

Benchmarking Greenhouse Gas Emissions from U.S. Wastewater Treatment for Targeted Reduction

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Abstract

To assess the national climate impact of wastewater treatment and inform decarbonization, we assembled a comprehensive greenhouse gas inventory of 15,867 facilities in the contiguous United States. Considering facility location and treatment configurations, we model on-site CH₄, N₂O, and CO₂ production, and emissions associated with energy, chemical inputs, and solids disposal. Our estimate of 42 million tonnes CO₂-eq·year⁻¹ is over 25% higher than current government national wastewater inventories. Without leak detection and repair programs, facilities with anaerobic digesters currently are responsible for 17 million tonnes CO₂-eq·year⁻¹ of fugitive methane, outweighing the greenhouse gas offsets achieved through on-site electricity generation. Treatment configurations designed for nitrification have the highest greenhouse gas emissions intensity, attributable to high energy requirements and N₂O production, and demonstrating current trade-offs between meeting nutrient removal and climate objectives. We include a geospatial analysis to highlight the scale and distribution of opportunities to reduce life cycle greenhouse gas emissions.

Keywords: wastewater, greenhouse gas emissions, methane, nitrous oxide, energy, carbon intensity

1 Wastewater treatment is essential for protecting public health and the environment. However,
2 treatment processes generate greenhouse gases (GHGs) while relying on energy and chemicals
3 whose production also contributes to total emissions.¹ Globally, the Intergovernmental Panel on
4 Climate Change (IPCC) estimated wastewater treatment emissions to be 0.38 Gt CO₂-eq in 2019,
5 on par with other key industries targeted for decarbonization, including the chemical industry (0.37
6 Gt CO₂-eq), cement (0.82 Gt CO₂-eq), and iron and steel (1.35 Gt CO₂-eq).² Yet, recent studies
7 find IPCC and U.S. Environmental Protection Agency (U.S. EPA) may underestimate methane
8 (CH₄) emissions from on-site processes alone by two-fold,^{3,4} and nitrous oxide (N₂O) emission
9 factors are often oversimplified or inaccurate.⁵ Thus, improved understanding of wastewater GHG
10 emissions is critical for meeting global climate targets, particularly as this sector grows with
11 increasing population and expansion of essential sanitary services.

12
13 On-site emissions at wastewater treatment plants (WWTPs, or water resource recovery facilities)
14 are dependent on wastewater characteristics (e.g. organics, nitrogen), treatment processes, level of
15 treatment, and plant size.^{3,5} N₂O emissions span multiple orders of magnitude, but appear
16 correlated with treatment objective.^{5,6} Biogas used for on-site power generation can reduce
17 imported energy, but CH₄ is emitted from leaking equipment and handling of treated solids.³
18 Additionally, upstream electricity emissions depend on treatment process power requirements and
19 local grid carbon intensity.

20
21 Given this complexity, emissions reduction strategies must consider key plant and geospatial
22 characteristics, energy, and material inputs, considerations not included in current national
23 emissions inventories.⁷ Internationally, several studies report national wastewater treatment
24 inventories (Supplementary Table S1), and all include on-site biogenic CH₄ and N₂O emissions.⁸⁻
25 ¹¹ However, we find inconsistencies in reporting emissions from other sources. For instance, U.S.
26 EPA does not include upstream energy emissions¹¹, and only one inventory considered on-site,
27 non-combustion CO₂ emissions.⁹ Seiple et al. catalogued U.S. facilities as part of their analyses to
28 quantify the energy potential from wastewater sludge but did not estimate GHG emissions or
29 energy consumption.¹²

30

31 Therefore, we developed a novel approach to inventory wastewater emissions based facility
32 location and treatment processes, accounting for includes on-site, upstream and downstream GHG
33 sources. We estimated on-site emissions from treatment processes, on-site and upstream emissions
34 from producing and using energy for facility operation and chemical production, and downstream
35 emissions from offsite disposal of treated solid waste. We used this approach to generate a national
36 emissions inventory of over 15,000 wastewater treatment plants across the contiguous United
37 States. Our approach allows policy makers and engineers to analyze trade-offs inherent to different
38 treatment technologies, and can inform interventions aimed at reducing emissions throughout
39 wastewater treatment. This method can be adapted as new measurement studies improve accuracy
40 of emissions estimates and associated emissions factors.

41
42 For clarity, the following terminology is used in all text and figures: CH₄, N₂O, and CO₂ emissions
43 are collectively described as “process emissions”, and refer to the gases produced on-site during
44 biological wastewater treatment processes, unless otherwise specified. CH₄ and N₂O produced
45 from biosolids disposal are distinguished as “landfill CH₄” and “land application N₂O.” Emissions
46 associated with natural gas include those from natural gas combusted on-site for heat
47 (boiler/drying/incineration) and chemical production, as well as upstream emissions from natural
48 gas extraction and distribution. Electricity associated emissions account for the full fuel cycle from
49 electricity generation (e.g, upstream of and at power plants).

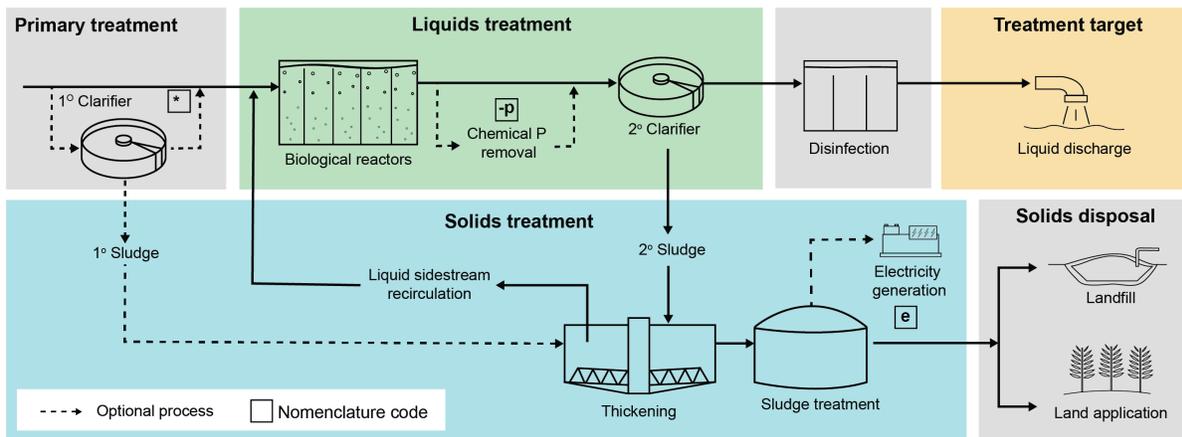
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51 **Main**

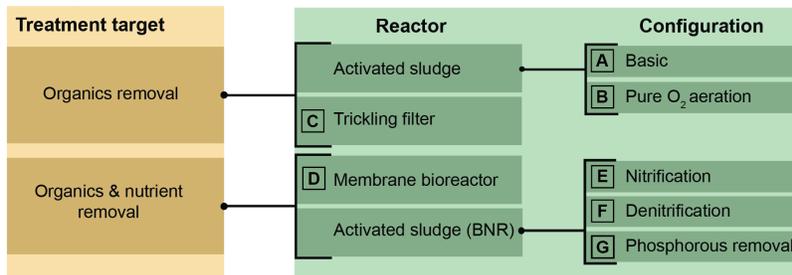
52 *Characterizing U.S. wastewater treatment facilities*

53 Our inventory includes 15,867 WWTPs in the contiguous United States. For each facility, we
54 assigned a treatment train based on publicly available data reported by U.S. EPA.^{13–16} We modeled
55 49 treatment configurations, representative of the major combinations of processes in the United
56 States. Each configuration, referred to with a unique alphanumeric code described in Figure 1,
57 includes liquids and solids treatment, and optional additional processes (full details in
58 Supplementary Methods). Our model uses energy and chemical requirements adapted from
59 previous process models,¹⁷ and determines process emissions based on treatment target and
60 existing unit processes.

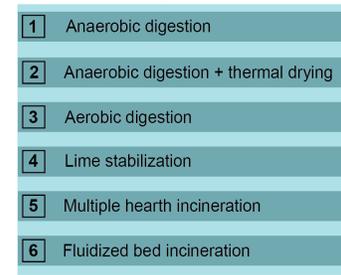
Modeled processes in treatment train configurations



Biological reactor for liquids treatment

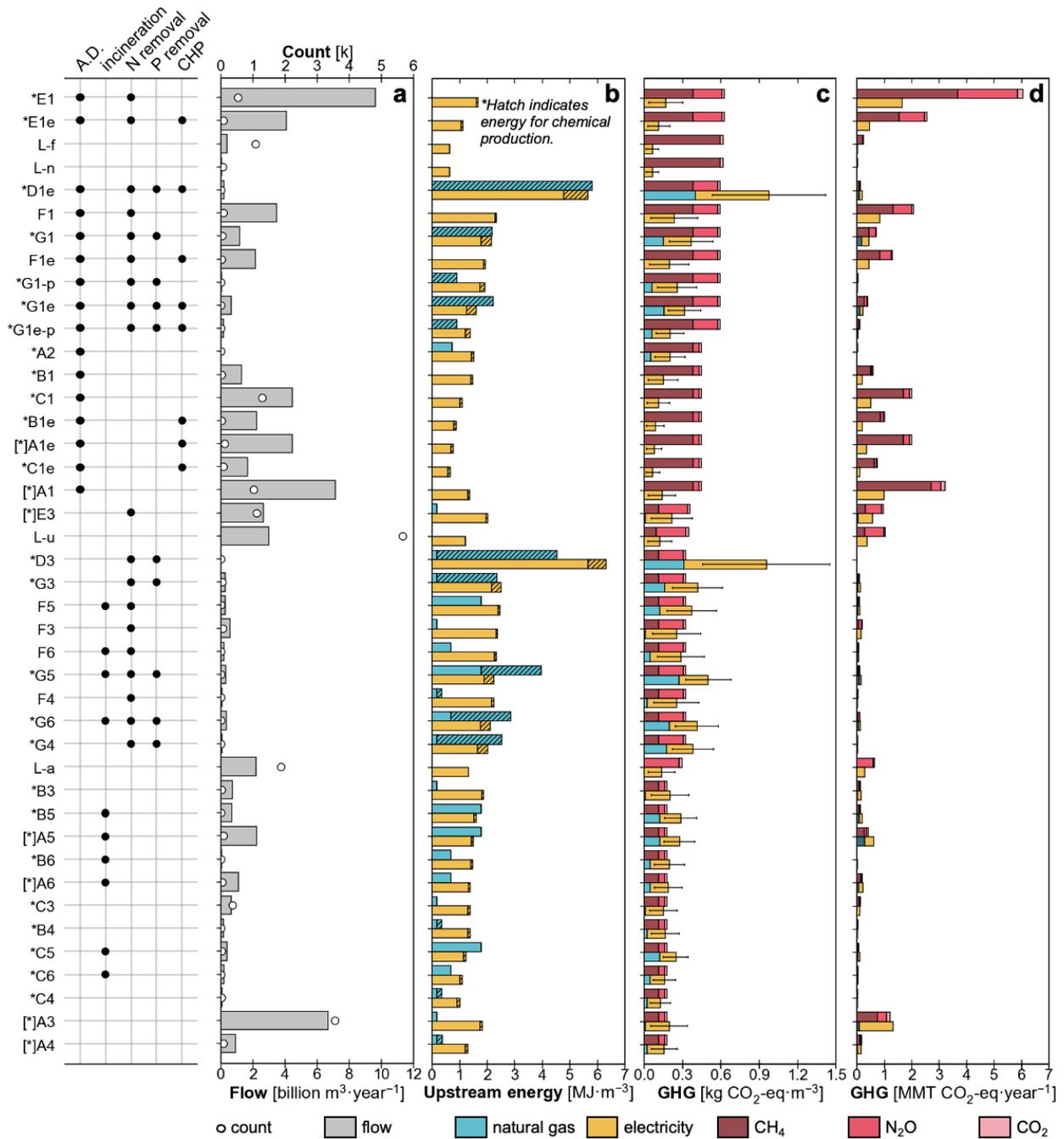


Solids management



61
 62 *Figure 1. Top panel: modeled unit processes for each treatment train, with all major energy consuming*
 63 *processes. Variations in treatment train are determined based on the biological reactor and its*
 64 *configuration (bottom left, in green) and solids management (bottom right). The following processes may*
 65 *also be included or excluded (indicated with the dashed lines): primary treatment, chemical phosphorous*
 66 *removal, and power generation. Naming convention for each treatment train is based on the combination*
 67 *of biological reactor and solids management. The * prefix is added to indicate the presence of primary*
 68 *treatment, and the suffixes -p and e indicate the presence of chemical phosphorous removal and power*
 69 *generation, respectively. All nomenclature codes are depicted in boxes next to the relevant process in this*
 70 *figure. Detailed descriptions of each treatment train can be found in Supplementary Tables S2 and S3.*

71 Figure 2A includes total number of facilities and corresponding treated flow for each treatment
 72 configuration. Basic activated sludge (code A) accounts for 4,746 facilities (30%) and treating 23
 73 billion m³·year⁻¹ (34% of annual flow). However, there are over 8,000 lagoons (aerobic, anaerobic,
 74 facultative, and unclassified) across the country, making them the most abundant technology
 75 despite only treating an estimated 8% of national flow. 32% of facilities use aerobic digestion
 76 (code 3) for solids treatment and 19% use anaerobic digestion (code 1). Facilities with anaerobic
 77 digestion treat 64% of total flow while those with aerobic digestion only treat 17%, indicative of
 78 the large size of facilities with anaerobic digestion. Additionally, 321 facilities recover energy
 79 from biogas production, accounting for 10% of plants with anaerobic digestion. Facilities with
 80 energy recovery are large, with an average flow rate of 139,000 m³·day⁻¹ (37 MGD).



81

82 Figure 2. Count, flow, energy, and emissions for treatment trains (identical configurations with and without
 83 primary treatment are combined). The salient features of trains are shown on the left (A.D.: anaerobic
 84 digestion; CHP: combined heat and power). Trains that begin with L- are lagoons. a: aerobic; n:
 85 anaerobic; f: facultative; and u: uncategorized, which we calculate based on the flow-weighted average of
 86 aerobic and anaerobic/facultative lagoons. Other codes are defined per logic in Figure 1. a, count and
 87 flowrate. b, energy consumption. Hatched areas represent energy used for chemical production (i.e.,
 88 methanol, acetic acid, hypochlorite, and lime). c-d, greenhouse gas emissions for each treatment train by
 89 volume treated (C) and annually (D). Red bars indicate on-site GHG emissions. The shade of red indicates
 90 whether these emissions are CH₄ (darkest shade), N₂O (medium), or CO₂ (lightest). Yellow bars indicate
 91 upstream emissions associated with providing electricity to the WWTP. The electricity emissions reflect

92 *national average carbon intensity of electricity production, with the error bars representing the standard*
93 *deviation of the national electricity grid. Blue bars indicate emissions associated with on-site natural gas*
94 *combustion (dark) and natural gas extraction and transportation (light). Emissions associated with*
95 *biosolids handling are not included in the figure due to their limited contribution to the total emission.*

96

97 The most common treatment train is basic activated sludge coupled with aerobic digestion (code
98 [*]A3), accounting for 22% (3,555) of all facilities and treating 10% of national flow (6.7 billion
99 m³·year⁻¹). A lower proportion of all facilities (7%), basic activated sludge with anaerobic
100 digestion ([*]A1) is the configuration that treats the most wastewater (17%). All nutrient
101 transformation configurations combined (codes D, E, F, G) account for a small portion of total
102 facilities (13%) but treat 39% of total national flow (26 billion m³·year⁻¹).

103

104 *Electricity and natural gas requirements*

105 We determined the electricity and natural gas needed for each treatment train (Figure 2B) by
106 expanding existing models¹⁷ to account for the full range of treatment configurations in the United
107 States. The least energy intensive configurations require less than 0.2 kWh electricity·m⁻³ and no
108 natural gas (trickling filter with anaerobic digestion (*C1e), anaerobic/facultative lagoons).
109 Conversely, the most intensive configurations use membrane bioreactors for biological nutrient
110 removal (*D1e and *D3) and consume over 1.5 kWh electricity·m⁻³, primarily for powering
111 bioreactors, and over 4.5 MJ natural gas·m⁻³, largely for producing acetic acid used in nutrient
112 removal.

113

114 With increased pumping and aeration for nitrification, the top electricity consuming configurations
115 biologically remove nutrients during secondary treatment (codes D, E F, G). Process electricity is
116 greater than electricity for chemical manufacturing, and accounts for over 80% of total electricity
117 in the top ten energy consuming configurations. However, in biological phosphorous removal
118 processes (codes D and G), acetic acid comprises a more sizeable share of electricity use (mean:
119 15%, range: 9 – 22%). Consequently, local grid mix will electricity emissions rather than chemical
120 manufacturing. Biological phosphorous removal requires the most natural gas, of which on
121 average 90% is used for acetic acid production, although this proportion decreases when solids are
122 stabilized with incineration. Reducing natural gas dependency will require more sustainable
123 chemical manufacturing and selection and reduced reliance on incineration.

124

125 *Carbon dioxide, methane, and nitrous oxide emissions*

126 Across different treatment trains, CH₄ and N₂O combined account for 88 – 96% of process
127 emissions, with CO₂ exceeding 10% only at facilities designed for organics removal and without
128 any anaerobic processes. The highest process emissions originate from facilities with nitrification
129 (code E), anaerobic or facultative lagoons (L-f and L-n), and anaerobic digestors (codes 1 and 2)
130 (Figure 2C). Nitrification with anaerobic digestion (*E1[e]) produce 0.63 kg CO₂-eq·m⁻³, with
131 61% from CH₄ and 36% from N₂O. Anaerobic and facultative lagoons produce 0.62 kg CO₂-
132 eq·m⁻³, 97% of which is CH₄. However, each configuration's contribution to annual emissions
133 depends on the abundance and flow rate of facilities (Figure 2D). Nationwide, nitrifying facilities
134 (code E) are the largest contributors, generating an estimated 9.6 million metric tonne (MMT)
135 CO₂-eq·year⁻¹, followed by activated sludge facilities (code A), which contribute 7.2 MMT CO₂-
136 eq·year⁻¹ despite a much lower flow-normalized emission rate. All types of lagoons, in contrast,
137 contribute 1.9 MMT CO₂-eq·year⁻¹.

138

139 *Total emissions by treatment configuration and nation-wide*

140 Total emissions include process emissions, energy emissions, and downstream emissions from
141 treated biosolids land application or landfill disposal. To facilitate comparison between generic
142 configurations, we calculated emissions intensity (kg CO₂-eq·m⁻³) for each treatment train (Figure
143 2C) using national average carbon intensity of the electrical grid. Total emissions associated with
144 inventoried facilities use the carbon intensity of the plant's local grid (Figure 2D, and Figures 4
145 and 5). Highest total emissions are from configurations removing nutrients with membrane
146 bioreactors: *D1e (1.61 kg CO₂-eq·m⁻³) and *D3 (1.32 kg CO₂-eq·m⁻³). For both trains, over 60%
147 of emissions are from energy consumption, attributable to the electricity requirement of membrane
148 systems and the natural gas needed for acetic acid production. The train with the next highest
149 carbon intensity is *G1 (1.00 kg CO₂-eq·m⁻³). Here, 63% of emissions are produced through
150 biological treatment (CH₄, N₂O) and 37% are from electricity and natural gas use. Understanding
151 whether emissions are driven by treatment processes or electricity requirements will inform
152 decarbonization strategies, particularly as the grid carbon intensity decreases over time.¹⁸ Biosolids
153 disposal never accounts for more than 15% of total emissions. Finally, by comparing identical

154 configurations with and without CHP, we find that energy recovery only reduces total emissions
 155 by 5 – 10%.

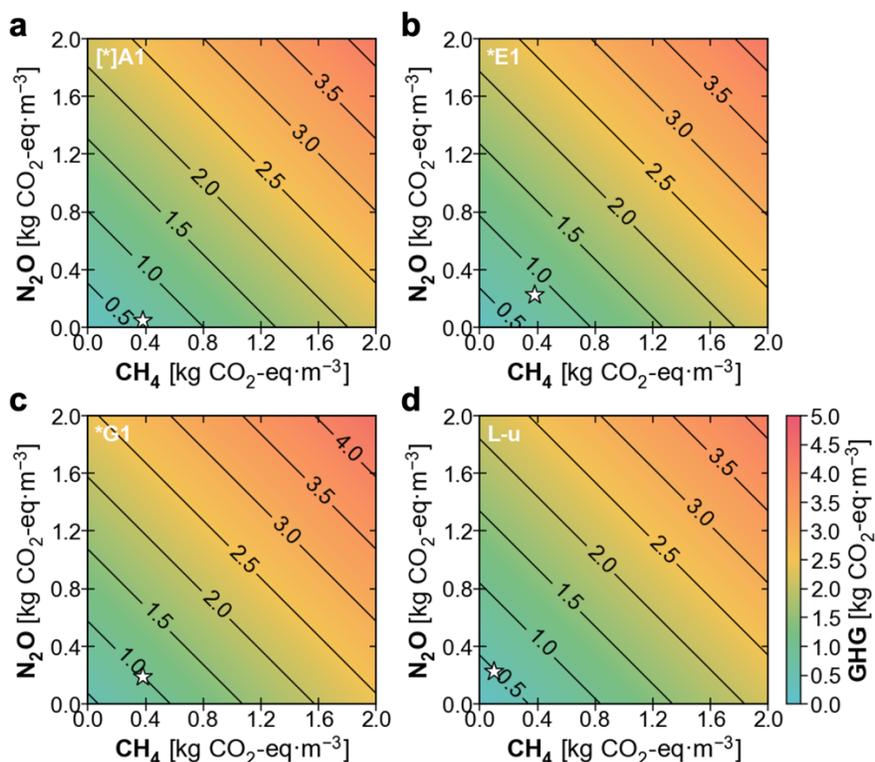
156
 157 Nationally, wastewater treatment produces 42 MMT CO₂-eq·year⁻¹ (Table 1). CH₄ dominates
 158 annual emissions (45%), followed by electricity (25%) and N₂O (20%). Because CH₄ and N₂O
 159 estimates depend on emissions factors, Figure 3 depicts a sensitivity analysis for key treatment
 160 trains, varying emissions factors according to the ranges observed in measurement studies.^{3,5}
 161 Supplementary Figure S1 includes similar plots for each treatment train. Given the range of current
 162 measurement data, our assumed emissions factors are conservative, limiting the influence of
 163 potential outliers. However, with the paucity of high-quality measurement data, the degree to
 164 which current emission factors range represent the true distribution of emissions remains to be
 165 determined.

166 *Table 1. Annual emissions from wastewater treatment in the United States*

Emissions Type		Annual Emissions (MMT CO ₂ -eq·year ⁻¹)	Percent of total emissions (%)
Process emissions (produced through biological treatment)	Methane	19	45
	Nitrous oxide	8.6	20
	Carbon dioxide	1.4	3.3
Energy emissions	Electricity*	11	25
	Natural gas (combustion for on- site processes & chemical production)	1.0	2.4
	Natural gas production & distribution	0.23	0.55
Downstream emissions from biosolid disposal	Landfill methane	0.48	1.1
	Land application nitrous oxide	0.83	2.0
<i>Total</i>		<i>42</i>	<i>100</i>

167 * Electricity estimates in the national inventory are based on local balancing area carbon intensities.

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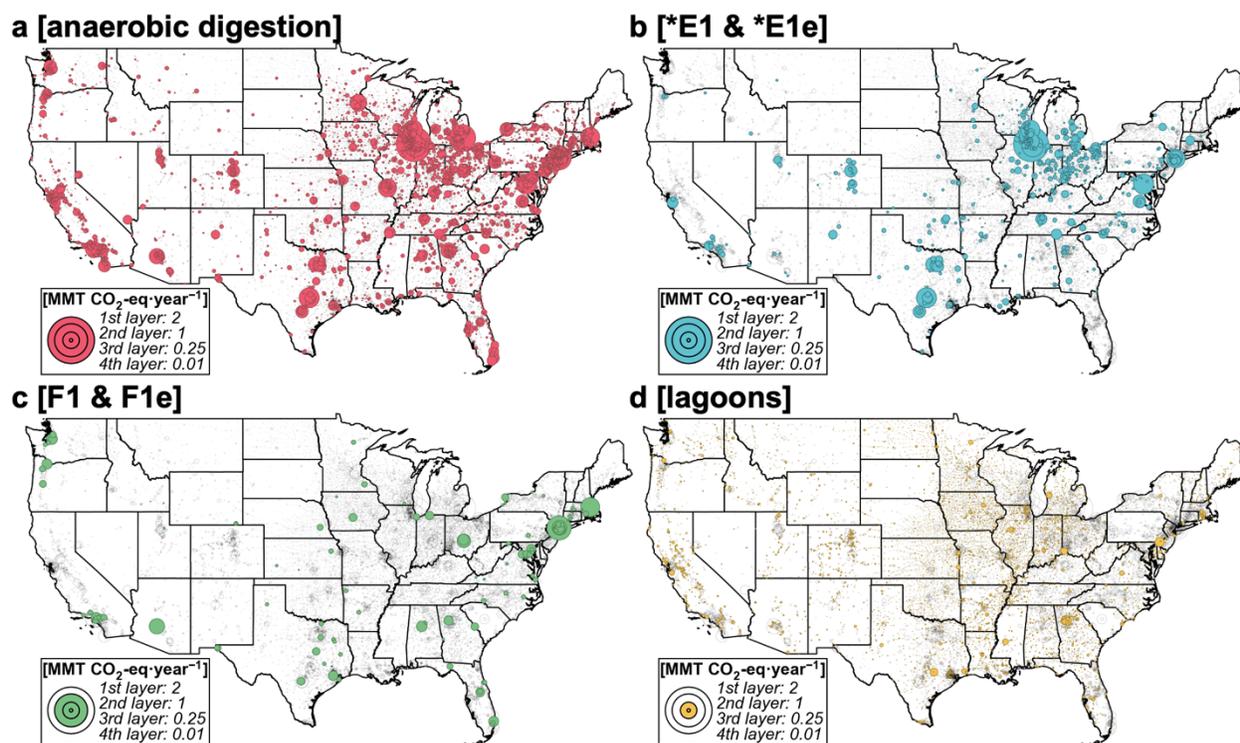


169
 170 *Figure 3. Sensitivity analysis of total GHG emission on CH₄ and N₂O emission factors for different*
 171 *treatment trains: A) [*]A1, B) *E1, C) *G1, and D) uncategorized lagoons. White stars in the heatmaps*
 172 *represent the baseline emission factors used in this study. Heatmaps for other treatment trains can be found*
 173 *in the Supplementary Information.*

174
 175 *National distribution of GHG emissions from WWTP*

176 Figure 4 depicts the geographic distribution of emissions from selected treatment configurations:
 177 anaerobic digestion, *E1[e], F1[e], and lagoons (see Supplementary Figure S2 for similar plots for
 178 each treatment trains). Emissions are highly distributed but cluster with major population centers,
 179 although nutrient removal configurations, particularly nitrification (*E1[e]), is more abundant in
 180 the eastern half of the country. The high density of anaerobic digestion facilities indicates that
 181 novel aerial techniques capable of surveying large geographic regions may be promising for leak
 182 detection.^{19,20} While lagoons account for 6.4% of emissions in our inventory, these facilities are
 183 small, highly distributed, and largely of unknown operation, thus posing a potential challenge to
 184 mitigation efforts. In aggregate, we find that 8% of facilities account for 80% of emissions (Figure
 185 5A) and treat 76% of total flow, reflecting the strong linear relationship between total emissions
 186 and total flow (Figure 5B). The largest 10 facilities in the country (0.06% of facilities, treating
 187 10% of national flow) disproportionately account for 11% of total emissions (Figure 5C).

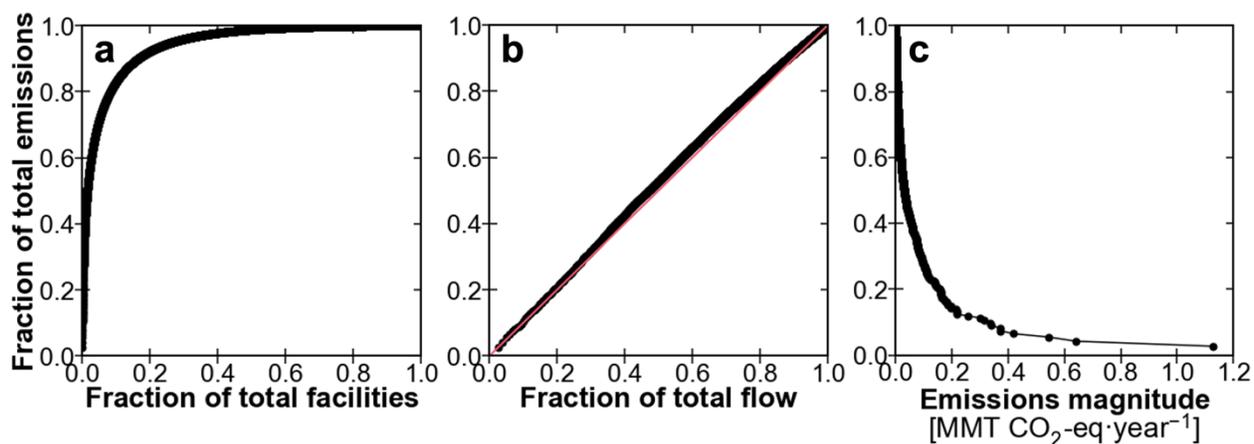
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189

190 Figure 4. Geographic distribution of emissions from selected treatment processes and trains: A) all
 191 facilities with anaerobic digestion (codes 1 and 2), B) *E1 and *E1e, C) F1 and F1e, and D) all lagoons
 192 (aerobic, anaerobic, facultative and unclassified). Legends from inner to outer rings represent annual
 193 emission of 0.01, 0.25, 1, and 2 MMT CO₂-eq, respectively. Non-shaded legend indicates no wastewater
 194 treatment plant has emission in the corresponding level.

195



196

197 Figure 5. Distribution of total emissions in the United States. In each plot, individual points represent a
 198 single facility, and the y-axis represents the fraction of total emissions. The x-axes represent: A) fraction of
 199 total facilities, B) fraction of total flow when facilities are sorted by flow rate from largest to smallest and
 200 the red line representing $x=y$, and C) magnitude of emissions from a single facility, with facilities sorted
 201 from lowest to highest emissions. The red line in B) represents parity of x- and y-axis values.

202

203 **Discussion and Conclusion**

204 We estimate that emissions from wastewater treatment in the United States are 42 MMT CO₂-
205 eq·year⁻¹, with CH₄ and N₂O accounting for 64% of emissions. Compared to previous works
206 (Supplementary Table 1), our approach integrates a greater number of emissions sources, including
207 electricity, CO₂ (fossil-origin), and biosolids disposal. We estimate GHG intensity for specific
208 treatment trains (0.34-1.61 kg CO₂-eq·m⁻³) are consistent with those modeled by U.S. EPA (0.5-
209 1.8 kg CO₂-eq·m⁻³), although the relative contributions of different components differ.²¹ Our
210 national estimate of CH₄ emission (19 MMT CO₂-eq·year) is comparable to that of Song et al.,
211 who estimate 10.9 ± 7.0 MMT CO₂-eq·year from centralized facilities only.³ Our nationwide
212 estimate for nitrous oxide (8.6 MMT CO₂-eq·year) is slightly lower than the reported values by
213 Song et al. 11.6 MMT CO₂-eq·year, calculated with emissions factors organized by bioreactor type
214 and using a Monte Carlo approach.⁵ While we use the same underlying data, the differences in
215 nationwide estimates reflect the overall high degree of uncertainty in nitrous oxide emissions
216 factors and the need for additional research in this area.

217

218 Methane emissions are the largest single contributor to annual emissions in our inventory. We find
219 85% (17.0 MMT·year⁻¹) of CH₄ is produced facilities with anaerobic digestion (code 1 or 2).
220 Anaerobic digestion produces energy on-site in the form of biogas, while reducing the spatial
221 footprint of WWTPs and providing additional opportunities for resource recovery.²² However,
222 currently fugitive CH₄ emissions outweigh climate benefits gained from renewable biogas. On a
223 volumetric basis, energy recovery (code suffix e) reduces emissions by 0.04 – 0.06 kg CO₂-eq·m⁻³
224 ³. In contrast, we estimate facilities with anaerobic digesters produce 0.4 kg CO₂-eq·m⁻³, increasing
225 estimated CH₄ emissions by 0.27 kg CO₂-eq·m⁻³ compared with aerobic digesters. Additional
226 research is necessary for inventories to reflect the variation within anaerobic digestion facilities,
227 as emissions will differ with reactor design, operation, and maintenance frequency. However, leak
228 detection and repair should immediately be adopted globally.

229

230 We developed N₂O emission factors adapted from those compiled by Song et al. 2024,
231 distinguishing based on treatment objectives (organics removal, nitrification, denitrification).⁵
232 However, 79% of the underlying measurement data comes from denitrifying systems.²³ Additional

233 measurements are needed from conventional activated sludge and nitrifying systems. Given the
234 high spatial and temporal variability in N₂O emissions from wastewater treatment,⁶ improving the
235 characterization of N₂O production is essential. Additionally, current N₂O mitigation efforts use
236 aeration, feed, and process optimization,²⁴ which are not captured in existing facility-level data.
237 Understanding current operation strategies and their impact on emissions should be a focus of
238 future research.

239
240 The relative importance of electricity generation (25% of total emissions) will decrease with grid
241 decarbonization efforts. While natural gas extraction and distribution is only 0.55% of total
242 emissions, we did not account for recent aerial surveys that find large upstream emissions from oil
243 and gas that are missing from official estimates.²⁵ Biosolids disposal through landfilling or land
244 application only contribute a small portion of total emissions (1.1% and 2.0%, respectively), but
245 CH₄ and N₂O from biosolids are poorly studied. We used IPCC's emission factor for land
246 application, which has a high uncertainty (0.003 – 0.03 kg N₂O-N·kg N⁻¹).²⁶ Recent studies
247 measured emissions when biosolids were used as an agricultural amendment, but were conducted
248 in Canada^{27–29} where the colder climate would affect microbial activity. We repeated our analysis
249 using measurement data from the Canadian studies, and found no meaningful difference in our
250 results compared with using IPCC's emission factor. Finally, our model did not account for CH₄
251 produced through different practices for biosolids dewatering and on-site storage, which also likely
252 contribute to fugitive CH₄ emissions.

253
254 U.S. EPA provides, to the best of our knowledge, the only other national level inventory of
255 wastewater treatment emissions in the United States. Our estimate of 42 MMT·year⁻¹ is 27% higher
256 than the EPA's estimate of 33 MMT, a difference largely attributable to our inclusion of electricity
257 associated emissions. Because we focus on emissions that can inform decarbonization efforts, we
258 do not include effluent discharge in our inventory while the EPA does. However, the total on-site
259 CH₄ and N₂O emissions in our inventory (28 MMT·year⁻¹) is similar to EPA's value of 29 MMT
260 in 2022. Notably, the relative contributions of the two gases differ, with CH₄ contributing 69%
261 (18.0 MMT·year⁻¹) in our inventory and only 41% (11.6 MMT) in the EPA inventory. This
262 difference is meaningful, as the relative importance of each gas will inform decarbonization
263 strategies and government investment. CH₄ and N₂O emissions are produced by different

264 wastewater treatment processes via distinct microbial pathways, which are impacted by local
265 climate (e.g. temperature and seasonal changes to operation⁶). When also considering differences
266 in atmospheric lifespan and global warming potential, mitigation approaches for CH₄ and N₂O will
267 differ substantially.

268
269 There are several limitations to the current inventory and opportunities for additional future
270 refinement. Importantly, improving emissions factors for CH₄ and N₂O will require direct
271 measurement studies across a full range of representative facilities, climates, and time periods, and
272 is necessary for determining emission profiles and evaluating performance of mitigation strategies.
273 Our results find a strong linear relationship between cumulative national flow rate and emissions.
274 However, most recent national flow data collected by the EPA on 2022 does not distinguish
275 between observed and design flow at facilities, meaning we likely overestimate the amount of
276 wastewater treated. Additionally, we use uniform average influent concentration for all facilities,
277 and do not account for variations in effluent requirements based on local regulations. We also
278 made the simplifying assumption that, within a particular treatment plant configuration, energy
279 consumption is directly proportional to flow rate (despite the potential for increased efficiency at
280 larger sizes).³⁰ Additionally, the energy requirements for lagoons may not reflect current designs
281 and operation.³¹ We use current IPCC assumptions that aerobic lagoons do not produce CH₄ and
282 that anaerobic lagoons do not produce N₂O. However, given lack of fully uniform mixing, and the
283 many connections between CH₄ and nitrogen microbial metabolism,³² it is likely both gases are
284 produced across all lagoon categories.

285
286 Our analysis only considers climate impact, but facility-level decision making requires more
287 comprehensive environmental assessment. For example, trickling filter configurations are among
288 those with the lowest total emissions. However, trickling filters have large spatial requirements
289 and require adequate hydraulic head differences across the plant to limit pumping requirements.
290 Additionally, because anaerobic digesters are the largest source of on-site emissions, facilities
291 using incineration (codes 5 and 6) compare favorably because they have lower on-site emissions.
292 However, incineration requires adequate pollution control measures to prevent release of
293 particulates, heavy metals, and volatile organic compounds, considerations that we do not capture.
294

295 Wastewater treatment is a growing sector inextricably linked to public and environmental health,
 296 and understanding its current climate change impact is critical for decarbonization efforts. This
 297 analysis provides a comprehensive inventory of emissions from over 15,000 wastewater treatment
 298 plants across the United States. We identify on-site emissions of CH₄ and N₂O as priorities for
 299 climate change mitigation efforts. Additionally, data generated from this work can be used in
 300 subsequent studies to analyze the effects of adopting novel resource recovery and decarbonization
 301 technologies.

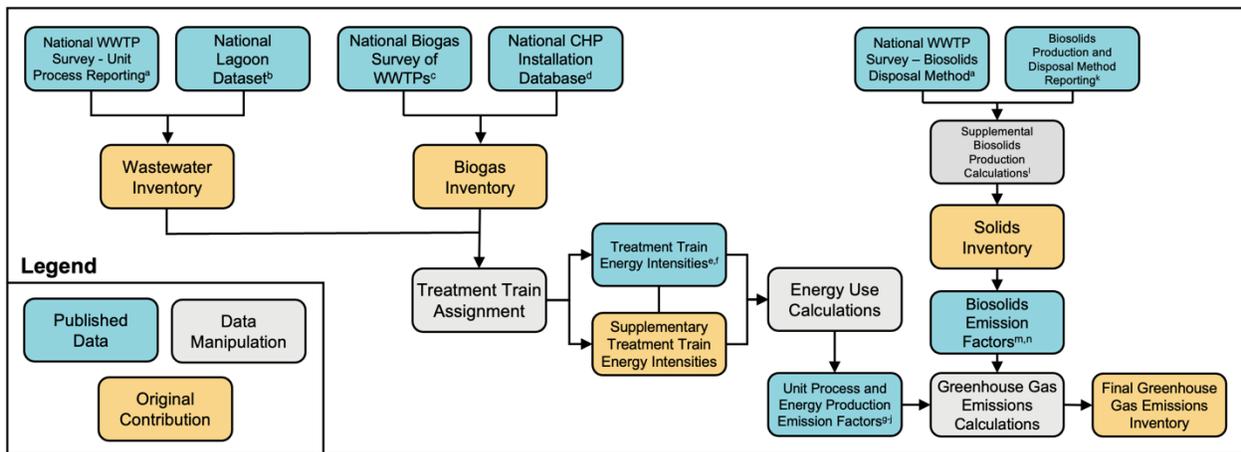
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303 **Methods**

304 *Facilities inventory development*

305 We integrate multiple national datasets to compile a national inventory of all wastewater treatment
 306 facilities in the United States, their energy requirements, and greenhouse gas emissions (Figure 6).
 307

307



308

309 *Figure 6. Methodology overview for construction of facility inventory and calculation of energy*
 310 *consumption and GHG emissions at each facility. References listed in the flow chart are: ^aClean*
 311 *Watersheds Needs Surveys (2004, 2008, 2012, 2022)^{13–16} ^bU.S. EPA’s inventory of lagoons serving as the*
 312 *primary method of wastewater treatment at a given facility³³ ^cWater Environment Federation survey of*
 313 *wastewater treatment plants with biogas production³⁴ ^dU.S. Department of Energy’s survey of facilities with*
 314 *combined heat and power³⁵ ^eTarallo et al, 2015 modelled energy requirements for treatment trains¹⁷ ^fU.S.*
 315 *EPA estimate of lagoon energy requirements³³ ^gGREET model³⁶ ^hIPCC emissions factors for lagoons³⁷*
 316 *ⁱSong et al 2023 methane emissions factors from wastewater treatment plants³ ^jSong et al 2024 nitrous*
 317 *oxide emissions factors for wastewater treatment plants⁵ ^kEPA annual report on biosolids production and*
 318 *disposal methods³⁸ ^lBiosolid calculations outlined in Seiple et al., 2017³⁹ ^mIPCC emissions factors for land*
 319 *applied biosolids²⁶ ⁿU.S. EPA’s LandGEM model for estimating methane emissions from landfills⁴⁰.*

320 For each facility in our national inventory (15,867 that reported non-zero flow in 2022), we assign
 321 one or more treatment trains based on the unit processes reported as part of facility operations

322 across the aggregated 2004, 2008, 2012, and 2022 Clean Watersheds Needs Surveys (CWNS). A
323 treatment train is defined in our work as a common set of unit operations designed to wastewater
324 pollution between the influent and effluent of the plant. We supplement CWNS data with
325 additional publicly available data that provide more granular or recent information, including:
326 EPA's Lagoon Inventory Dataset,³³ Water Environment Federation's (WEF) Water Resource
327 Recovery Facilities Biogas Database,³⁴ and U.S. Department of Energy's (DOE) Combined Heat
328 and Power Installation Database.³⁵ Full details are provided in Supplementary Methods.

329
330 From the cumulative unit process list, we assign one or more treatment trains as an alphanumeric
331 code for each facility based on those previously defined by Tarallo et al., 2015,¹⁷ with
332 modifications to reflect additional possible combinations of liquids and solids treatment processes.
333 Each treatment train is a unique combination of unit processes based on secondary treatment
334 technology, nutrient removal, and biosolids management. Treatment train key processes and
335 naming convention are included in Figure 1. Each treatment train includes a solids and liquids
336 treatment component, with additional optional processes for primary treatment, chemical
337 phosphorous removal, and CHP for energy recovery. Supplementary Tables S2 and S3 describe
338 key characteristics of the solids and liquids treatment processes, respectively. For the purposes of
339 assigning a treatment train, we disregard the presence of tertiary treatment processes, unless related
340 to nutrient removal.

341
342 Using available unit process data, we assigned treatment trains to 10,964 facilities, approximately
343 69% of the national fleet. For the 1,992 facilities with only partial unit process data available (i.e.,
344 plants that provide information on secondary treatment or solids management but not both), we
345 assigned treatment trains based on the most common treatment train of the same plant size and
346 EPA region, considering key unit processes present (activated sludge, biological nutrient removal,
347 aerobic/anaerobic digesters, lime stabilization, incineration, and trickling filters). For the
348 remaining facilities with either insufficient partial data or fully absent data (2,911 facilities), we
349 assigned a treatment train based on the most common treatment train of the same plant size and
350 EPA region (see Supplementary Table S5 for size breakdown and details on facilities with missing
351 data).

352

353 *Facility-level emissions associated with energy*

354 For all treatment trains in the national inventory, we calculated electricity and natural gas
355 consumption, as well as on-site electricity generation from biogas utilization. We use energy
356 calculations from the results of process models in GPS-XTM reported by Tarallo et al., 2015.¹⁷
357 Because our study includes treatment trains beyond those reported by Tarallo et al., we use mass
358 and heat balances for unit processes to determine energy requirements for treatment trains that
359 were not modeled previously.¹⁷ Full details are included in Supplementary Methods.

360
361 To estimate the GHG emissions associated with electricity consumption, we assigned emissions
362 factors (kg CO₂-eq·kWh⁻¹) based on the balancing region where each facility is located. There are
363 134 balancing authority areas across the United States that provide boundaries for maintaining a
364 load-interchange-generation balance of energy resources,⁴¹ and the energy mix contributing to the
365 grid in each balancing area differs. We use the NREL Standard Scenarios Cambium data for 2020
366 to calculate the electricity emissions factor (kg CO₂-eq·kWh⁻¹) using total emission (kg CO₂-eq)
367 from a given balancing area divided by the net power generated.¹⁸ We use the mid-case scenario
368 based on central parameter values, including future electricity consumption, fuel costs, and
369 technology selection. We also calculate full fuel cycle GHG emissions for electricity and natural
370 gas using the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET)
371 model.³⁶ Additional details are provided in Supplementary Methods.

372

373 *Carbon dioxide, methane, and nitrous oxide*

374 We estimated total CO₂, CH₄, and N₂O from biological treatment processes, referred to here as
375 “process emissions” for brevity. For CO₂, we assumed 15% of influent carbon is of fossil origin,
376 and 35% of influent COD (400 mg·L⁻¹) is released as CO₂ during biological treatment.⁴² To
377 determine CH₄ and N₂O production, we used emissions factors based on the presence of key unit
378 processes or treatment targets. For example, anaerobic digesters and nutrient removal processes
379 emit methane and nitrous oxide, respectively. For CH₄, we used data reported by Song et al. 2023
380 to assign emissions based on whether a facility contains an anaerobic digester.³ For N₂O, we use
381 a modified approach based the emissions factors compiled in Song et al., 2024, assigning emissions
382 factors based on treatment objectives: organics removal, nitrification or full denitrification (see
383 Supplementary Methods for full details).⁵ For lagoons, we use IPCC values for aerobic, anaerobic,

384 and facultative lagoons.³⁷ For uncategorized lagoons, we use a flow weighted average of the three
385 other types of lagoons in the contiguous United States. For specific emissions factors and
386 additional details, see Supplementary Methods.

387

388 *Biosolids associated emissions*

389 We estimate biosolids production from 2,877 facilities using EPA's Biosolids Biennial Report for
390 2020-2021.³⁸ This report documents the volume of biosolids produced at a subset wastewater
391 treatment facilities, and their ultimate disposal through incineration, landfilling, or land
392 application. For the remaining facilities, we estimate production using methods previously
393 described (see Supplementary Methods for full details).¹² For land applied biosolids, we used the
394 IPCC emissions factor for organic soil amendments.⁴³ For landfills, we used U.S. EPA's Landfill
395 Gas Emissions Model (LandGEM) to estimate emission factors for CH₄ from municipal solid
396 waste landfill.⁴⁰ Full details are included in Supplementary Methods.

397

398 **Data Availability**

399 The data used in the analysis and figures are publicly available except the underlying data from
400 process models in Tarallo et al. 2015, which was made available to the authors upon request. Data
401 from the Clean Watersheds Needs Survey is available through the U.S. EPA
402 (<https://www.epa.gov/cwns>). Data on electricity generation from biogas is available through the
403 Department of Energy's Combined Heat and Power Installation Database
404 (<https://doe.icfwebservices.com/chp>) and the Water Environment Federation's Water Resource
405 Recovery Facilities Biogas Database (<https://www.resourcerecoverydata.org/>). Additional data on
406 the presence of lagoons is available through the U.S. EPA ([https://www.epa.gov/small-and-rural-
wastewater-systems/lagoon-wastewater-treatment-systems#dataset](https://www.epa.gov/small-and-rural-wastewater-systems/lagoon-wastewater-treatment-systems#dataset)). Balancing area data is
407 available through the National Renewable Energy Laboratory (<https://scenarioviewer.nrel.gov/>).

409

410 **Code Availability**

411 Code supporting this study is available at https://github.com/jiananf2/US_WWTP_GHG.

412

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432
433 **Author contributions**
434 Conceptualization was performed by J.S.D., J.B.D, M.M.B., M.A., S.H.E., J.F., J.M. Methodology
435 were developed by J.S.D., S.H.E., J.B.D., J.F., J.S.G., A.R.H., M.M.B., M.A., J.M. Validation was
436 conducted by J.F., S.H.E., A.R.H., C.P. Data Curation was performed by J.F., A.H., C.P., M.B.
437 Formal analysis and software development was performed by J.F., J.S.D., P.Z., S.H.E., A.R.H.,
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440 and editing was performed by all authors. Funding acquisition was conducted by J.S.D., J.B.D.,
441 and J.M. Supervision was performed by J.S.D., J.B.D., J.S.G., and S.H.E.

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537

Supplementary Information

for

Benchmarking Greenhouse Gas Emissions from U.S. Wastewater Treatment for Targeted Reduction

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This Supplementary Information contains 48 pages, 15 figures, and 22 tables.

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1 **1. Supplementary Results**

2
3

Table S1. Summary of recent national-level wastewater treatment plan greenhouse gas inventories.

	European Union ¹	China ²	China ³	U.S. ⁴	U.S. (this work)
Methodology					
	Bottom-up ^a	Bottom-up ^a	Bottom-up ^a	Top-down ^b	Bottom-up ^a
Emission breakdown ^c					
Electricity generation	Y (2)	Y (2)	Y (2)	N	Y (2)
Natural gas	N	N	N	N	Y (2)
Biological process CH ₄	Y (1)	Y (1, 2)	Y (2)	Y (1, 2)	Y (1, 2)
Biological process N ₂ O	Y (1, 2)	Y (1, 2)	Y (2)	Y (1, 2)	Y (1, 2)
Onsite non-combustion CO ₂ (biogenic)	N	Y ^d (2)	N	N	N
Onsite non-combustion CO ₂ (fossil)	N	Y ^d (2)	N	N	Y (2)
Sludge handling	Y (2)	N	N	Y (2)	Y (1,2)
Sludge disposal	N	N	N	N	Y (1, 3)
Effluent discharge	Y (1)	Y (1)	N	Y (1)	N
Infrastructure	Y (2)	N	N	N	N
Results					
Flow (billion m ³ /year)	N/A	67 ^e	65	N/A	67
Emission (million tonne CO ₂ -eq/year)	34	30 ^e	56	35	42

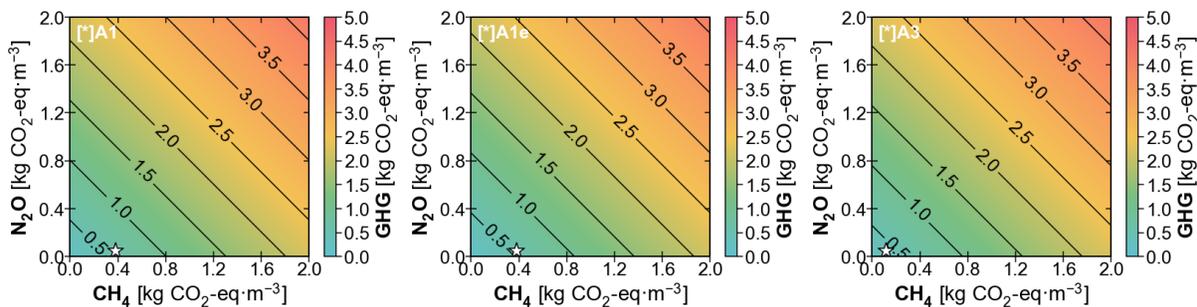
4 ^a Bottom-up: facility-level emission data aggregated to national level emission.
 5 ^b Top-down: national level emission directly estimated based on national level flow rate or population data.
 6 ^c Y/N represents whether an emission type was included, followed by sources in the parenthesis (1= IPCC, 2=literature
 7 and/or government reports, 3=process modeling)
 8 ^d Fossil and biogenic emissions are not differentiated.
 9 ^e Flow and emission in 2019.

10

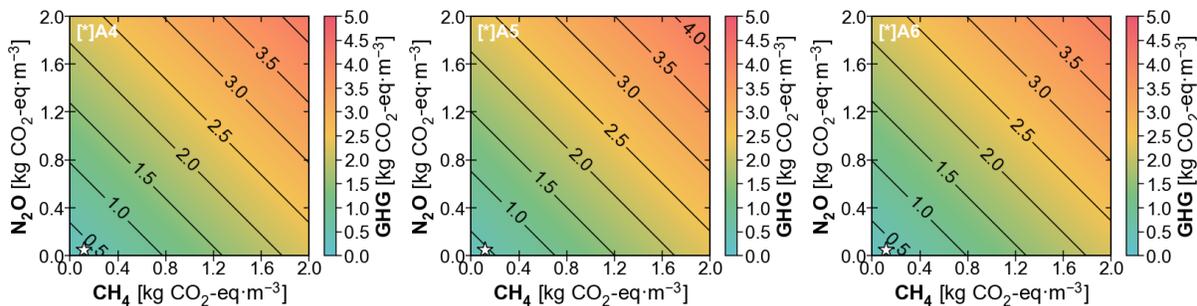
11 We include the following supplementary files with tabulated results in spreadsheet format:

- 12 1. **Supplementary Dataset A:** Wastewater treatment inventory of facilities.
- 13 2. **Supplementary Dataset B:** Greenhouse gas emissions results for each treatment train.
 14 Includes count, flow, energy requirement, per volume greenhouse gas emissions, and
 15 annual GHG emissions.
- 16 3. **Supplementary Dataset C:** Greenhouse gas emissions inventory, including facility level
 17 results including identifying information and greenhouse gas emissions for each facility.

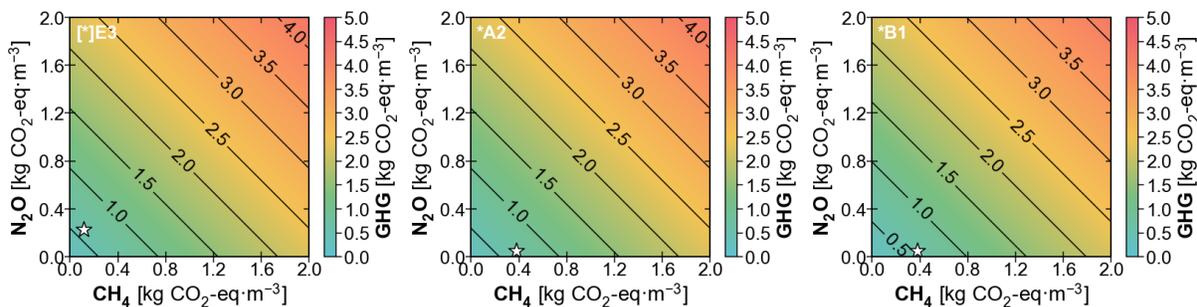
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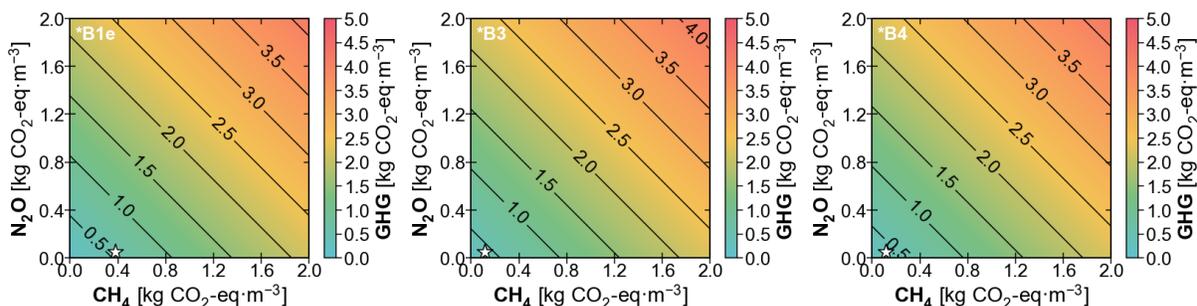
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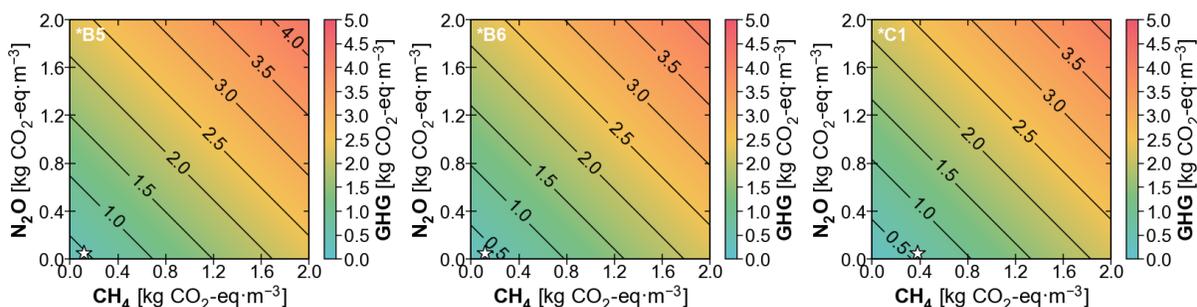
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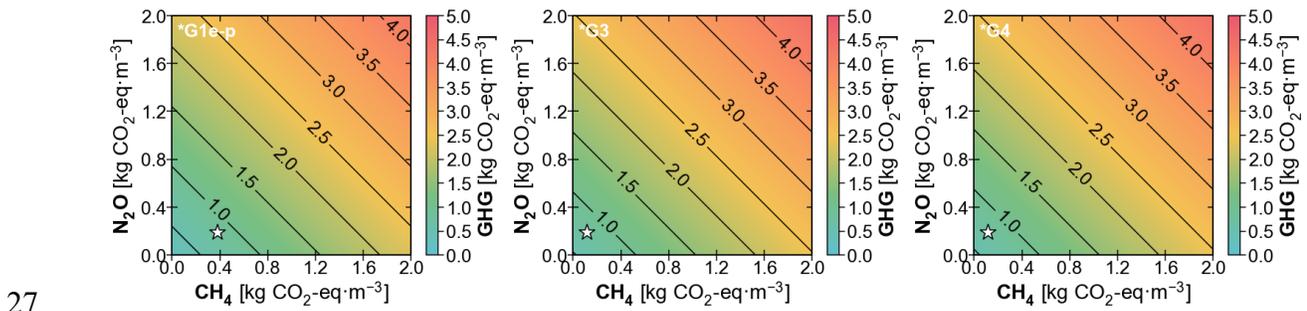
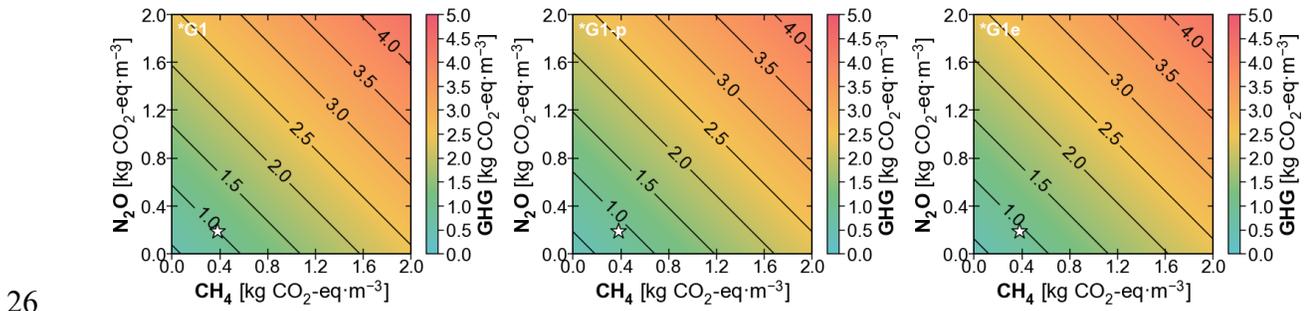
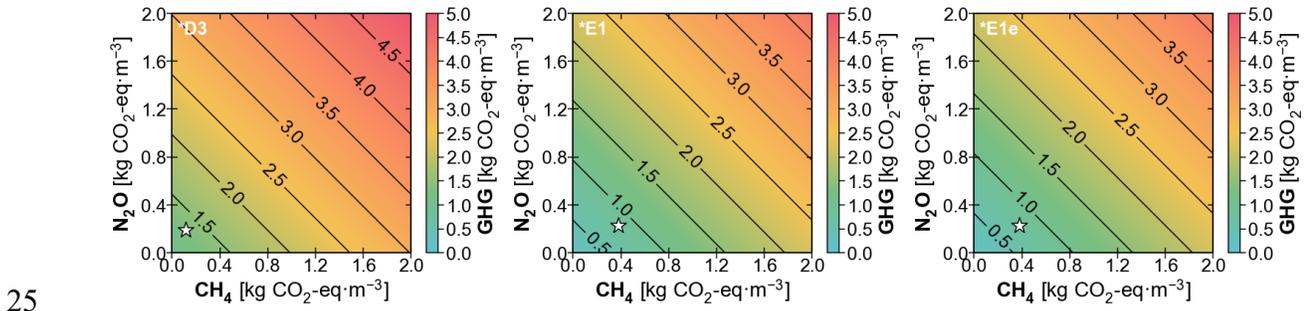
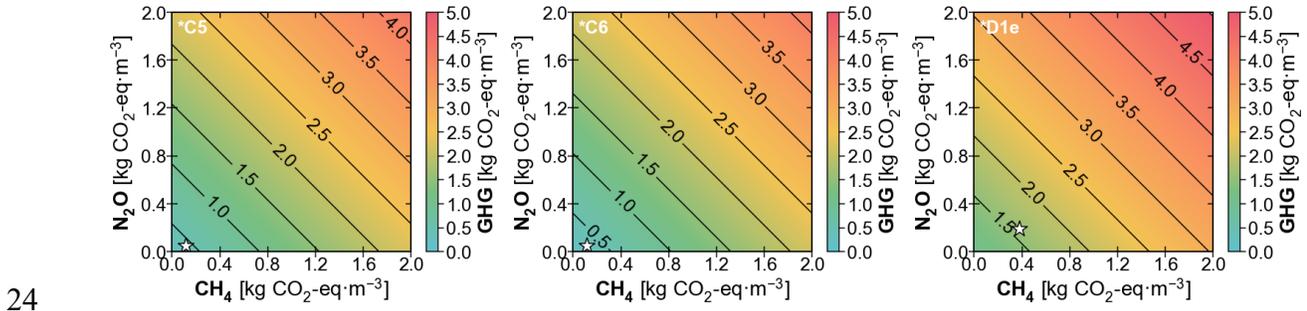
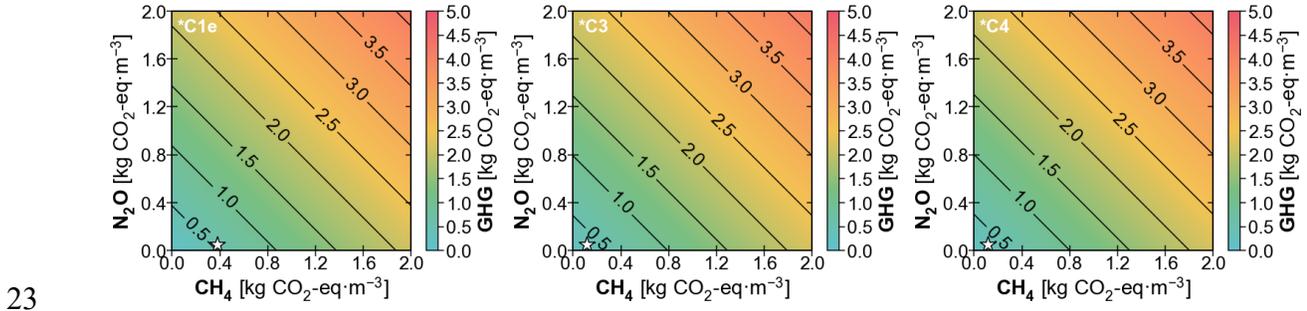


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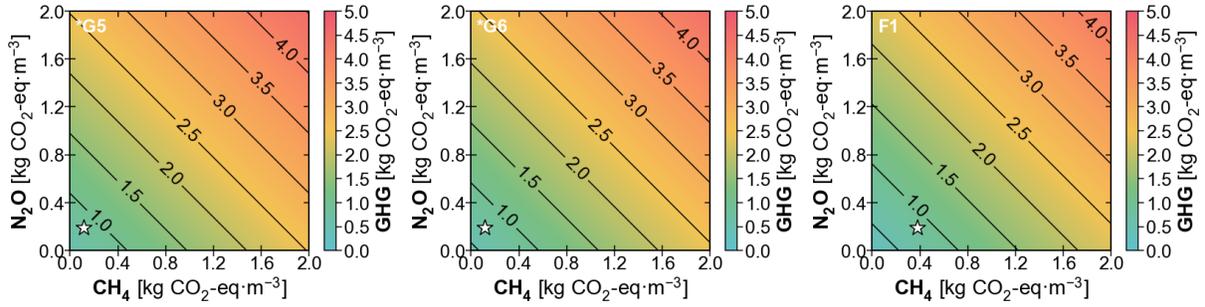


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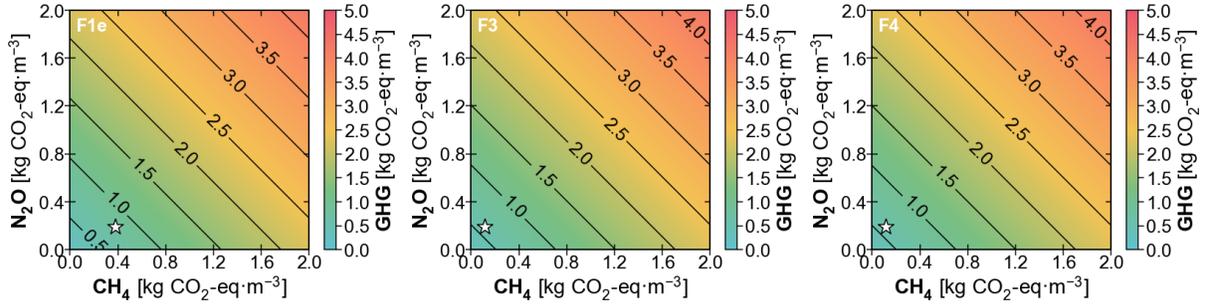




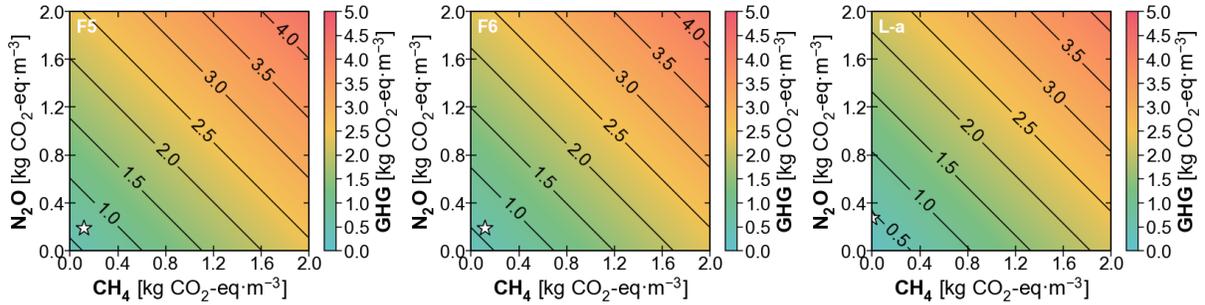
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Figure S1. Sensitivity analysis of total GHG emission on CH₄ and N₂O emission factors for all treatment trains. White stars in the heatmaps represent the baseline emission factors used in this study.

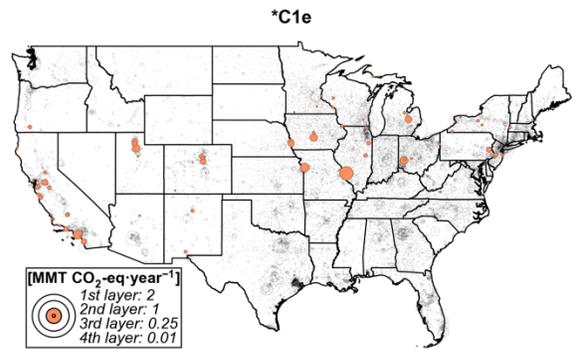
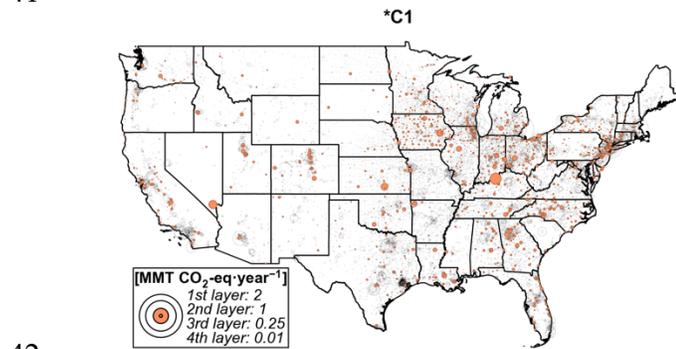
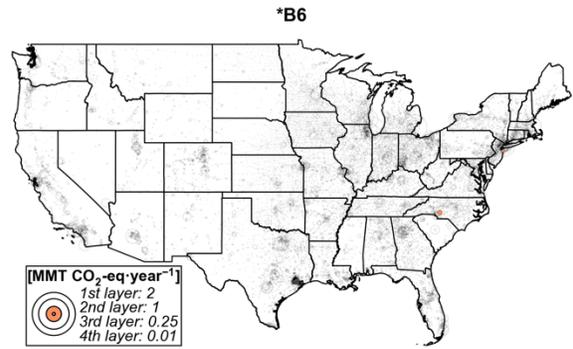
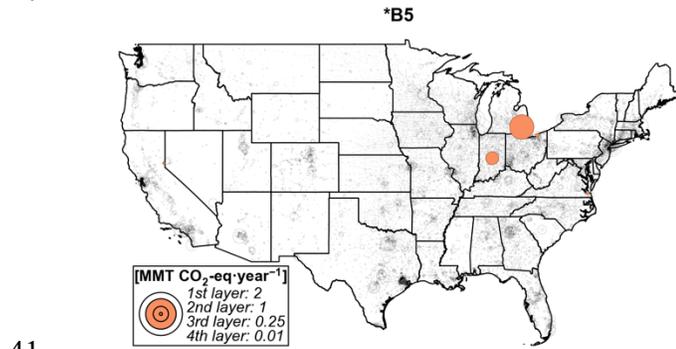
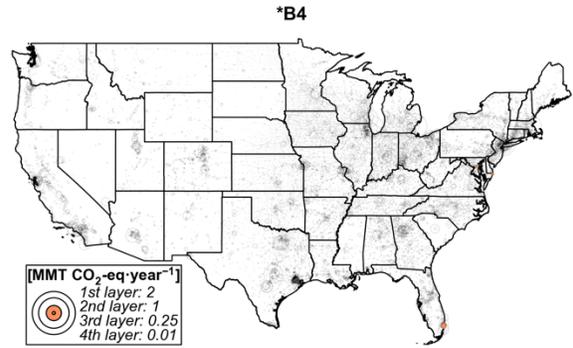
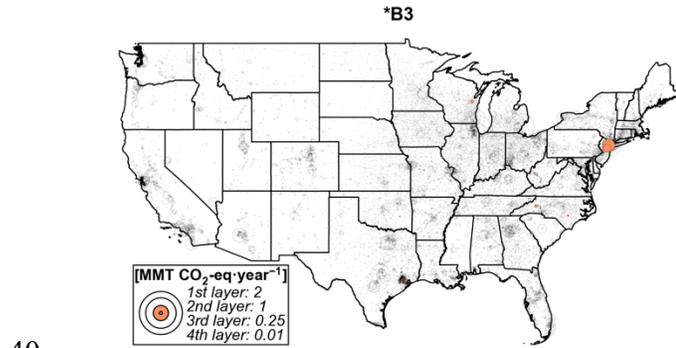
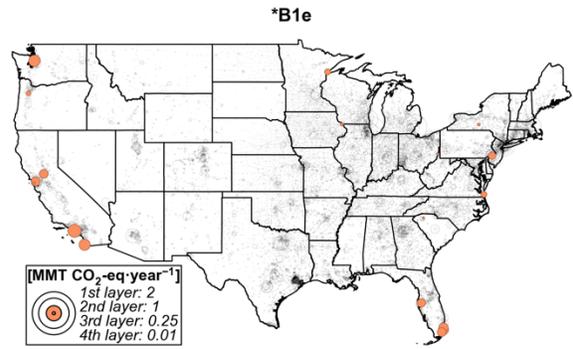
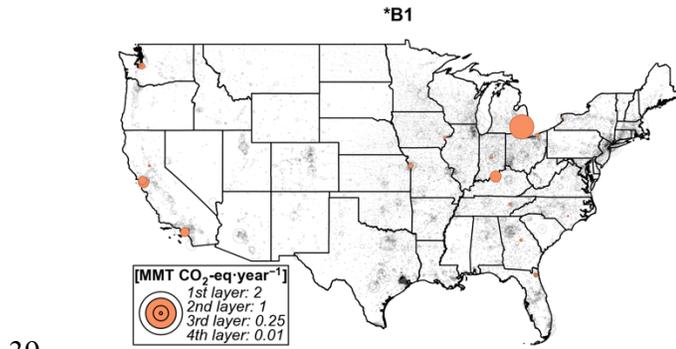


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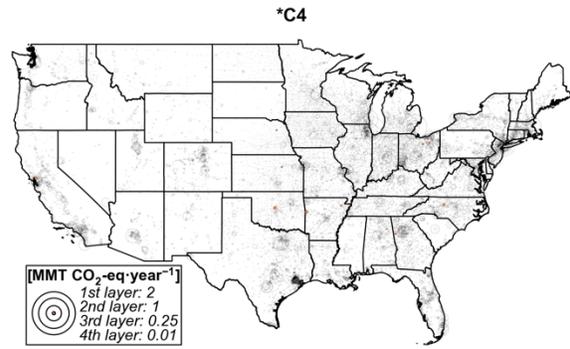
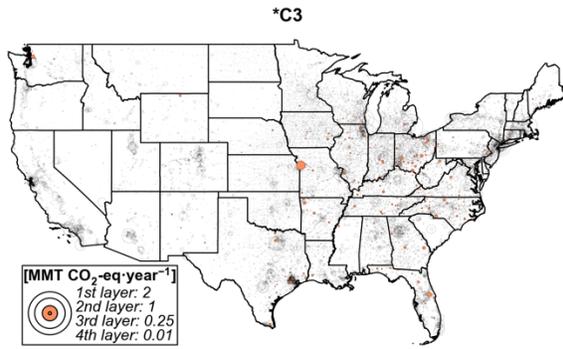
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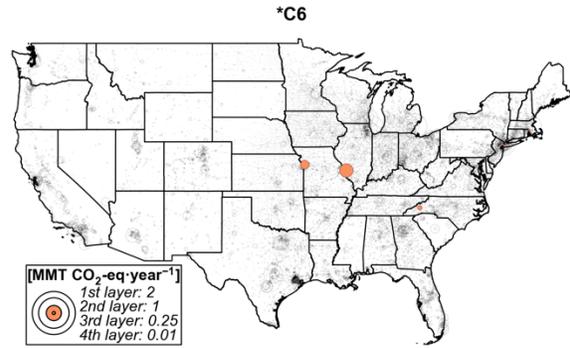
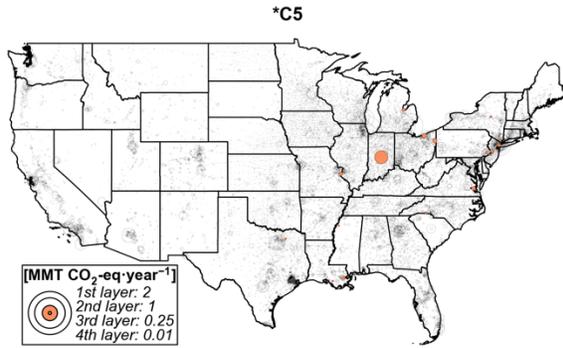
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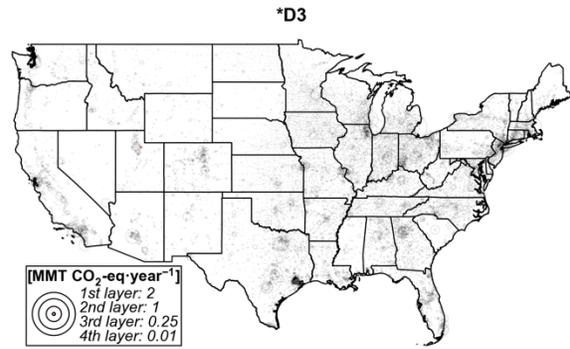
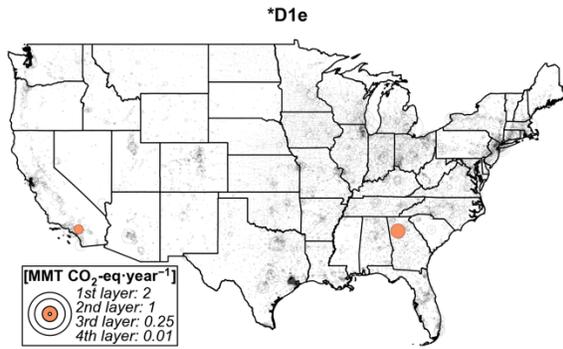
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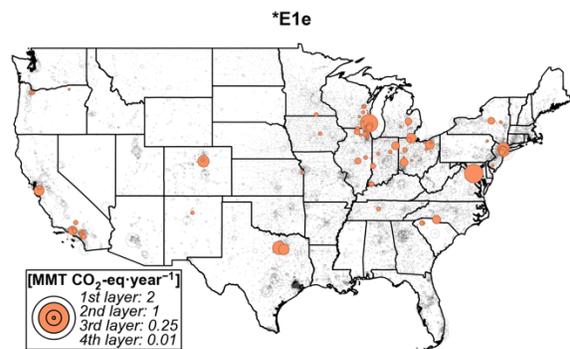
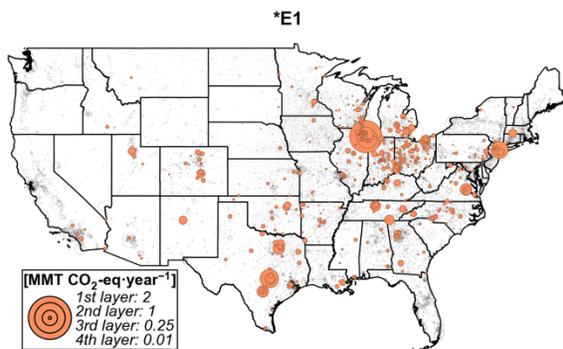
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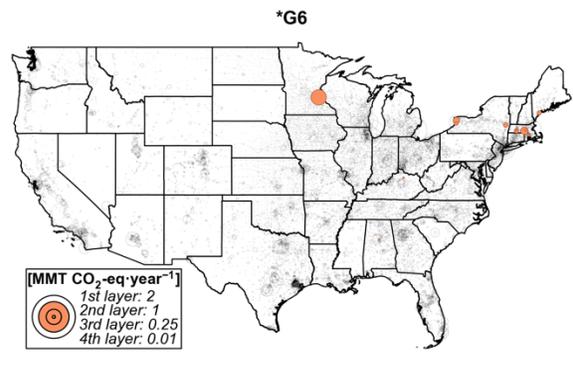
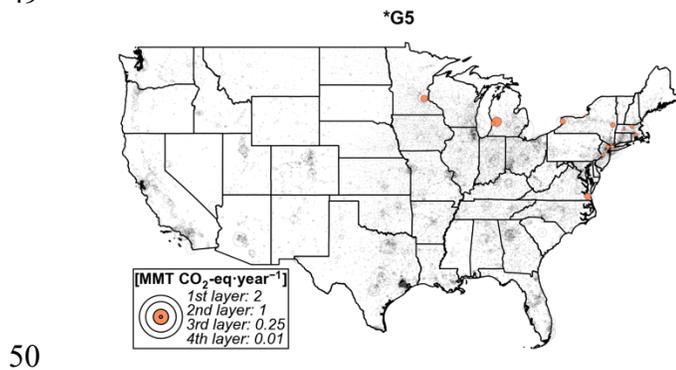
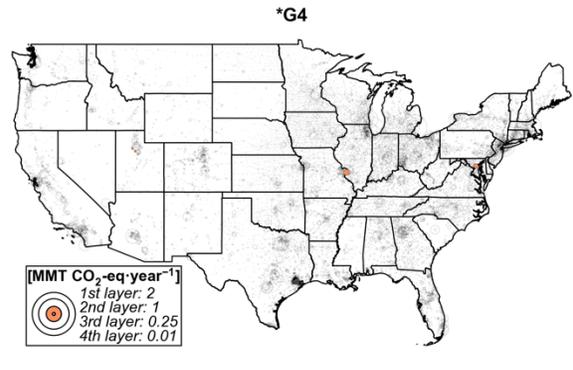
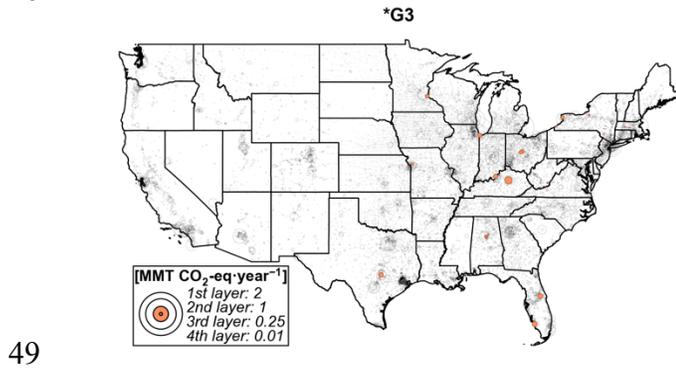
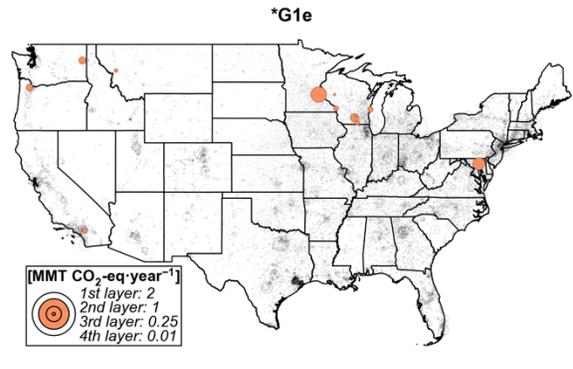
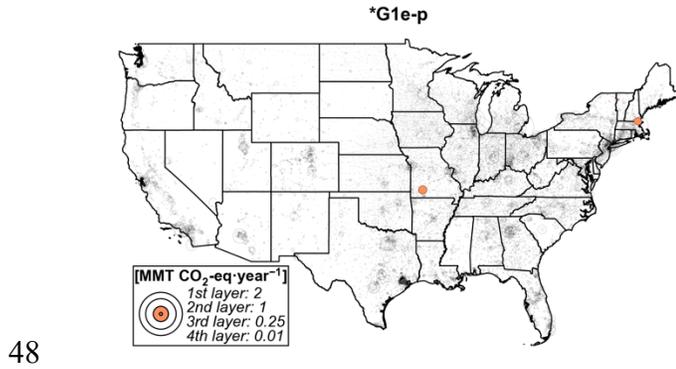
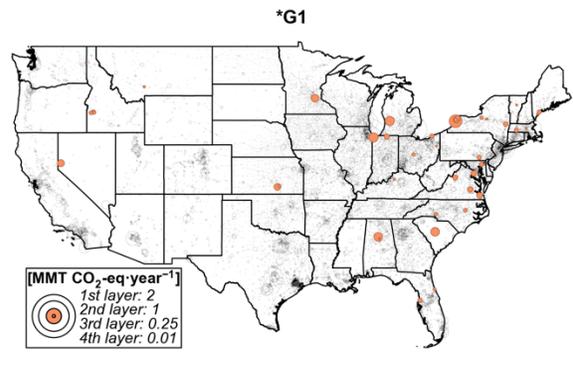
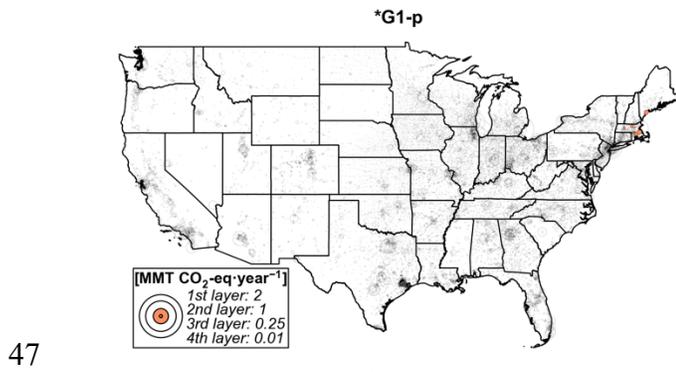


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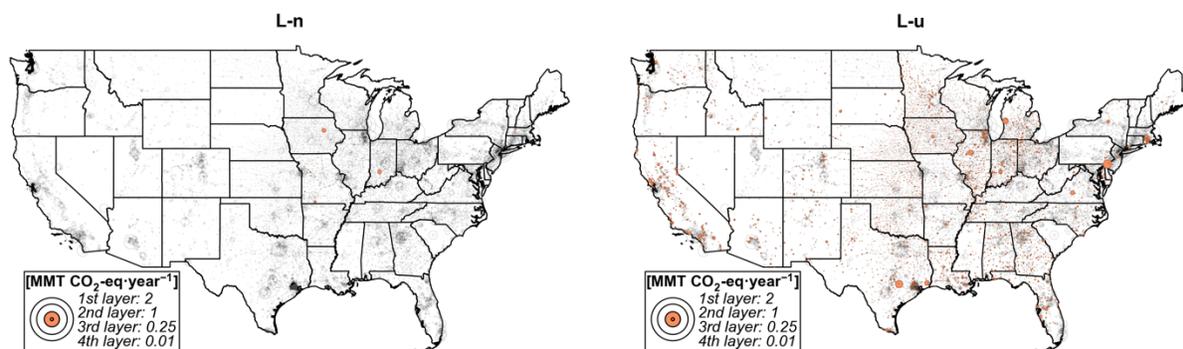


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55
56 **Figure S2.** Geographic distribution of emissions from all treatment trains. Legends from inner to outer
57 rings represent annual emission of 0.01, 0.25, 1, and 2 million metric tonne (MMT) CO₂-eq, respectively.
58 Non-shaded legend indicates no wastewater treatment plant has emission in the corresponding level.

59 **2. Supplementary Methods**

60 2.1. Treatment train assignments

61 2.1.1. Description of treatment trains

62 We used Tarallo et al., 2015 as a baseline for establishing treatment trains for each facility in our
 63 database. However, to better represent the full range of wastewater treatment plant
 64 configurations in the United States, we supplemented the treatment trains defined in Tarallo et
 65 al., 2015 with additional combinations of liquids and solids processes.⁵ **Table S2** and
 66 **Table S3** provide a summary of key distinguishing features of the respective liquid and solids
 67 processes whose energy intensities were modeled using GPS-X in Tarallo et al., 2015. There are a
 68 total of seven different liquids treatment processes, which can occur with or without primary
 69 treatment and chemical phosphorous removal, and six different solids treatment configurations,
 70 one of which includes combined heat and power (CHP). **Table S4** is a direct comparison of the
 71 treatment train codes employed in Tarallo et al., 2015 to the treatment train codes used in this
 72 work. Due to the frequent use of modeling results from Tarallo et al., 2015 in this document, we
 73 refer to all treatment trains using our treatment train naming convention followed by the Tarallo
 74 et al., 2015 code in parenthesis, sometimes abbreviated as a ‘WERF’ code.

75

76 **Table S2.** Liquid treatment codes with key parameters informing energy requirements. ‘WERF Liquid
 77 Code’ refers to the naming system used in Tarallo et al., 2015.

Liquid Code (El Abbadi et al.)	WERF Liquid Code (Tarallo et al., 2015)	Primary Treatment	Secondary Treatment			Chemical Inputs
			Treatment Objective	Reactor Design	Chemical Phosphorous Removal	
A	C	No	Organics Removal	Activated Sludge – Basic	No	Hypochlorite
*A	B	Yes	Organics Removal	Activated Sludge – Basic	No	Hypochlorite
*B	O	Yes	Organics	Activate Sludge – Pure Oxygen	No	Hypochlorite
*C	D	Yes	Organics	Trickling Filter	No	Hypochlorite
*D	N	Yes	Phosphorous Removal	Membrane Bioreactor	No	Hypochlorite, Acetic Acid
E	E	No	Nitrification	Activated Sludge - Nitrification	No	Hypochlorite
*E	F	Yes	Nitrification	Activated Sludge - Nitrification	No	Hypochlorite
F	I	No	Nitrogen Removal	Activated Sludge - BNR	No	Hypochlorite
*G	G	Yes	Phosphorous Removal	Activated Sludge - BNR	No	Hypochlorite, Acetic Acid
*G-p	H	Yes	Phosphorous Removal	Activated Sludge - BNR	Yes	Hypochlorite, Acetic Acid

78
79
80

Table S3. Solids treatment codes with key parameters informing energy requirements. ‘WERF Solids Code’ refers to the naming system used in Tarallo et al., 2015.

Solids Code (El Abbadi et al.)	Solids Stabilization	Recirculation	Chemical Inputs	Natural Gas Requirements	Biogas Use
1	Anaerobic digestion	After digestion and subsequent dewatering	None	Building heating	Building heat; anaerobic digester heating; excess gas is flared
1e	Anaerobic digestion + CHP	After digestion and subsequent dewatering	None	None [†]	Building heat; anaerobic digester heating; power generation from biogas offsets electricity requirements
2	Anaerobic digestion + direct thermal drying	After digestion and subsequent dewatering	None	Direct thermal drying	Building heat; anaerobic digester heating; direct thermal drying (alongside grid natural gas)
3	Aerobic digestion	After digestion and subsequent dewatering	None	None	N/A
4	Lime stabilization (Class B)	Dewatering and then recirculation before lime stabilization	Lime	Building heating; lime production	N/A
5	Multiple hearth incineration	Dewatering and then recirculation before incineration	None	Building heating; incineration	N/A
6	Fluidized bed incinerator	Dewatering and then recirculation before incineration	None	Building heating; incineration	N/A

81 [†]Note that for treatment train *G1e (G1E), we modified the WERF energy calculations to assume that all
82 biogas is used to offset natural gas requirements from the grid.

83
84
85

Table S4. Comparison between treatment train codes used in this paper and those used by Tarallo et al., 2015.

El Abbadi et al. code	WERF code (Tarallo et al., 2015)
*A1	B1
*A1e	B1E
*A3	B2
*A4	B3
*A2	B4
*A5	B5
*A6	B6
A1	C1

A1e	C1E
A3	C2
A4	C3
A5	C5
A6	C6
*C1	D1
*C1e	D1E
*C3	D2
*C4	D3
*C5	D5
*C6	D6
E3	E2
*E3	E2P
*E1	F1
*E1e	F1E
*G1	G1
*G1e	G1E
*G3	G2
*G4	G3
*G5	G5
*G6	G6
*G1-p	H1
*G1e-p	H1E
F1	I1
F1e	I1E
F3	I2
F4	I3
F5	I5
F6	I6
*D1	N1
*D1e	N1E
*D3	N2
*B1	O1
*B1e	O1E
*B3	O2
*B4	O3
*B5	O5
*B6	O6
L-a	LAGOON_AER
L-n	LAGOON_ANAER
L-f	LAGOON_FAC
L-u	STBL_POND/LAGOON_OTHER

87 2.1.2. Assigning treatment trains to CWNS facilities

88

89 *Creating list of cumulative unit processes*

90 We used data from the U.S. EPA's Clean Watersheds Needs Survey (CWNS) to identify active
91 wastewater treatment plants in the United States, and the treatment processes present at these
92 facilities as of 2022. Because not all facilities reported updated unit processes in the 2022 CWNS,
93 we used the 2022 data in tandem with past surveys from 2004, 2008, and 2012 to form a more
94 complete dataset of active treatment processes. When more granular or up-to-date external datasets
95 were available, such as those regarding biogas utilization and treatment lagoons, we supplemented
96 the unit processes reported in CWNS, as elaborated below.

97

98 To develop a cumulative list of unit processes at each facility, we first aggregated unit process data
99 across all CWNS surveys. We removed both duplicate unit processes and unit processes from 2008
100 and 2012 flagged for abandonment. In CWNS 2004, 2008, and 2012, flags indicating nutrient
101 removal for each facility are reported separately from unit processes. We use these indicators
102 (labeled 'PRES_AMMONIA_REMOVAL,' 'PRES_NIT_REMOVAL,' and
103 'PRES_PHOSPHOROUS_REMOVAL' in CWNS) in addition to reported unit processes to
104 identify facilities with nitrification, biological nutrient removal, or phosphorous removal. In our
105 final treatment train dataset (Supplementary File A), we use a modified unit process code
106 'NIT_FLAG' to distinguish the facilities where nitrification was added via the
107 'PRES_AMMONIA_REMOVAL' field; however, it is worth noting that some facilities may have
108 nitrification reported in the form of both the ammonia removal flag ('NIT_FLAG') and the unit
109 process ('NIT').

110

111 CWNS does not specify whether biogas is used for heating to offset natural gas combustion, or as
112 a biogenic fuel to produce electricity. Thus, we cross-referenced two additional databases to
113 identify facilities that utilize digester biogas to produce electricity: the U.S. Department of
114 Energy's (DOE) Combined Heat and Power Installation Database and the Water Environment
115 Foundation's (WEF) Water Resource Recovery Facilities Biogas Database.^{6,7} The DOE CHP
116 database catalogs CHP installations across multiple industries through 2024 and was filtered to
117 wastewater treatment facilities with biogas utilization technology installed before 2022 prior to
118 incorporating it into treatment train assignments. The WEF database, originally developed based
119 on a 2013 survey, was accessed prior to a website update which removed the option for users to
120 download national data. Though the WEF website recommends that users cite the database as
121 being last updated in 2024, we cannot confirm whether the data has been updated past 2013 without
122 scraping the new web interface. Consequently, data previously downloaded from the retired
123 interface, which only included CHP installations through 2013, was used for treatment train
124 assignments.

125

126 CWNS also includes data on the presence of lagoons at treatment facilities, but does not require
127 reporting the specifications of lagoon operation. Thus, lagoons can be reported as aerated,

128 anaerobic, or facultative, but some are simply reported as “Lagoon, Other”. We supplemented
 129 CWNS data with EPA’s Lagoon Inventory Dataset (2022) to identify any additional lagoon-based
 130 facilities not reported in CWNS, and to determine lagoon type where possible.⁸ Because lagoons
 131 are more common in smaller, rural wastewater treatment facilities, we conducted an additional
 132 manual check on facilities with lagoons which reported flow rates greater than 10 MGD (n = 42).
 133 Using publicly available information, we verified whether or not a lagoon was present at these
 134 facilities. In this manner, we removed treatment lagoons from eight facilities. Facilities which have
 135 been modified with manual checks are noted accordingly in the “UP_ID_NOTE” column of the
 136 facility inventory dataset (Supplementary File A).

137
 138 Lastly, if multiple secondary and/or solids treatment processes were reported across the four
 139 surveys, only the most recently reported process(es) were retained. Consequently, excluding
 140 secondary and/or solids treatment processes, if a unit process was reported in a less recent dataset
 141 (e.g., 2004, 2008, or 2012) but not in the 2022 CWNS, it was still considered an active component
 142 of the facility.

143

144 *Assigning treatment trains*

145 By searching for key combinations of treatment processes in the cumulative unit process list, we
 146 assigned one or more treatment trains for facilities with sufficient unit process data . For facilities
 147 with partial unit process data available, we assigned treatment trains based on the most common
 148 treatment train(s) of the same plant size and EPA region with specific unit processes present.
 149 Lastly, for the remaining facilities with insufficient unit process data available, we assigned
 150 treatment trains based on the most common treatment train(s) of a similar flow rate for the same
 151 EPA region (**Table S5**). If the most common treatment train for a particular plant size and EPA
 152 region utilizes biogas for electricity, the non-electricity producing version of that treatment train
 153 was assigned for facilities with partial or insufficient unit process information, except for facilities
 154 that explicitly flagged as producing electricity in one or more of the supplemental biogas databases.
 155 Additionally, **Table S6** summarizes how facilities were assigned treatment trains based on data
 156 availability.

157

158 **Table S5.** Most common treatment train(s) by facility size and EPA region in 2022.

2022 Flow Rate (MGD)	EPA Region	Most Common Treatment Train
Less than 2	1	L-a (LAGOON_AER)
	2	A3 (C2)
	3	A3 (C2)
	4	L-u (STBL_POND)
	5	L-u (STBL_POND)
	6	L-u (STBL_POND)
	7	L-u (STBL_POND)
	8	L-f (LAGOON_FAC)

	9	L-u (STBL_POND)
	10	L-u (STBL_POND)
2 - 4	1	*A1 (B1)
	2	*A1 (B1)
	3	*C1 (D1)
	4	A3 (C2)
	5	*C1 (D1)
	6	A3 (C2)
	7	*C1 (D1)
	8	L-a (LAGOON_AER)
	9	L-a (LAGOON_AER)/L-u (STBL_POND)
	10	L-a (LAGOON_AER)
4 - 7	1	*A1 (B1)
	2	*A1 (B1)
	3	*C1 (D1)
	4	*C1 (D1)
	5	*E1 (F1)
	6	A3 (C2)
	7	*C1 (D1)
	8	*C1 (D1)
	9	L-u (STBL_POND)
	10	*A1 (B1)
7 - 16	1	*A1 (B1)
	2	*C1 (D1)
	3	*A1 (B1)
	4	*A3 (B2)
	5	*E1 (F1)
	6	A3 (C2)
	7	*C1 (D1)
	8	*C1 (D1)
	9	*A1 (B1)
	10	*A1 (B1)
16 - 46	1	*A6 (B6)
	2	*A1 (B1)
	3	*G1 (G1)/F1 (I1)
	4	*A1 (B1)
	5	*E1 (F1)
	6	*E1 (F1)
	7	*A1 (B1)

	8	*C1 (D1)
	9	*A1 (B1)
	10	*A1 (B1)/F1 (I1)
46 - 100	1	*G6 (G6)/*G1-p (H1)/F5 (I5)
	2	*A1 (B1)
	3	F1 (I1)
	4	L-a (LAGOON_AER)/F1 (I1)
	5	*E1 (F1)
	6	*E1 (F1)
	7	*C1 (D1)
	8	*C1 (D1)
	9	*A1 (B1)
	10	*G1 (G1)/F1 (I1)/*B1 (O1)
Greater than 100	1	F1 (I1)
	2	*E1 (F1)/F1 (I1)
	3	*A1 (B1)
	4	*B1 (O1)
	5	*E1 (F1)
	6	*E1 (F1)
	7	*A6 (B6)/*C1 (D1)/*C6 (D6)
	8	*E1 (F1)
	9	*B1 (O1)
	10	F1 (I1)

159

160

Table S6. Breakdown of treatment train assignment mechanism based on availability of unit process data.

EPA Region	Sufficient Unit Process Information		Partial Unit Process Information		Insufficient Unit Process Information	
	Count	Total Flow (MGD)	Count	Total Flow (MGD)	Count	Total Flow (MGD)
1	356	1,734.639	124	324.885	69	77.262
2	480	4,688.991	116	633.427	183	96.478
3	616	3,576.490	117	240.808	179	127.540
4	1,307	6,642.39	310	910.013	440	1,016.749
5	2,871	9,448.227	381	591.557	394	510.480
6	1,603	4,534.983	558	823.167	623	957.418
7	2,017	2,712.010	208	169.266	511	38.721
8	796	1,229.560	50	172.788	272	152.987

9	424	3,782.210	76	703.427	145	966.682
10	494	1,691.528	52	116.430	95	28.654
<i>Total</i>	<i>10,964</i>	<i>40,041.028</i>	<i>1,993</i>	<i>4,691.768</i>	<i>2,910</i>	<i>3,966.971</i>

161
 162 Because facilities often do not report every single unit process required for a particular treatment
 163 train configuration, treatment train assignments were made based on the presence or absence of a
 164 key subset of unit processes for each configuration. For instance, the treatment train *D3 (N2) is
 165 assigned when a facility reports both a membrane bioreactor and aerobic digestion. With this logic,
 166 some facilities may report enough unit processes to obtain multiple different treatment train
 167 assignments. For example, a facility in CWNS may report both pure oxygen activated sludge and
 168 basic activated sludge. We consider it likely that both processes were reported to describe the same
 169 pure oxygen activated sludge system, rather than the possibility that a facility contains two separate
 170 activated sludge systems, one using oxygen and one using air. Thus, we prioritized the assignment
 171 of treatment trains based on liquids process in the following order, an approach that also allows us
 172 to minimize the number of facilities assigned multiple treatment trains:

- 173
- 174 1. Activated sludge biological nutrient removal, phosphorus;
 - 175 2. Activated sludge biological nutrient removal, nitrogen;
 - 176 3. Nitrification;
 - 177 4. Pure-oxygen activated sludge; and
 - 178 5. Basic activated sludge.
- 179

180 Using the example described above, if a facility were to report all the unit processes required for
 181 both *B5 (O5) and *A5 (B5), it would only be assigned *B5 (O5), i.e. we assumed that a facility
 182 does not have both basic activated sludge and pure oxygen activated sludge, but rather all activated
 183 sludge facilities onsite use pure oxygen. The same logic applies for activated sludge-based nutrient
 184 removal systems. For additional information on treatment train assignment methodology, please
 185 see `tt_assignments_2022.ipynb` posted on the public repository for this analysis.

186

187 2.1.3. Multiple treatment train assignments

188 Using the treatment train assignment methodology described above, it was possible for multiple
 189 treatment trains to be equally well-matched for a single facility, even after unit processes flagged
 190 for abandonment and outdated secondary/solids unit processes were removed from the cumulative
 191 unit process list. We found a total of 1,500 facilities could be assigned multiple treatment trains.
 192 For instance, the Detroit Sewage Treatment Plant reports activated sludge, anaerobic digestion,
 193 chemical phosphorus removal, multiple hearth incineration, a configuration not accounted for in
 194 Tarallo et al., 2015. Subsequently, this facility was assigned the treatment trains *B1 (O1) and *B5
 195 (O5). Another notable instance of a facility receiving multiple treatment train assignments is that
 196 of nitrifying trickling filters, a configuration also not accounted for in Tarallo et al., 2015. Because
 197 our treatment train assignment methodology accounts for facilities that use a trickling filter or

198 nitrification, but not both, if both nitrification and a trickling filter were reported as unit processes
 199 for a given facility, it was assigned both a nitrifying (liquids code E) and trickling filter treatment
 200 train (liquids code C).

201
 202 Out of the 1,500 facilities with multiple treatment train assignments, 349 facilities reported
 203 multiple key secondary and/or solids processes in the most recent survey available for that facility.
 204 The remaining facilities consisted of combinations of treatment trains involving one or multiple
 205 types of lagoons, or a trickling filter coupled with another liquids treatment method. The majority
 206 (63% of the facilities) of the 349 facilities with multiple secondary/solids processes were instances
 207 of both aerobic and anaerobic digesters being present in a single facility. Approximately 21% of
 208 facilities with multiple secondary/solids processes reported digestion in addition to incineration.

209
 210 We conducted further manual verification on a selection of large and small facilities with multiple
 211 secondary and/or solids treatment processes. While not a representative sample, these checks
 212 confirm that facilities may, in reality, have multiple secondary/solids processes in parallel or in
 213 series. However, it is also possible the second process was reported by mistake. Because
 214 verification of all facilities would require substantial manual effort, we chose to limit the number
 215 of multiple treatment train assignments by removing outdated secondary/solids processes. More
 216 specifically, if a facility reported different secondary/solids treatments across different survey
 217 years, we retained the processes reported most recently and disregarded the less recently reported
 218 ones. For the remaining facilities that still had enough unit process information to be assigned
 219 multiple treatment trains, we assumed that flow is split evenly across all identified trains. Note that
 220 facilities with multiple, conflicting solids processes in this category make up approximately 9% of
 221 the national fleet by volume of treated wastewater and 2% of total facilities.

222
 223 2.2. Treatment train energy requirements

224 2.2.1. Energy requirement calculation

225 We calculated the required electricity and natural gas inputs for each treatment train using the unit
 226 process energy requirements for the modeled treatment trains reported in Tarallo et al., 2015.
 227 **Table S7** lists these unit processes grouped by liquids treatment, solids treatment, and plant-wide
 228 loads at a modeled plant. Energy requirement per volume of treated wastewater varies for
 229 individual pieces of equipment across the treatment trains based on treatment objectives,
 230 recirculation configurations, and the presence/absence of CHP.

231
 232 **Table S27.** Key energy consuming processes used in calculating electricity and natural gas requirements
 233 for treatment trains.

	Liquid Stream Processes	Solids Processes	Plant-wide
--	-------------------------	------------------	------------

Electricity	<u>Equipment</u> Influent pump station Screening & grit removal Primary clarifiers Biological reactor (blowers/pump as necessary based on design configuration) Final clarifies & recirculated activated sludge pumping Disinfection <u>Chemicals</u> Hypochlorite production Acetic acid production	<u>Equipment</u> Gravity thickener Mechanical thickener Stabilization process (digester, incinerator, lime stabilization unit) Side stream pump Dewatering Drying <u>Chemicals</u> Lime production	Odor control Site lighting
Natural Gas	<u>Equipment (via boiler)</u> Anaerobic digester heating <u>Chemicals</u> Acetic acid production	<u>Chemicals</u> Lime production	Building heating (via boiler)

234

235 In **Table S8**, we list all the treatment trains used in this analysis, grouped into categories based on
 236 how we determined energy values per volume of treated wastewater. ‘WERF Trains’ refers to the
 237 treatment configurations with full energy requirements modeled and reported in Tarallo et al.,
 238 2015. For one treatment train, *G1e (G1E), we used the energy intensity values reported in Tarallo
 239 et al., 2015 with minor modifications. Finally, ‘New Trains’ refers to configurations that were not
 240 modeled in Tarallo et al., 2015 for which we used combinations of energy values for liquids and
 241 solids processes reported in Tarallo et al., 2015 with modifications documented below.

242

243 **Table S8.** Overview of all treatment trains used in our analysis, grouped based on whether they are WERF
 244 Trains reported in Tarallo et al., 2015, modified WERF trains, or new trains reported for this first time in
 245 this analysis.

	WERF Trains	Modified WERF Trains	New Trains
El Abbadi et al. Code	*A1, *A1e, *A2, *A5, *A6, A4, *C1, E3, *E3, *E1, *G1, *G1-p, F4, *D1, *D3, *B1	*G1e	*A3, *A4, A1, A1e, A3, A5, A6, *C1e, *C3, *C4, *C5, *C6, *E1e, *G3, *G5, *G6, *G1e-p, F1, F1e, F5, F6, *D1e, *B1e, *B3, *B4, *B5, *B6
WERF Code	B1, B1E, B4, B5, B6, C3, D1, E2, E2P, F1, G1, H1, I2, I3, N1, N2, O1	G1E	B2, B3, C1, C1E, C2, C5, C6, D1E, D2, D3, D5, D6, G2, G3, F1E, G5, G6, H1E, I1, I1E, I5, I6, N1E, O1E, O2, O3, O5, O6

246

247 2.2.2. Modified treatment train - *G1e

248 We made slight modifications to the treatment train *G1e (G1E) energy requirements compared
 249 to values reported by Tarallo et al., 2015. In the reported configuration, *G1e includes power
 250 generation through CHP, as well as a natural gas input from the grid of 1,600 MJ/day. However,

251 we noted that *G1e (G1E) is the only train reported in Tarallo et al., 2015 with CHP that also uses
 252 natural gas from the grid. The *G1 (G1) train, upon which *G1e (G1E) is based, does not import
 253 any natural gas either. Thus, for our analysis we removed the imported natural gas for *G1e (G1E),
 254 and scaled back onsite electricity production accordingly. Specifically, the 1,600 MJ/day of natural
 255 gas from the grid was replaced by 1,600 MJ/day of biogas from the anaerobic digester diverted to
 256 the boiler instead of directed to the generator, as originally reported in Tarallo et al., 2015:
 257

259
$$\text{Reported Generator Efficiency} = \frac{5,760 \text{ kWh/day produced from generator}}{62,300 \text{ MJ/day into generator}} = 9.24\%$$

258
 260
$$\text{Modified Electricity Production} = (62,300 \text{ MJ/day as biogas} - 1,600 \text{ MJ/day to boiler}) * 9.24\%$$

 261
$$= 5,609 \text{ kWh/day}$$

 262

263 To account for the reduced electricity supply from the generator, we increased the electricity
 264 requirement from the grid accordingly.
 265

266 2.2.3. New Treatment Trains

267 We calculated the energy requirements for new treatment trains using combinations of liquids and
 268 solids treatment processes reported by Tarallo et al., 2015, with modifications to specific unit
 269 processes, as deemed necessary. **Table S9** summarizes our approach for deriving energy values
 270 from WERF treatment trains, a detailed discussion of which is provided below.
 271

272 **Table S9.** Descriptions of how energy values were derived for new treatment trains in this study. We use
 273 our nomenclature with the corresponding WERF code included parenthetically. The process models from
 274 Tarallo et al., 2015 used as a baseline for determining energy requirements for new treatment train
 275 configurations are listed in the source configuration columns.

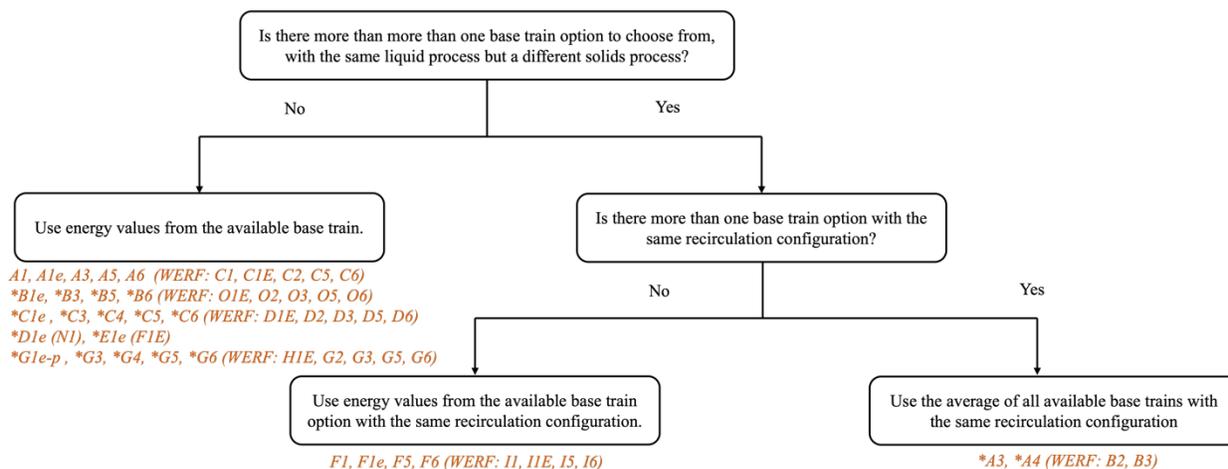
New Treatment Train	Source Configuration (Liquid Process)	Source Configuration (Solids Stabilization)
*A3 (B2)	*A1 (B1)/*A2 (B4) (identical liquids treatment energy requirements)	Aerobic digester energy calculated using influent chemical oxygen demand from *A1 (B1) as input to linear regression. Average thickener values for gravity + mechanical thickeners present.
*A4 (B3)	Average *A5 (B5) and *A6 (B6)	Lime production energy calculated using average dosing rate. Lime stabilization process energy using average of A4 (C3) and F4 (I3). Average thickener values for gravity + mechanical thickeners present.
A1 (C1)	A4 (C3)	Basic activated sludge cluster for anaerobic digestion (*A1 (B1)/*A1e (B1E)/*E1, P1, P1E). Average thickener values for mechanical thickener only present.

A1e (C1E)	A4 (C3)	Basic activated sludge cluster for anaerobic digestion (*A1 (B1)/*A1e (B1E)/*E1, P1, P1E). Average thickener values for mechanical thickener only present. Biogas produced based on linear regression of influent chemical oxygen demand. Electricity generated based on biogas produced and generator efficiency of 0.0925.
A3 (C2)	A4 (C3)	Aerobic digester energy calculated using influent chemical oxygen demand from A4 (C3) as input to linear regression. Thickener average values for mechanical thickener only present.
A5 (C5)	A4 (C3)	*A5 (B5) for incinerator. Thickener average values for mechanical thickener only present.
A6 (C6)	A4 (C3)	*A6 (B6) for incinerator. Thickener average values for mechanical thickener only present.
*C1e (D1E)	*C1 (D1)	Electricity generated based on biogas produced and generator efficiency of 0.0925.
*C3 (D2)	*C1 (D1)	Aerobic digester energy calculated using influent chemical oxygen demand from *C1 (D1) as input to linear regression. Thickener average values for mechanical thickener only present.
*C4 (D3)	*C1 (D1)	Lime production energy calculated using average dosing rate. Lime stabilization process energy using average of A4 (C3) and F4 (I3). Average thickener values for gravity thickener only.
*C5 (D5)	*C1 (D1)	*A5 (B5) for incinerator. Thickener average values for gravity thickener only present.
*C6 (D6)	*C1 (D1)	*A6 (B6) for incinerator. Thickener average values for gravity thickener only present.
*E1e (F1E)	*E1 (F1)	Electricity generated based on biogas produced and generator efficiency of 0.0925.
*G3 (G2)	*G1 (G1)/*G1e (G1E) (identical liquids treatment energy requirements)	Aerobic digester energy calculated using influent chemical oxygen demand from *G1 (G1) as input to linear regression. Average thickener values for gravity + mechanical thickeners present.
*G4 (G3)	*G1 (G1)/*G1e (G1E) (identical liquids treatment energy requirements)	Lime production energy calculated using average dosing rate. Lime stabilization process energy using average of A4 (C3) and F4 (I3). Average thickener values for gravity + mechanical thickeners present.
*G5 (G5)	*G1 (G1)/*G1e (G1E) (identical liquids treatment energy requirements)	*A5 (B5) for incinerator. Average thickener values for gravity + mechanical thickeners present.

	treatment energy requirements)	
*G6 (G6)	*G1 (G1)/*G1e (G1E) (identical liquids treatment energy requirements)	*A6 (B6) for incinerator. Average thickener values for gravity + mechanical thickeners present.
*G1e-p (H1E)	*G1-p (H1)	Electricity generated based on biogas produced and generator efficiency of 0.0925.
F1 (I1)	F3 (I2)	Nutrient Removal anaerobic digestion cluster (*G1 (G1)/*G1e (G1E)/*G1-p (H1)/*D1 (N1)) for anaerobic digester energy. Thickener average values for mechanical thickener only present.
F1e (I1E)	F3 (I2)	Nutrient Removal anaerobic digestion cluster (*G1 (G1)/*G1e (G1E)/*G1-p (H1)/*D1 (N1)) for anaerobic digester energy. Thickener average values for mechanical thickener only present. CHP energy production based on *G1e (G1E).
F5 (I5)	F4 (I3)	*A5 (B5) for incinerator. Thickener average values for mechanical thickener only present.
F6 (I6)	F4 (I3)	*A6 (B6) for incinerator. Thickener average values for mechanical thickener only present.
*D1e (N1E)	*D1 (N1)	Electricity generated based on biogas produced and generator efficiency of 0.0925.
*B1e (O1E)	*B1 (O1)	*B1 (O1). Energy production from *A1e (B1E).
*B3 (O2)	*B1 (O1)	Aerobic digester energy calculated using influent chemical oxygen demand from *B1 (O1) as input to linear regression. Thickener average values for gravity thickener only present.
*B4 (O3)	*B1 (O1)	Lime production energy calculated using average dosing rate. Lime stabilization process energy using average of A4 (C3) and F4 (I3). Thickener average values for gravity thickener only present.
*B5 (O5)	*B1 (O1)	*A5 (B5) for incinerator. Thickener average values for gravity thickener only present.
*B6 (O6)	*B1 (O1)	*A6 (B6) for incinerator. Thickener average values for gravity thickener only present

277 *Liquids treatment processes*

278 To determine the energy requirement of the liquids process of a new treatment train, we used the
 279 energy requirements from a ‘base train’, a WERF train with reported energy values in Tarallo et
 280 al., 2015. A base train will have the same liquid treatment process as the corresponding new train,
 281 but a different solids treatment process. **Figure S3** summarizes the logic for selecting the base train
 282 for the liquid treatment process.
 283



284
 285 **Figure S3.** Logic for selecting the base train for liquids treatment train processes in all new trains. Relevant
 286 trains for each approach are listed in orange. We identified all WERF trains with the same liquid treatment
 287 process, and, when possible, selected a base train based on similar side-stream recirculation configurations.
 288

289 When only one base train option was available to choose from, we used the reported values for the
 290 corresponding new train’s liquid process. For example, A4 (C3) is the only train with this particular
 291 liquid configuration with reported energy values. Thus, when calculating energy requirements for
 292 the liquid portion of A1 (C1), A1e (C1E), A3 (C2), A6 (C5) and A6 (C6), we must take the A train
 293 values reported in A4 (C3). We apply this approach for the following trains: A1 (C1), A1e (C1E),
 294 A3 (C2), A6 (C5), A6 (C6), *C1e (D1E), *C3 (D2), *C4 (D3), *C5 (D5), *C6 (D6), *E1e
 295 (F1E), *G3 (G2), *G4 (G3), *G5 (G5), *G6 (G6), *G1e-p (H1E), *D1e (N1E), *B1e (O1E), *B3
 296 (O2), *B4 (O3), *B5 (O5), and *B6 (O6).
 297

298 However, the energy requirements within the liquids treatment portion of a train may vary with
 299 downstream solids treatment processes. Thus, where more than one base train option was
 300 available, we selected the base train for the new train configuration based on side-stream
 301 recirculation associated with downstream solids processing. Side-stream composition and solids
 302 content is impacted by whether or not recirculation occurs before or after the solids treatment
 303 process. In the models used by Tarallo et al., 2015, dewatering and recirculation occur *before*
 304 incineration and lime stabilization, but for aerobic and anaerobic digestion, the solids stream is
 305 dewatered *after* the stabilization in the digester (see **Figure S4**).
 306

307 For example, when determining the energy requirements for F1 (I1), there are two liquid treatment
 308 train options to choose from: the F train coupled with aerobic digestion, F3 (I2), or lime
 309 stabilization, F4 (I3). We choose to draw values from the configuration with aerobic digestion,
 310 rather than lime stabilization, for closer alignment in recirculation configuration which can affect
 311 the energy requirements of the unit processes downstream of recirculation (biological reactor
 312 blowers, final clarifiers, recirculating activated sludge pumping). Finally, if multiple treatment
 313 trains are available to select from with the same recirculation configuration, we used the average
 314 value of the energy requirements from these trains. Note that this only occurred when calculating
 315 energy requirements for *A3 (B2) and *A4 (B3).
 316

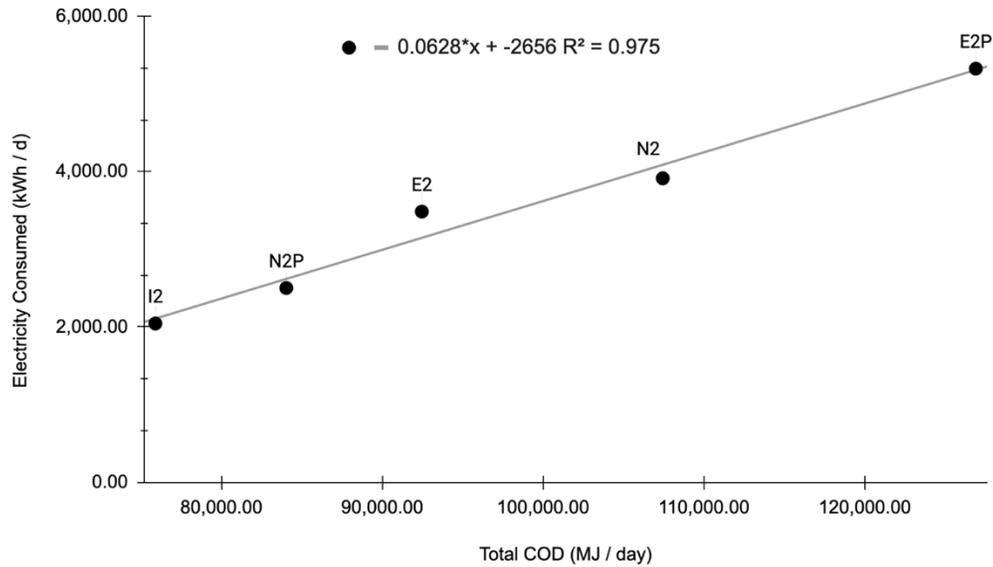
<u>Solids Stabilization Configurations</u>	<u>Code</u>
Anaerobic Digestion → Dewatering	1
Anaerobic Digestion → Dewatering → Direct Thermal Drying	2
Aerobic Digestion → Dewatering	3
Dewatering → Lime Stabilization	4
Dewatering → Multiple Hearth Incineration	5
Dewatering → Fluidized Bed Incineration	6

317
 318 **Figure S4.** Solids stabilization configurations with dewatering sequence.
 319

320 *Solids treatment processes*

321 Energy requirements for solids treatment processes vary based on the upstream treatment.
 322 Consequently, we used data reported in Tarallo et al., 2015 to extrapolate electricity and natural
 323 gas requirements for the solids treatment component of the new treatment trains.
 324

325 **Aerobic digestion.** Using data reported by Tarallo et al., 2015, we found a linear relationship
 326 between aerobic digester requirements and influent chemical oxygen demand (COD), the
 327 embedded chemical energy of wastewater. This is consistent with the typical assumption that
 328 electricity consumption is driven by aeration to support COD degradation.⁹ For each new treatment
 329 train, we calculated the expected influent chemical COD to the aerobic digester using the COD
 330 flow rate (reported by Tarallo et al., 2015 in MJ/day) leaving the mechanical and/or gravity
 331 thickeners, as reported for the liquid base train. For example, we used COD leaving the gravity
 332 and mechanical thickeners in *A1 (B1) to determine the influent COD to the aerobic digester in
 333 *A3 (B2). Using the linear best-fit for the WERF trains (**Figure S5**), we calculated electricity
 334 consumption for each new train (**Table S10**).
 335



336
337 **Figure S5.** Electricity consumption for aerobic digestion as a function of total COD into the digester. Note
338 that the x-axis starts at 75,000 MJ/day.

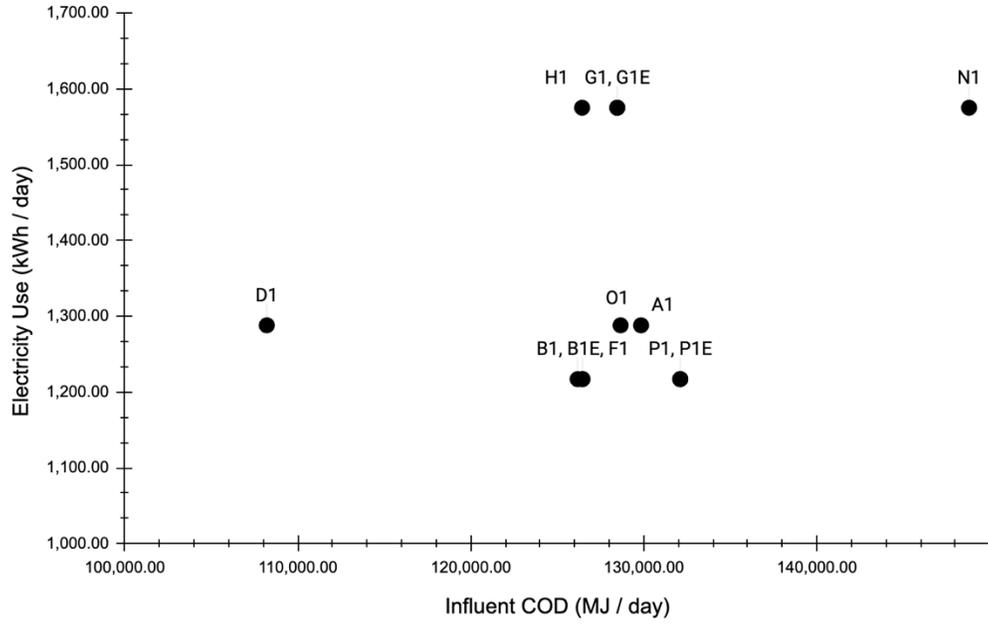
339
340 **Table S10.** Calculated electricity consumption for new treatment trains with aerobic digestion for solids
341 treatment.

New Train	Liquid Train	Solids Train	COD to Digester (MJ/d)	Electricity Consumed by Digester (kWh/d)
*A3 (B2)	*A1 (B1)	*E3 (E2P)	126,439.00	5,284.37
A3 (C2)	A4 (C3)	*D3 (N2)	109,939.00	4,248.17
*C3 (D2)	*C1 (D1)	*D3 (N2)	108,205.00	4,139.27
*G3 (G2)	*G1 (G1)	*E3 (E2P)	128,460.00	5,411.29
*B3 (O2)	*B1 (O1)	*E3 (E2P)	128,653.00	5,423.41

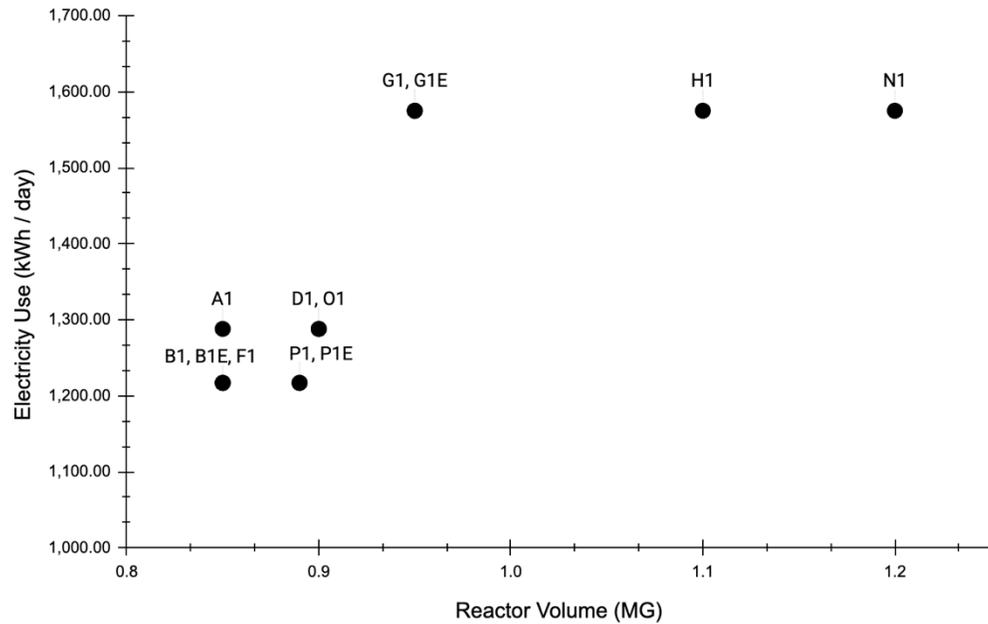
342
343 **Anaerobic digestion - electricity requirement.**

344 We did not observe a linear relationship between electricity required for anaerobic digestion in
345 WERF modeled treatment trains and available parameters, such as influent COD (**Figure S6**) or
346 bioreactor volume (**Figure S7**). However, electricity requirements appear to cluster roughly into
347 groups, with lower electricity for trains without nutrient removal (*A1 (B1), *C1 (D1), *B1
348 (O1), and WERF trains A1 and P1 which are not included in our analysis) and greater electricity
349 needed for nutrient removal (*G1-p (H1), *G1 (G1), *D1 (N1)). Thus, to create treatment trains
350 A1/A1e (C1/C1E) (activated sludge without primary treatment), we used the electricity
351 requirement from *A1 (B1), activated sludge with primary treatment. For F1 (I1), biological
352 nitrogen removal activated sludge without primary treatment, we used the *G1-p (H1)/*G1
353 (G1)/*D1 (N1) energy requirement, all of which are equivalent.

354

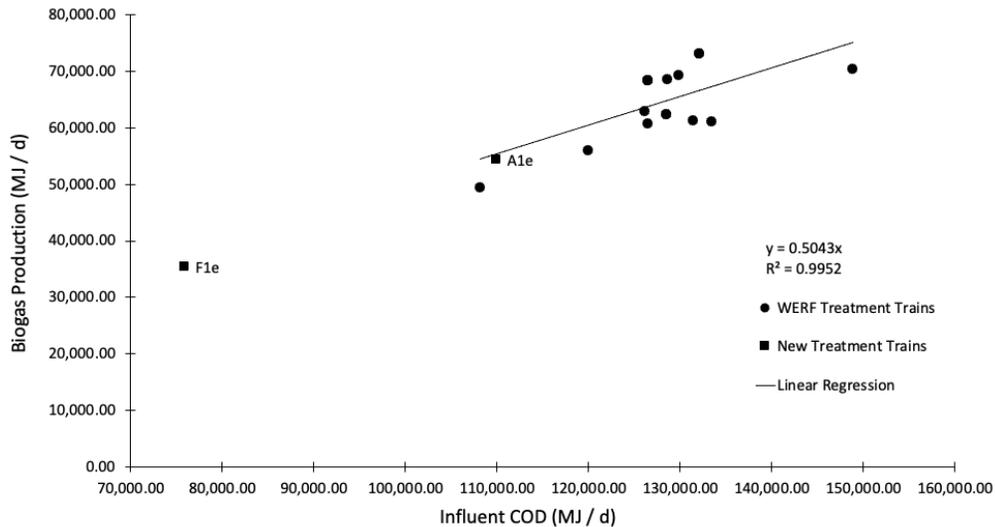


355
 356 **Figure S6.** Electricity consumption as a function of influent COD for anaerobic digestion treatment trains
 357 reported in Tarallo et al., 2015. Note that the x and y-axes start at 100,000 MJ COD / day and 1,000 kWh/day
 358 respectively.
 359



360
 361 **Figure S7.** Electricity consumption as a function of bioreactor volume for anaerobic digestion treatment
 362 trains reported in Tarallo et al., 2015. Note that the y-axis starts at 1,000 kWh/day.
 363

364 **Anaerobic digestion - biogas production.** In the WERF treatment trains, we observed a linear
 365 relationship between biogas production and influent COD. We used a linear regression with a fixed
 366 y-intercept at the origin to determine the average biogas production per unit of COD influent, as
 367 depicted in **Figure S8**. From these regression results, we calculated biogas production for new
 368 treatment trains A1e (C1E) and F1e (I1E) using the estimated influent COD to the anaerobic
 369 digester, a value dependent on the liquid train the new treatment train is based on. For A1e (C1E),
 370 we approximated the influent COD to the anaerobic digester as the effluent COD from the
 371 mechanical thickener of A4 (C3). For F1e (I1E), the influent COD is approximated as the effluent
 372 COD of the mechanical thickener of F3 (I2). For new treatment trains *C1e (D1E), *E1e (F1E),
 373 *G1e-p (H1E), *D1e (N1E) and *B1e (O1E), we use the biogas production reported for the non-
 374 electricity producing version of the treatment train published in Tarallo et al., 2015. Influent COD
 375 and predicted biogas production are included in **Table S11**.
 376



377 **Figure S8.** Linear regression used to estimate daily biogas production. For new treatment trains A1e (C1E)
 378 and F1e (I1E), we calculated biogas production based on the influent COD to the digester. For treatment
 379 trains *C1e (D1E), *E1e (F1E), *G1e-p (H1E), *B1e (O1E), and *D1e (N1E), we used the biogas
 380 production rate reported in Tarallo et al., 2015 for the non-electricity producing versions of these trains.
 381 Note that the x-axis starts at 70,000 MJ / day.
 382

383 **Table S11.** Predicted daily biogas yield for new treatment trains.
 384

	Influent COD (MJ/day)	Predicted Biogas Production (MJ/day)
A1e (C1E)	109,939	58,484
*C1e (D1E)	108,205	49,300
*E1e (F1E)	126,173	62,900
*G1e-p (H1E)	126,428	60,700
F1e (I1E)	75,899	45,986

*D1e (N1E)	148,796	70,400
*B1e (O1E)	128,653	68,500

385

386 **Anaerobic digestion - energy generation.** Our analysis includes seven new treatment trains with
 387 CHP for onsite electricity production: A1e (C1E), *C1E (D1E), *E1e (F1E), *G1e-p (H1E), F1e
 388 (I1E), *D1e (N1E), and *B1e (O1E). WERF provides modeled energy values for three treatment
 389 trains with CHP: *A1e (B1E), *G1e (G1E) and P1E, all of which produce different amounts of
 390 energy per day. Thus, we assigned energy production values for new treatment trains based on the
 391 estimated amount of biogas produced and an average generator efficiency of 0.0925, calculated
 392 based on the WERF treatment trains that utilize biogas for electricity generation.

393

394 **Lime stabilization.** We determined energy requirements for lime stabilization using the
 395 assumptions reported by Tarallo et al., 2015. Following their approach, we assume Class B lime
 396 stabilization is used to achieve a reduced pathogen level, as opposed to complete removal.¹⁰
 397 Energy requirements for lime stabilization treatment trains can be broken up into two components:
 398 the natural gas and electricity needed to produce the lime itself (typically offsite), and electricity
 399 needed onsite to operate the lime stabilization unit. For the process electricity required to operate
 400 the lime stabilization unit, we use the average of the two reported WERF trains with lime
 401 stabilization, A4 (C3) and F4 (I3).

402

403 Tarallo et al., 2015 report the electricity and natural gas required to produce lime offsite (**Table**
 404 **S12**) and assume a dose of 85 lbs of lime per ton of wet weight into the lime stabilization unit.
 405 However, mass flow data is only reported in total suspended solids (TSS) concentration (lbs
 406 TSS/day) and flow rate (MGD/day) entering the lime stabilization unit, and wet weight is not
 407 provided. Subsequently, to estimate the energy needed for lime production for our new treatment
 408 trains *A4 (B3), *C4 (D3), *G4 (G3), and *B4 (O3), we calculated lime dosing as a function of
 409 TSS using provided energy values. Because Tarallo et al., 2015 process model documentation
 410 (provided by the authors for use in this work) only includes supplemental mass balance data with
 411 TSS concentration for F4 (I3) and not A4 (C3), we use the energy requirements for lime
 412 stabilization reported in F4 (I3) to calculate the amount of lime used per day, and in turn the amount
 413 of lime needed per lb of TSS. Calculations are included in **Table S13**.

414

415 **Table S12.** Energy requirements for lime production reported in Tarallo et al., 2015 and used as model
 416 inputs.

Energy input for lime production	Quantity
Electricity (kWh/lb lime)	0.028056
Natural gas (MJ/lb lime)	2.3319

417

418 **Table S13.** Calculations for determining lime dosage as a function of TSS.

F4 (I3) Lime Calculations

Reported Fuel Used for Chemical Production	MJ/day	7,178.48
Reported Electricity Used for Chemical Production	kWh/day	86.3657
Calculated lime production/day - using electricity	lbs lime/day	3,078
Calculated lime production/day - using fuel	lbs lime/day	3,078
Reported cake production	lbs TSS/day	12,314
Calculated lime dose	lbs lime/lb TSS	0.25

419

420 Because we only have full information for calculating lime dosing and energy requirements for
 421 one treatment train, we examined the potential variability if lime stabilization were used across all
 422 treatment trains. Thus, using available cake concentrations and flow rates reported by Tarallo et
 423 al., 2015, we estimated the total amount of lime needed for stabilization for the treatment trains
 424 showed in **Table S14** and calculated the corresponding natural gas and electricity requirements
 425 using the dosing rate calculated in **Table S13**. **Table S14** includes values for all treatment trains,
 426 and **Table S15** reports summary statistics. We used the average energy values for lime production
 427 from across all modeled WERF trains for the new treatment trains with lime stabilization.

428

429 **Table S14.** Predicted electricity and natural gas required to stabilize the cake generated from the WERF
 430 treatment train. We used the mass balance data available for WERF trains to estimate the energy
 431 requirements based on the mass of the cake leaving the dewatering process across all configurations. For
 432 the treatment train naming system, we list our code first, followed by the Tarallo et al., 2015 code in
 433 parenthesis. Treatment trains with only values in parenthesis are those which are not included in our
 434 analysis.

Treatment Train	Electricity Required (kWh/d)	Natural Gas Required (MJ/d)
(A1)	67.21	5,586.49
*A5 (B5)	126.22	10,490.66
*A6 (B6)	126.14	10,483.85
*A1 (B1)	64.53	5,363.17
*A1e (B1E)	64.53	5,363.17
*A2 (B4)	64.53	5,363.17
E3 (E2)	69.46	5,773.22
*E3 (E2P)	81.52	6,775.48
*E1	69.68	5,791.42
*G1 (G1)	79.90	6,640.90
*G1e (G1E)	79.89	6,640.43
*G1-p (H1)	95.75	7,958.76
F3 (I2)	67.16	5,582.16
F4 (I3)	86.37	7,178.48

(L1)	117.29	9,748.99
(M1)	114.27	9,497.64
*D1 (N1)	95.89	7,970.31
*D3 (N2)	88.43	7,349.69
A4 (C3)	109.00	9,030.00
Average	87.78	7,294.10

435
436
437

Table S15. Summary statistics for energy required for lime stabilization across all WERF trains. We used the mean energy requirement in all new trains with lime stabilization.

Expected Energy Requirement		
	Electricity (kWh/day)	Natural Gas (MJ/day)
Mean	87.78	7,294.08
Minimum	64.53	5,363.17
Maximum	126.22	10,490.66
Standard Deviation	21.60	1,793.97

438
439
440
441
442
443
444

Incineration. Tarallo et al., 2015 only model two treatment trains with incineration, one with multiple hearth incineration (MHI) and one with fluidized bed incineration (FBI). Thus, for all new treatment trains with incineration, we use the electricity and natural gas required for incineration in *A5 (B5) (MHI) or *A6 (B6) (FBI), based on the respective type of incinerator in the new train.

445
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452

Ancillary solids treatment processes. In addition to the main solids stabilization process, energy is required for ancillary processes such as solids thickening and dewatering. Across all reported solids treatment trains, there are minor fluctuations in energy requirements for gravity and mechanical thickener requirements. Therefore, for all new treatment trains, we use the average energy requirements for thickeners based on the following configurations: gravity thickener only, mechanical thickener only, and both thickeners present. Additionally, energy is used for dewatering, which remains constant across all WERF trains at 89 kWh. These values are summarized in **Table S16**.

453
454

Table S16. Energy requirements calculated for thickeners, inclusive of dewatering energy use.

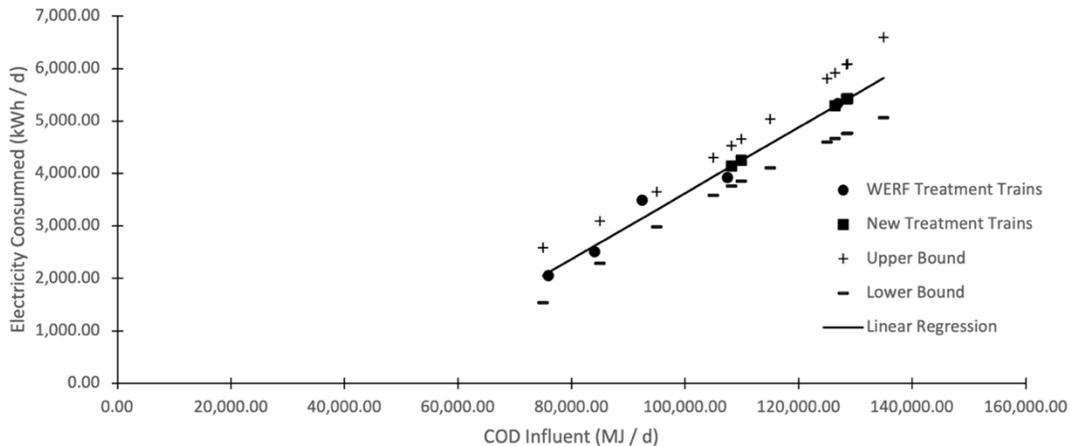
Configuration	Gravity Thickener Energy (kWh)	Mechanical Thickener Energy (kWh)
Gravity Thickener Only	27.5	0.0
Mechanical Thickener Only	0.0	162.3
Both Thickeners Present	24.1	157.1

455

456 *Sensitivity analysis*

457 We conducted an uncertainty analysis to evaluate the impact of key assumptions on the calculated
 458 energy requirements for all new treatment trains. We developed upper and lower bounds based on
 459 key unit processes including aerobic digestion, anaerobic digestion, and lime stabilization.
 460 However, we did not include any liquids processes or minor steps in the solids treatment processes
 461 (e.g. thickening), which exhibit minimal variation in energy inputs across the WERF treatment
 462 train model results. For all energy values calculated using linear regression (electricity
 463 consumption by aerobic digesters and electricity production from anaerobic digester biogas), we
 464 determine the associated 95% confidence intervals (CI) to use as upper and lower bounds on these
 465 inputs. For unit processes where energy values were selected based on similar treatment objectives
 466 (anaerobic digester electricity consumption), as well as lime stabilization, we use the lowest and
 467 highest energy requirements reported across all WERF treatment trains as the lower and upper
 468 bounds, respectively.

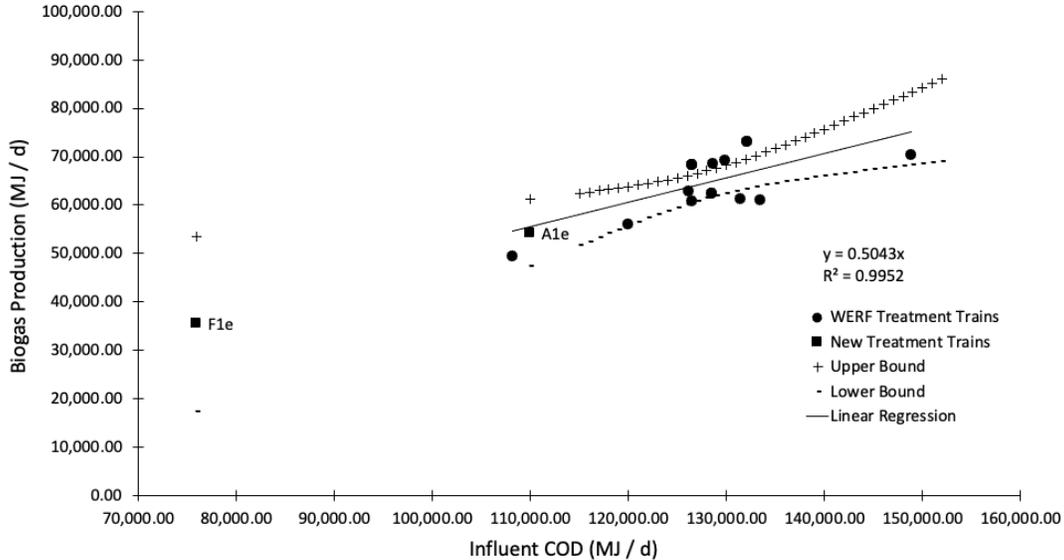
469
 470 **Aerobic digestion.** To determine the uncertainty associated with energy required for aerobic
 471 digestion, we calculate 95% CIs on the linear regression used to determine the relationship between
 472 influent COD and electricity requirement (**Figure S9**). Upper and lower bounds of the 95% CI
 473 were used as the upper and lower bounds in our sensitivity analysis for the following relevant
 474 treatment trains: *A3 (B2), A3 (C2), *C3 (D2), *G3 (G2), and *B3 (O2).
 475



476
 477 **Figure S9.** Uncertainty bounds of linear regression used to estimate electricity demand of aerobic digesters
 478 in sensitivity analysis. We calculated the 95% CI on electricity consumption values calculated using linear
 479 regression.

480
 481 **Anaerobic digestion - electricity.** For upper and lower bounds on electricity demands for
 482 anaerobic digesters, we used the highest and lowest reported electricity value for trains modeled
 483 in Tarallo et al., 2015: *A1 (B1) and *G1 (G1), respectively. These bounds contribute to the
 484 sensitivity analysis for the following trains: A1 (C1), A1e (C1E), F1 (I1), F1e (I1E), and *B1e
 485 (O1E).
 486

487 **Anaerobic digestion - biogas production.** To assess uncertainty in biogas production, we use the
 488 95% CIs on the linear regression used to determine biogas production based on influent COD,
 489 applicable to treatment trains A1e (C1E) and F1e (I1E) (**Figure S10**). Upper and lower CIs are
 490 used as inputs for the sensitivity analysis. For the remaining treatment trains, modeled biogas
 491 production is reported in Tarallo et al., 2015 and thus we do not apply a sensitivity analysis.

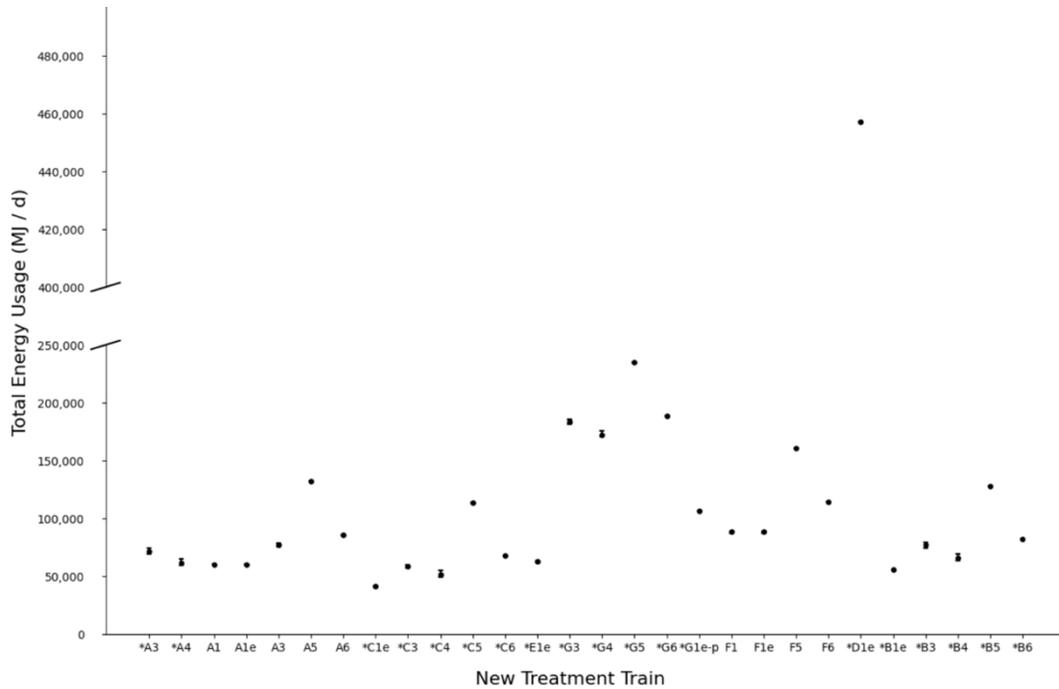


492 **Figure S10.** Uncertainty bounds of linear regression used to estimate biogas production of anaerobic
 493 digesters in sensitivity analysis.
 494

495 **Lime production.** For lower and upper bounds on energy required for lime production, we used
 496 the treatment trains with the lowest and highest theoretical energy requirements for lime
 497 production, *A1 (B1) and *A5 (B5). For the electricity required for the process of lime
 498 stabilization itself, we use the energy requirements from the least and most energy intensive lime
 499 treatment trains, F4 (I3) and A4 (C3), as lower and upper bounds.
 500

501 **Sensitivity analysis results.** **Figure S11** depicts the ranges we observe in energy estimates across
 502 new treatment trains. With current assumptions, new trains involving lime production/stabilization
 503 or aerobic digesters have the greatest range of possible energy intensities. However, when
 504 compared to the range in energy intensities across all treatment trains, the variability associated
 505 with our assumptions is far less than the variability between different treatment trains.
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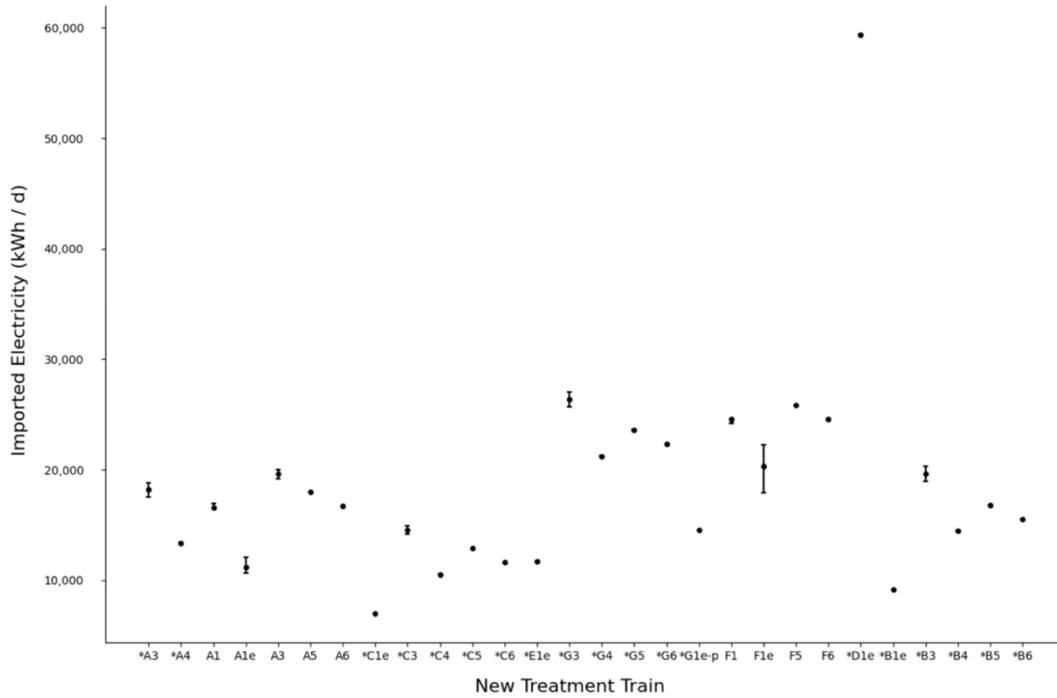


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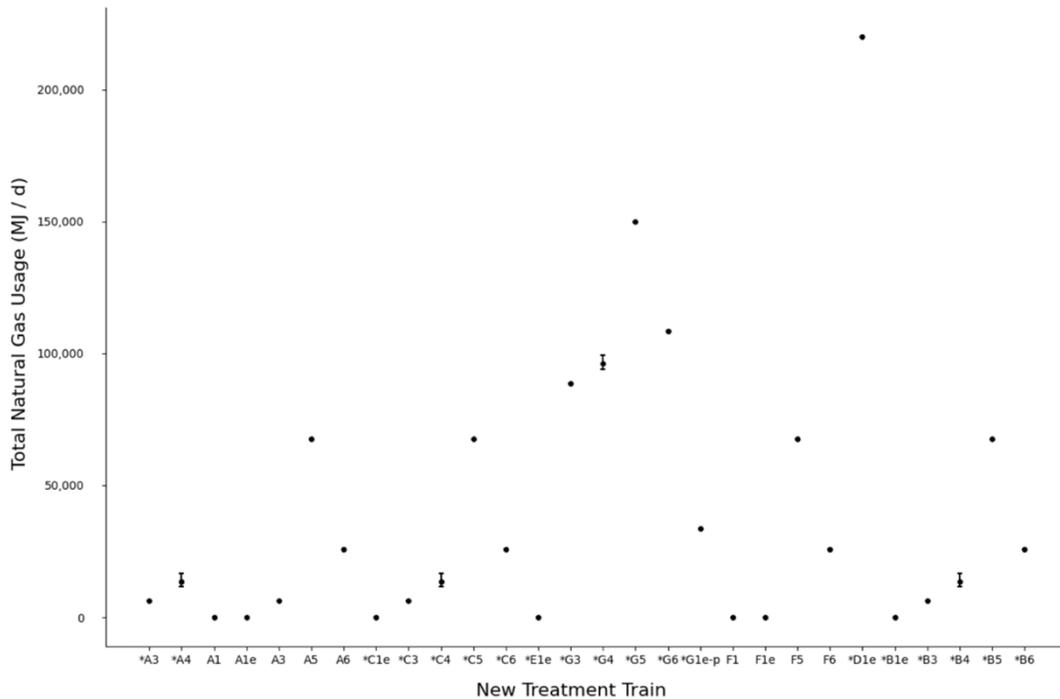
Figure S11. Sensitivity of total energy requirement to variability of model results from Tarallo et al., 2015. Lower and upper bounds were determined by considering the modeled range of energy requirements in each process of a treatment train. Where only the selected energy intensity point is visible, differences in values are too small to be apparent at a scale which allows for comparison between all treatment trains.

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Figure S12 depicts a sensitivity analysis for the imported electricity requirement, which captures variability in our assumptions regarding energy generated onsite. This figure also captures the variability observed in energy requirements for aerobic digestions, more visible here when separated out from the natural gas requirements, which are included in **Figure S13**. We observe the greatest variability in treatment train F1e (I1E), reflective of the wide 95% CI associated with the linear regression used to determine biogas production. This high uncertainty reflects the fact that the influent COD for the F1E (I1E) treatment train is far lower than values reported for other WERF treatment trains with anaerobic digestion. However, even in this instance, the variability remains acceptable when considering the differences in imported energy requirements that exist between different treatment trains.



525
 526 **Figure S12.** Sensitivity of imported electricity. Lower and upper bounds were determined by considering
 527 the modeled range of energy requirements in each process of a treatment train. For trains with anaerobic
 528 digestion, we also consider the range in biogas production rate and corresponding electricity consumption.
 529 Where only the selected energy intensity point is visible, differences in values are too small to be apparent
 530 at a scale which allows for comparison between all treatment trains.
 531



532
 533 **Figure S13.** Sensitivity of imported natural gas. Lower and upper bounds were determined by considering
 534 the modeled range of energy requirements in each process of a treatment train. Where only the selected

535 energy intensity point is visible, differences in values are too small to be apparent at a scale which allows
 536 for comparison between all treatment trains.

537

538 2.2.4. Electricity carbon intensity

539 Greenhouse gas (GHG) emission factors for production of different types of electricity were
 540 assigned according to values in Table S17. This table also includes emissions associated with
 541 producing and burning natural gas.

542

543 **Table S17.** Greenhouse gas emissions factors for electricity by power plant type, and for natural gas,
 544 including emissions from extraction and distribution systems, power plant construction, and combustion.¹¹

Power plant type	GHG emissions (g CO ₂ -eq/MJ)
Natural Gas	24
Coal	18
Nuclear	1.9
Wind	2.9
Solar	10
Biomass	19
Geothermal	1.4
Hydro	2.1
Natural gas system	GHG emissions (g CO ₂ -eq/MJ)
Extraction and distribution emissions	13
Combustion emissions	56

545

546 2.3. Non-combustion on-site emissions of CH₄, N₂O, and CO₂

547 We estimate CH₄ and N₂O emissions using emissions factors reported in literature. All emissions
 548 are converted to equivalent CO₂ emissions based on their 100-year Global Warming Potential,
 549 29.8 for methane and 273 for nitrous oxide.¹²

550

551 For CH₄ emissions (**Table S18**), we use emissions factors from Song et al¹³ based on the presence
 552 or absence of an anaerobic digester at the facility. For lagoons, we use IPCC emissions factors for
 553 anaerobic, aerobic, and facultative lagoons. For the uncategorized lagoons emissions factor, we
 554 use the national flow-weighted average of emission factors for aerobic, anaerobic, and facultative
 555 lagoons.¹⁴ To estimate nitrous oxide emissions (**Table S19**), we use the 376 nitrous oxide emission
 556 factor observations reported by Song et al, 2024.¹⁵ Using their reported literature database, we
 557 categorized each measurement into a nutrient removal category (organics removal, nitrification,
 558 denitrification) based on reported treatment configuration. Where the listed reactor design could
 559 be configured for multiple treatment objectives, we used the process descriptions provided in the
 560 original publication cited by Song et al. Next, we calculated emissions factors for each treatment
 561 objective using measurements identified by Song et al. as being conducted at either bioreactor or
 562 facility level scale, and from full-scale facilities only (i.e. excluding emissions factors from pilot
 563 scale facilities). Of the 281 reported emissions factors, 221 were for BNR facilities, 33 were from
 564 nitrification facilities, and 22 from organics removal facilities.

565

566 **Table S18.** Emissions factors for methane.

Category	CH ₄ [g CH ₄ /m ³]
Facility with anaerobic digestion ¹³	12.700
Facility without anaerobic digestion ¹³	3.767
Aerobic lagoon ¹⁴	0
Anaerobic lagoon ¹⁴	20
Facultative lagoon ¹⁴	20
Uncategorized lagoon	3.75

567

568 **Table S19.** emissions factors for nitrous oxide based on facility type.

Category	N ₂ O [%]
Facility with nitrification	1.3
Facility with biological nutrient removal	1.1
Facility with organics removal only	0.28
Aerobic lagoon ¹⁴	1.6
Anaerobic lagoon ¹⁴	0
Facultative lagoon ¹⁴	0
Uncategorized lagoon	1.3

569

570 We also included process (non-combustion) CO₂ emissions, produced by biological processes
 571 onsite. The carbon content in wastewater consists of two components: the fraction produced from
 572 short-lived biogenic material (modern) and fraction derived from fossil-origin carbon. Recent
 573 studies on the fraction of fossil-origin carbon in wastewater are discussed in detail in
 574 **Supplementary Note 1**. In our analysis, we assumed that the influent COD is 400 mg/L for all
 575 treatment trains and 15% of the influent COD is fossil-origin, a mid-range of the values reported
 576 in the literature, which range from 4-25%.¹⁶⁻¹⁸ We assume 65% of influent COD is assimilated
 577 into biomass and the rest released as CO₂.¹⁷

578

579 2.4. Biosolids handling

580 2.4.1. Biosolids production and disposal

581 The U.S. EPA releases an annual report specifying the amount of biosolids produced through
 582 wastewater treatment and the treatment facility's selected disposal method, typically incineration,
 583 landfilling, or land application.¹⁹ We removed the top and bottom 10% of facilities from this
 584 dataset, ranked by flow-weighted biosolids production rate (i.e., the ratio of biosolids produced to
 585 wastewater influent) as outliers. This results in a coverage of 2,877 facilities, leaving a significant
 586 data gap in the amount and fate of biosolids at most treatment facilities in our inventory. Therefore,
 587 we supplemented the EPA dataset by estimating biosolids production based on facility flow rate
 588 using equations (1-3) from Seiple et al.²⁰ This approach assumes total sludge (M_T) is the sum of
 589 the sludge produced during primary treatment (M_P) and secondary treatment (M_S), as per Equation
 590 1. For treatment trains without primary treatment, M_P is zero.

$$M_T = M_P + M_S \quad [1]$$

591 For facilities with primary treatment, we used Equation 2 to estimate M_P as a function of average
 592 influent flow rate to the facility (Q), total suspended solids (TSS), and the fraction of solids
 593 removed during primary settling (f). We used the average flow rate for each facility, as reported
 594 in CWNS. We assumed an average value of 260 mg/L for TSS, and an f value of 0.6.²⁰

$$M_P = Q * TSS * f \quad [2]$$

596
 597 We used Equation 3 to calculate the total solids produced in secondary treatment. Here, biosolids
 598 production is again a function of flow rate (Q), as well as the biological oxygen demand entering
 599 the plant (BOD_5 , or S_0 in Equation 3), assumed to be a standard concentration of 230 mg/L. The
 600 share of BOD_5 assumed to be converted into excess biomass is k , assumed to be 0.4, and f_v is the
 601 ratio between the fraction of TSS that is volatile suspended solids, assumed to be 0.85.

$$M_S = Q \left[(k * S_0) + \left(((1-f) * TSS) * (1-f_v) \right) \right] \quad [3]$$

603
 604 The estimated biosolids amount for those facilities is further adjusted if solid digestion is present.
 605 Specifically, we assumed a VSS/TSS ratio of 0.6 for produced solids and a VSS reduction ratio of
 606 0.425 after anaerobic digestion and 0.475 after aerobic digestion.²¹ Note whenever multiple
 607 treatment trains are assigned to a facility, we assumed equal division of flow and calculated
 608 biosolids amount separately before adding them to get the total biosolids amount.

609
 610 Next, we estimated fate of the captured biosolids for the facilities with a calculated biosolids
 611 amount. We first used biosolids disposal methods identified in CWNS to identify the biosolids fate
 612 and, whenever multiple fates are indicated for one facility, we used ratios in **Table S20** to split the
 613 biosolids. Due to limited data, we assume biosolids are split evenly when a facility implements
 614 two methods of disposal. When all three methods are implemented, we assume half of solids are
 615 incinerated onsite, a conservative approach with regards to greenhouse gas emissions because
 616 incineration produces CO_2 but not CH_4 or N_2O . Because biosolids handling is a small fraction of
 617 overall facility emissions (3.1%), these assumptions are not driving results. Future research can
 618 improve understanding of the fate of biosolids from wastewater treatment across the United States.

619
 620 **Table S20.4** Assumed breakdown of biosolids handling for different technologies.

Data set indicates:	Share of Biosolids		
	Landfill	Land Application	Incineration
Landfill only	100%	0	0
Land application only	0	100%	0
Incineration only	0	0	100%
Landfill and land application	50%	50%	0
Land application and incineration	0	50%	50%

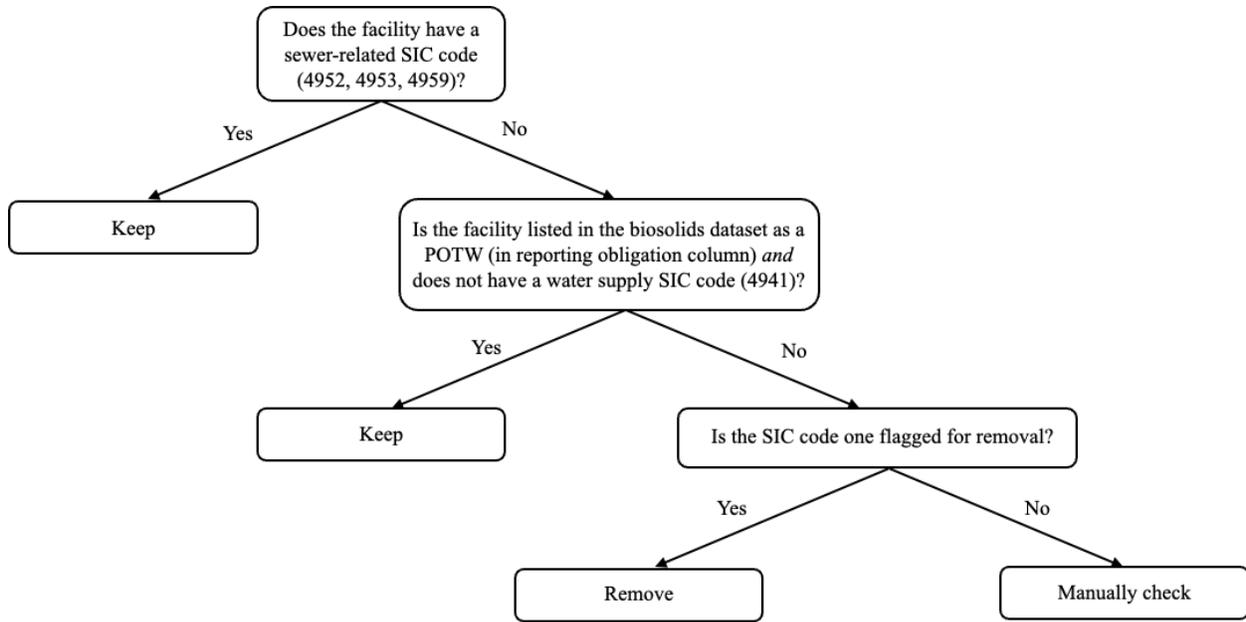
Landfill and incineration	50%	0	50%
Landfill, land application, and incineration	25%	25%	50%

621
 622 For the facilities where biosolids handling is not indicated through EPA’s biosolids database or
 623 through CWNS, we estimated biosolids fate based on assigned treatment trains. For facilities with
 624 only one treatment train, we assumed all biosolids are incinerated if the treatment train includes
 625 incineration. Otherwise, we assumed equal amount of biosolids are landfilled and land applied.
 626 For plants with more than one treatment train, we first calculated biosolids produced from
 627 incineration trains using the methods mentioned above, then the remaining of biosolids were
 628 evenly split between landfill and land application. While land application may be more common
 629 in many places across the United States,²² states are increasingly banning land application of
 630 biosolids out of concerns of PFAS entering the food system.²³ This changing regulatory context
 631 which will rapidly shift the distribution of biosolids fates, impacting resulting emissions.

632
 633 To improve estimates of biosolid production, we used the EPA Biosolids Annual Report which
 634 contains biosolids generation and management practice information submitted by wastewater
 635 treatment plants electronically through the NPDES eReporting Tool.¹⁹ The biosolids dataset
 636 includes facilities that produce biosolids beyond just municipal wastewater treatment plants, many
 637 of which may have nearly identical names to the facilities in our wastewater treatment plant
 638 inventory despite being separate facilities. However, the dataset lacks a common but unique
 639 facility identification number (such as CWNS number) to directly match a facility in the Biosolids
 640 Report to the facilities in our inventory. Thus, we first removed facilities listed in the Biosolids
 641 Report that likely were not wastewater treatment plants.

642
 643 The workflow for filtering biosolid permits is depicted in **Figure S14** and uses the standard
 644 industrial classification (SIC) codes associated with each NPDES permit, obtained from the
 645 national SIC code database maintained by U.S. EPA on facilities requiring environmental
 646 regulation.²⁴ First, we kept all facilities that had SIC codes affiliated with sewer-systems (4952,
 647 4953, and 4959). Next, we checked which facilities were listed as publicly owned treatment works
 648 (POTW) in the Reporting Obligation(s) column of biosolids report data. Because POTW may be
 649 either wastewater or drinking water facilities, we kept all facilities that were listed as POTW but
 650 did *not* also have a water supply SIC code (4,941). Of the remaining facilities, we removed all
 651 facilities with SIC codes that make them unlikely to be municipally-owned wastewater treatment
 652 facilities (listed in **Table S21**, descriptions from the NAICS and SIC Crosswalk).²⁵ We kept all
 653 facilities that do not have an SIC code match. Following these automated filtering steps, we
 654 manually checked publicly available online information on the remaining facilities. There were
 655 five facilities that required manual checks, summarized in **Table S22**, none of which were
 656 municipal wastewater treatment plants and thus were removed from the dataset.

657



658
659 **Figure S14.** Biosolids permit filtering workflow.
660

661 **Table S21.** SIC codes associated with facilities in the biosolids dataset that were flagged for removal. A
662 facility was removed from the Biosolids Dataset if it failed the first two exclusion criteria in Figure S14,
663 and was associated with one of the SIC codes listed in this table.

SIC Code	Description
1389	Oil & gas field services
1522	Residential construction
2011	Meat packing plants
2491	Wood preserving
2493	Reconstituted wood products
2621	Paper mills
2899	Chemical preparation (spice/food extraction)
3171	Handbags & purses
3331	Primary copper
3498	Fabricated pipe & fitting
3533	Oil and gas field machinery
3743	Railroad equipment
4011	Railroads
4581	Airports
4911	Electric services
5075	Heating & cooling
5541	Gas station services
5812	Eating places
6514	Dwelling operators (residential)
6515	Mobile homes

6531	Real estate agents & managers
7011	Hotels & motels
7032	Sporting and recreation camps
7033	Trailer parks/campsites
7041	Membership hotels
7997	Sports/recreation clubs
7999	Amusement and recreation
8051	Skilled nursing care
8063	Psychiatric hospitals
8211	Schools
8221	Colleges & universities
8661	Religious organizations
9223	Correctional facilities
9711	National security

664

665 **Table S22.** List of facilities manually inspected for inclusion or exclusion from biosolids dataset. Note
 666 facility names appear as written in the downloaded EPA report.

Facility Name	SIC Code and Description	Notes
Live Oak County Safety Rest Area WWTF	7299 (misc. personal services)	Rest area waste facility – not a municipal wastewater treatment facility
Bayou Club WWTP	8641 (civic & social association)	Wastewater treatment at a club – not a municipal wastewater treatment facility
GE Packaged Power Jport	3511 (turbines/turbine generators) 7699 (repair services)	General Electric is a private company – not municipal wastewater treatment facility
Sigmatpro WWTP	6519 (real property lessors)	Sigma Pro is a private company - not municipal wastewater treatment facility
US DOE/Savannah River Site	2819 (industrial inorganic chemicals) 9611(administration of general economic programs)	US Department of Energy facility – not a municipal wastewater treatment plant

667

668 2.4.2. Biosolids emission factors

669 The methane emission rate for biosolids sent to landfills is derived from the Landfill Gas Emissions
 670 Model (LandGEM). LandGEM is used by the U.S. EPA to estimate emission rates for total landfill
 671 gas, methane, carbon dioxide, non-methane organic compounds, and individual air pollutants from
 672 municipal solid waste (MSW) landfills²⁶. We used the first-order decomposition rate equation
 673 (Supplementary Equation 4) to model annual methane generation from landfills.

674

$$675 \quad Q_{CH_4} = \sum_{i=1}^n \sum_{j=0.1}^1 kL_0 \left(\frac{M_i}{10} \right) e^{-kt_{ij}} \quad [4]$$

676 where:

677 Q_{CH_4} is annual methane generation in the year of the calculation (m³/year),

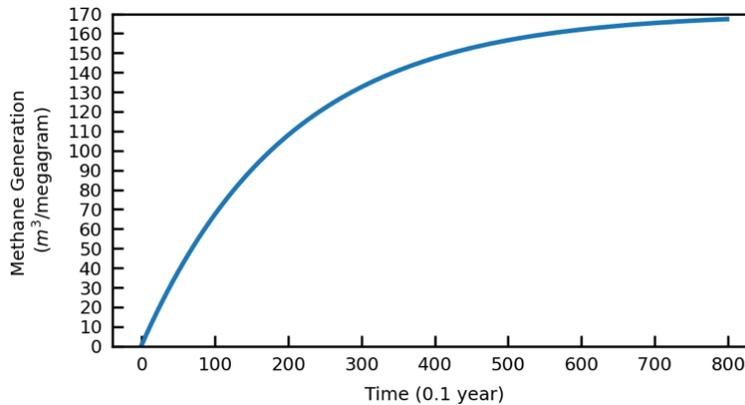
678 $\sum_{i=1}^n$ is summing over each year of waste accepted into the landfill (from year 1 to year n),

679 $\sum_{j=0.1}^1$ is dividing each year into 10 increments of 0.1 years,

680 k is methane generation rate constant (year^{-1}),
 681 L_0 is potential methane generation capacity ($\text{m}^3/\text{megagram}$),
 682 M_i is the mass of waste accepted in the i^{th} year (megagram),
 683 t_{ij} is the age of the j^{th} increment of waste M_i accepted in the i^{th} year (decimal years, e.g., 3.2 years).
 684

685 LandGEM calculates the CH_4 produced each year from the waste deposited (**Figure S15**). CH_4
 686 generation decreases as waste decomposes, governed by the first-order decay constant (k) and the
 687 potential methane generation capacity (L_0). We use regulatory default values, according to Clean
 688 Air Act conventional: $k = 0.05 \text{ year}^{-1}$, $L_0 = 170 \text{ m}^3 \cdot \text{megagram}^{-1}$. These regulatory defaults were
 689 developed for compliance purposes and are therefore conservative values intended to protect
 690 human health. The density of CH_4 is assumed to be $0.68 \text{ kg}/\text{m}^3$ at $15 \text{ }^\circ\text{C}$ and 1 atm^{27} .

691
 692 The model results show that CH_4 generation is $8.312 \text{ m}^3/\text{megagram}$ (equivalent to $5.65 \text{ kg}/\text{tonne}$
 693 at $15 \text{ }^\circ\text{C}$ and 1 atm) in the first year from the waste deposited. The total CH_4 generation will reach
 694 $167.303 \text{ m}^3/\text{megagram}$ (equivalent to $113.766 \text{ kg}/\text{tonne}$ at $15 \text{ }^\circ\text{C}$ and 1 atm) when summing all
 695 years since the waste was accepted into the landfill (from year 1 to year 80).



696
 697 **Figure S15.** Cumulative methane emission from the biosolids landfill over 80 years.
 698

699 CH_4 generation is highest in the first year and decreases as the waste decomposes over time. Since
 700 this study focuses on the short-term impact of emissions, the CH_4 generation rate in the first year—
 701 $5.652 \text{ kg}/\text{tonne}$ at $15 \text{ }^\circ\text{C}$ and 1 atm —was used as the CH_4 emission factor for analysis.

702
 703 For biosolids used in land application, the N_2O is the primary greenhouse gas of concern.²⁸ We
 704 assume a 5% nitrogen weight percentage in sludge and use the IPCC emissions factor of 0.01 kg
 705 $\text{N}_2\text{O}-\text{N}/\text{kg N}$ in biosolids.^{28,29} To explore the sensitivity of these values, we tested emissions factors
 706 reported in the literature for biosolids produced from anaerobic digestion, aerobic digestion, and
 707 lime stabilization.^{30–32} We find no meaningful difference in results, particularly when considering
 708 the magnitude of emissions associated with biosolids is substantially smaller than other emissions
 709 sources. The carbon in biosolids is overwhelmingly biogenic.³³ We therefore assume all CO_2 from
 710 incineration is biogenic and therefore do not include it in our emissions estimates. The amounts of
 711 CH_4 and N_2O from incineration are minimal as well.

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3. Supplementary Note 1: fossil origin carbon in wastewater

GHG emission guidelines traditionally focus on CH₄ and/or N₂O emissions, excluding CO₂ emissions arising from biological treatment processes. This exclusion is based on the argument that such emissions primarily originate from biogenic organic matter in human excreta or food waste, and therefore, they are typically not accounted for in national total emissions.³⁴ Nevertheless, wastewater treatment plants also emit fossil CO₂ and relying only on the assumption that all on-site CO₂ emissions are biogenic may lead to an underestimation of GHG emissions. The IPCC 2006 Guidelines established an international convention that discourages the reporting of non-biogenic CO₂ from activities in the waste sector. However, IPCC 2019 acknowledges the need for future improvements to the IPCC Guidelines, including a method for estimating non-biogenic emissions associated with wastewater treatment operations and wastewater discharges.³⁵ The proportions of biogenic and fossil carbon fractions depend on various factors, including wastewater characteristics and type. In many cases, accurate data regarding the origin of waste is either unavailable or outdated.

Griffith et al.¹⁶ reported that 25% of the total organic carbon (TOC) in wastewater originates from fossil sources, likely derived from cleaning products, pharmaceuticals, and fossil-fuel-based items. Another study conducted by Law et al.³⁶ suggested that existing GHG accounting guidelines, which assume that all CO₂ emissions from wastewater are biogenic, may lead to an underestimation of emissions. They conducted radiocarbon isotopes research and declared that 4-14% of TOC in wastewater is of fossil origin. Additionally, Liu et al.¹⁸ indicated that fossil carbon constitutes 3-10% of the total carbon in the mixed sludge. Their study revealed the effect of digestion on the removal of fossil carbon from wastewater as well as the CO₂ emissions from wastewater. Wang et al.³⁷ constructed an emission inventory of wastewater treatment facilities for CH₄, N₂O and CO₂ emissions from different treatment processes, energy consumptions, and effluent discharge for the time-period from 2006 to 2019 in China. However, the study did not distinguish between fossil CO₂ and biogenic CO₂ emissions from biological treatment but regarded CO₂ emission as the sum of fossil CO₂ and biogenic CO₂ emissions. Additional widespread measurements of CO₂ emissions at wastewater treatment plants that quantifies the portion that is of fossil carbon will improve wastewater treatment plant greenhouse gas inventories.

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