues related to the technical feasibility of offsetting heat and electricity generation, there are economic and operational challenges to operating anaerobic sludge digesters and CHP systems. As there may not be sufficient biosolids produced at facilities that treat less than 5 MGD to make biogas-fueled CHP techno-economically feasible,[70] we have replotted the potential for biogas to meet electricity demand at large facilities with inflows of >5 MGD in Figure 3C. While large facilities tend to operate more energy intensive process and have lower offset potentials, they also process more

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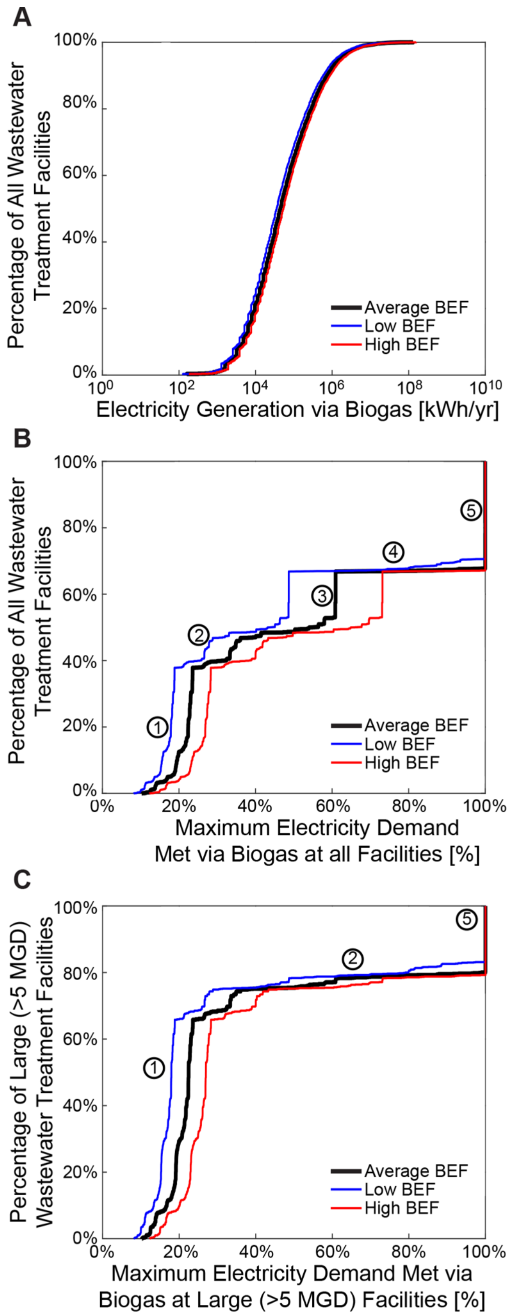

Figure 3. Cumulative distribution function of the potential for biogas-fueled electricity generation to reduce net electricity demand at wastewater treatment plants in the CWNS database at an average heat production of 9.24 MJ/m^3 of biogas. (A) Treatment facility level estimates of electricity generation via biogas combustion using an average, low, and high biogas electricity factor (BEF). The ratio of electricity generation via biogas to the electricity demand at (B) all facilities and (C) large (>5 MGD capacity) facilities. The circled numbers indicate different levels of treatment intensity, as described in the text, with more intense levels of treatment (e.g., nutrient control and tertiary treatment) represented by the regions with lower numbers.

wastewater and have larger biogas generation potential on a per facility basis.

Air Emission Reduction Benefits from Biogas-Fueled Heat and Electricity Generation. Installing anaerobic digestion and biogas utilization for heat and electricity generation at all POTWs that do not currently have these processes installed would produce air emission reduction benefits of $395 million (in 2012 USD) annually or a 25% reduction in air emission damages from wastewater treatment (Figure 4). If biogas generation was installed only at facilities

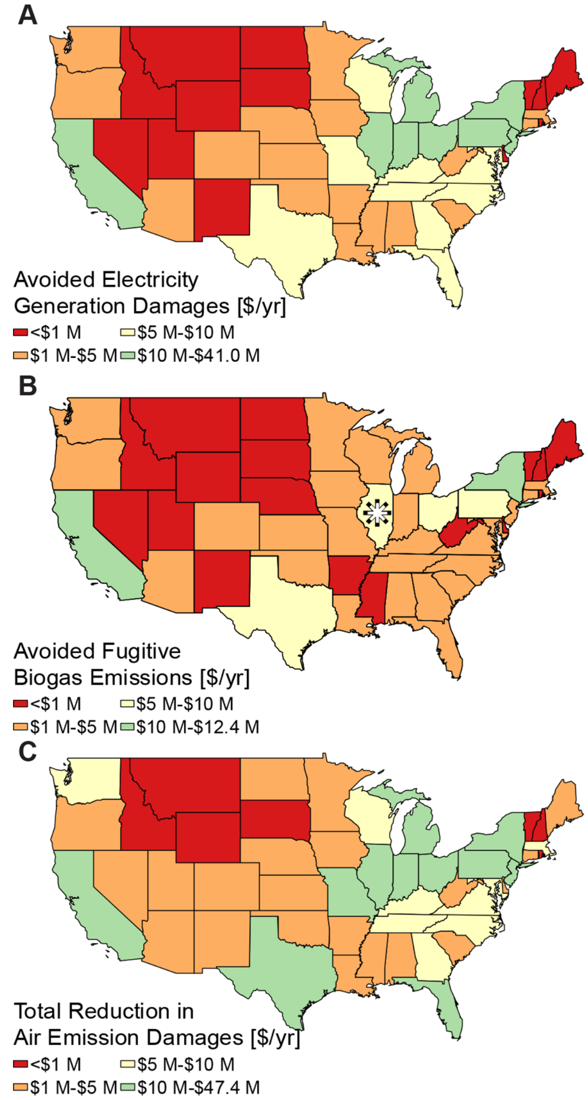

Figure 4. Air emission reduction benefits from (A) reduced electricity generation and (B) increased control of fugitive biogas and reduced natural gas combustion. The asterisks in Panel B indicate states where reduced natural gas combustion would produce at least $100,000 (in 2012 USD) in benefits. However, there are $1.9 M (in 2012 USD) additional damages occurring from facilities upgraded to combust biogas. (C) Nationwide there is the potential for up to $406 M/yr (in 2012 USD) in air emission reduction benefits from upgrading all POTWs to anaerobic digestion and biogas-fueled CHP. Benefits are tabulated in SI Section 5.2 and Tables S10−S11.

that treat more than 5 MGD, the air annual emission reduction benefits of biogas-fueled electricity and heat generation would be $254 million. These large facilities are therefore responsible for 84% of the air emission reduction benefits from biogas-fueled heat and electricity generation.

Nationwide, biogas-fueled heat and electricity generation could potentially offset $289 million in damages from the grid. As shown in Figure 4A, these benefits are greatest in states with grids that are heavily reliant on coal (e.g., Pennsylvania and Ohio) or have large populations (e.g., New York and

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California). There are small benefits in avoided natural gas combustion associated with combusting biogas ($11.2 million in 2012 USD) and even smaller additional damages resulting from biogas combustion emissions at upgraded facilities ($1.9 million in 2012 USD). Finally, an additional $92.7 million (in 2012 USD) reduction in annual air emission damages could be immediately realized through utilization of biogas at facilities that currently vent their biogas (Figure 4B).

Uncertainty Analyses. To assess the uncertainty in our air emission damage results we performed Monte Carlo analyses by assigning a distribution of values to influent wastewater flow rate, electricity demand of the unit processes, chemical dosing required for operating these processes, and on-site emissions from wastewater treatment processes. Total damages are robust to uncertainty in these input parameters, varying less than 4% (Figure 5A). The primary contribution to this uncertainty originates from uncertainty in the electricity consumption, which itself is a function of the influent flow rate and the demand from unit processes. The results of the one-at-a-time analyses are reported in SI Sections 6.3−6.6, 7.0, and Tables S15−S23.

These results are also sensitive to the VSL and SCC (Figure 5B). In the baseline analysis, we used a VSL of $8.6 M (in 2012 USD) to value damages of CAPs. Varying the VSL from $4 M-$10 M (in 2012 USD) produces a range in CAP damages from $430 M/yr (VSL of $4 M) to $1080 M/yr (VSL of $10 M). The SCC used in the base case analysis was $43/short ton of CO_2 (in 2012 USD). The damages are approximately $320 M/yr and $960 M/yr when the SCC is $20/short ton and $60/short ton, respectively. The assumed VSL and SCC significantly impact the final air emission damages associated with municipal wastewater treatment and benefits of installing anaerobic digestion.

Finally, we performed sensitivity analyses on the electricity self-sufficiency of POTWs (Figure 5C) and the amount of electricity that could be generated from biogas (SI Section 8 and Figure S4). The biogas heat production factors and power to heat ratios corresponding to the high and low BEFs used in this analysis are presented in SI Table S4. The electricity self-sufficiency and electricity generated are dependent on several variables, including the wastewater flow rate, the BEF, and the unit electricity consumption. The low and high electricity self-sufficiency cases are shown in blue and red in Figure 5C and have a different shape than the baseline assumptions. The most significant difference is the number of plants capable of achieving complete electricity self-sufficiency. In the high electricity self-sufficiency case, 55% of systems could generate enough electricity from biogas-fueled electricity generation to meet all of their electricity needs. In the low electricity self-sufficiency case, only about 30% are capable of achieving complete electricity self-sufficiency. Analysis on the impact of BOD_5 loading due to the variability of wastewater flow rate on biogas-fueled electricity generation can be found in SI Section 8.0 and Figure S4.

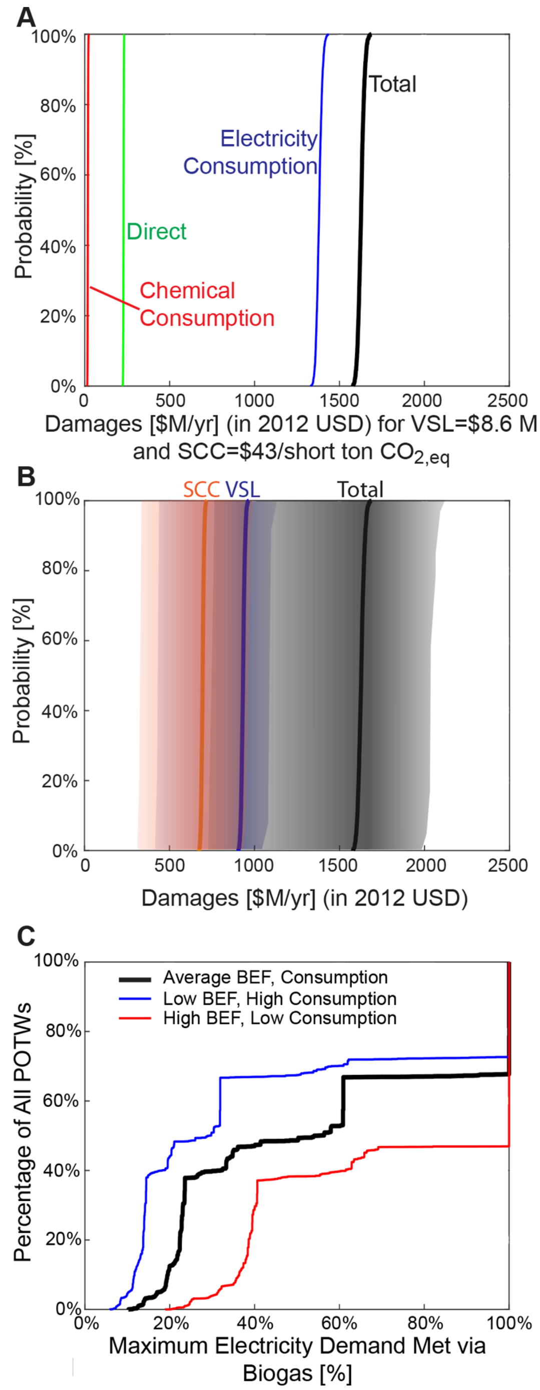

Figure 5. (A) Cumulative distribution function (CDF) of air emission damages from wastewater treatment, with variability due to wastewater flow, chemical dosing, and electricity consumption for individual unit processes. The contributions of chemical consumption, direct emissions of VOCs and GHGs, and electricity consumption to the CDF of total air emission damages are highlighted in red, green, and blue, respectively. (B) Sensitivity of the CDF of total air emission damages to selected values for the SCC ($20-$60/short ton $CO_{2,eq}$) in orange and the VSL ($4-$10 M in 2012 USD) in purple. (C) CDF of the energy self-sufficiency of wastewater treatment facilities as a function of uncertainty around the Biogas Electricity Factor (BEF) and the unit process electricity consumption.

■ DISCUSSION

In 2012, wastewater treatment processes in the United States generated approximately $1.63 billion in air emission damages. Electricity consumption was the largest source of these damages, contributing $1.38 billion in air emission damages resulting from the consumption of 19 500 GWh of electricity. Projected increases of 20−25% in US wastewater treatment capacity by 2032[1] suggests that the electricity consumption and air emission damages of wastewater treatment will also increase.

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Onsite biogas generation and combustion for heat and power is a viable approach for reducing electricity and natural gas consumption at many US POTWs. While there are several approaches to biogas generation at municipal water treatment plants, the most common is anaerobic sludge digestion. More than 16% of US POTWs have anaerobic sludge digestion (representing 38% of wastewater treatment capacity), but only 1% of facilities report currently utilizing biogas to meet onsite energy needs.[52] Installing biogas-fueled CHP systems at these POTWs could reduce the air emission damages from wastewater treatment by approximately 6%.

Despite this opportunity, there are several barriers to the widespread adoption of biogas-fueled CHP systems. Given limited budgets for capital investments, POTWs have frequently identified the large upfront capital costs for installing CHP systems as a major barrier to adoption.[71] The current capital costs for CHP systems range from $1,800 to $5,000/kW of installed capacity, depending on the type of system.[51] Improving the quality of biogas (i.e., increasing the CH_4 concentration) by removing impurities (e.g., CO_2 or H_2S) is another substantial challenge for making biogas combustion and sale to the natural gas grid more attractive.[51,71]

Another barrier for implementation, especially for systems that treat less than 5 MGD, is inadequate biosolids production.[70] More than 90% of the POTWs in our analysis have a capacity of <5 MGD, and these small facilities contribute only 14.3% of the total biogas-fueled heat and electricity generation potential. Co-digestion of other organic wastes (e.g., food waste) is one approach for lowering the minimum economically viable digester size, but this requires a steady organics stream.[51,52] Developing new technologies to lower the size at which energy recovery is economically viable is a vital area of research that would reduce the electricity consumption and air emissions associated with wastewater treatment. Small, decentralized wastewater treatment systems would also enable other environmental benefits, including source separation, gray water reuse, and the ability to design systems to target specific pollutants.[29,72]

Finally, there are several policy interventions that could support POTW implementation of biogas-fueled heat and electricity generation. First, as noted above, the most significant barrier to implementation is the upfront capital costs and long payback periods associated with the required equipment. Policies that offer financial assistance or that compensate POTWs for their air emission reduction benefits from installing biogas-fueled CHP systems would make the process more economically attractive. There is also some uncertainty around the net national benefits from GHG reduction resulting from installing biogas-fueled heat and electricity generation. Policies that expand data collection and reporting could help quantify this benefit and justify policy interventions.

■ IMPLICATIONS

For infrastructure to be sustainable it must achieve its mission while balancing its costs, social impacts, and environmental impacts. For wastewater treatment, the largest source of air emission damages are associated with electricity generation.[30,34,56] Building sustainable POTWs in the future therefore means increasing POTW energy efficiency and reducing the air emissions associated with consumed electricity. The latter is likely to happen over the coming decades, as the grid reduces its reliance on coal. The former may be addressed through expanded biogas-fueled CHP systems. Our work suggests potential CAP and GHG emission reduction benefits of $289 M (in 2012$) annually. Furthermore, as many states[38,39] move to reduce the climate impacts of water and wastewater treatment, capturing and using fugitive biogas offers a relatively straightforward solution. There are approximately $91.6 million (in 2012 USD) in climate benefits from avoided emissions of 1.5 million tons $CO_{2,eq}$ of methane in biogas.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b04649.

(1) wastewater treatment unit process descriptions and inputs; (2) data sources; (3) a summary of the method for estimating air emissions and damages associated with wastewater treatment; (4) tabulated emissions and damages from Figures 2 and 3; (5) tabulated emissions and damages from electricity emissions using Graff Zivin et al. emissions factors; (6) uncertainty analyses for emissions and damages from wastewater treatment; (7) chemical manufacturing location sensitivity analyses; and (8) uncertainty analysis on biogas-fueled electricity generation (PDF)

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■ NOMENCLATURE

Symbols

BEF	Biogas Electricity Factor [kWh/m^3]
c_p	Heat capacity [J/g·°C]
d	Marginal damages per short ton of air emissions [$/ton]
D	Nationwide damages from air emissions [$/yr]
e	Unit emissions [g/m^3], [g/kWh], [g/g-chemical]
E	Electricity demand [kWh/yr]
HHV	Higher Heating Value [J/m^3]
M	Mass of pollutants [g/yr]
R	Ratio of biogas-fueled heat or electricity generation to heat or electricity demand [-]
ρ	Density [g/m^3]
T	Temperature [°C]
$\forall$	Volume of wastewater treated [m^3/yr]
W	Electricity consumed during wastewater treatment process [kWh/m^3]

Subscripts

baseline	Baseline scenario (no additional biogas-fueled CHP systems installed)
biogas	Biogas generation scenario
electricity	Electricity
g	Unit process
i	POTW
influent	Influent wastewater

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j	Air pollutant (i.e., NO_x, SO_2, $PM_{2.5}$, VOC, CO_2, CH_4, N_2O)
k	County
l	State
mf	Electricity emissions factor
net	Net baseline electricity demand
NG	Natural gas
sludge	Sludge
thermal	Thermal energy
treat	Emissions from the treatment facility that are released during wastewater treatment

Superscripts

Bio	Emissions of biodegradation of organics in wastewater
Comb	Emissions from combustion of biogas
Elec	Emissions from generating electricity consumed to drive wastewater treatment
NG	Emissions from natural gas combustion

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