Supporting Information

SI File Name: Bath WRRF Supporting Tables and Figures

Paper Title: Effect of Nutrient Removal and Resource Recovery on Life Cycle Cost and Environmental Impacts of Small Scale Wastewater Resource Recovery Facility

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Contents: 24 Pages, 2 Figures, 21 Tables

The supplementary materials contain the items listed in the below table of contents including system diagrams of the assessed water resource recovery facility (WRRF) configurations, data and calculations used to generate the life cycle inventory (LCI), life cycle cost assessment (LCCA) methods, and grouping of unit processes used for the results presentation. Tables and figures appear in the order that they are referenced in the paper.

Table of Contents

S1. Supplementary Tables and Figures Referred to in the Methods Section

S1.1. WRRF Process Diagrams

Figure S1 presents a process diagram of the legacy WRRF showing internal flows, system inputs, and sources of process greenhouse gas (GHG) emissions.

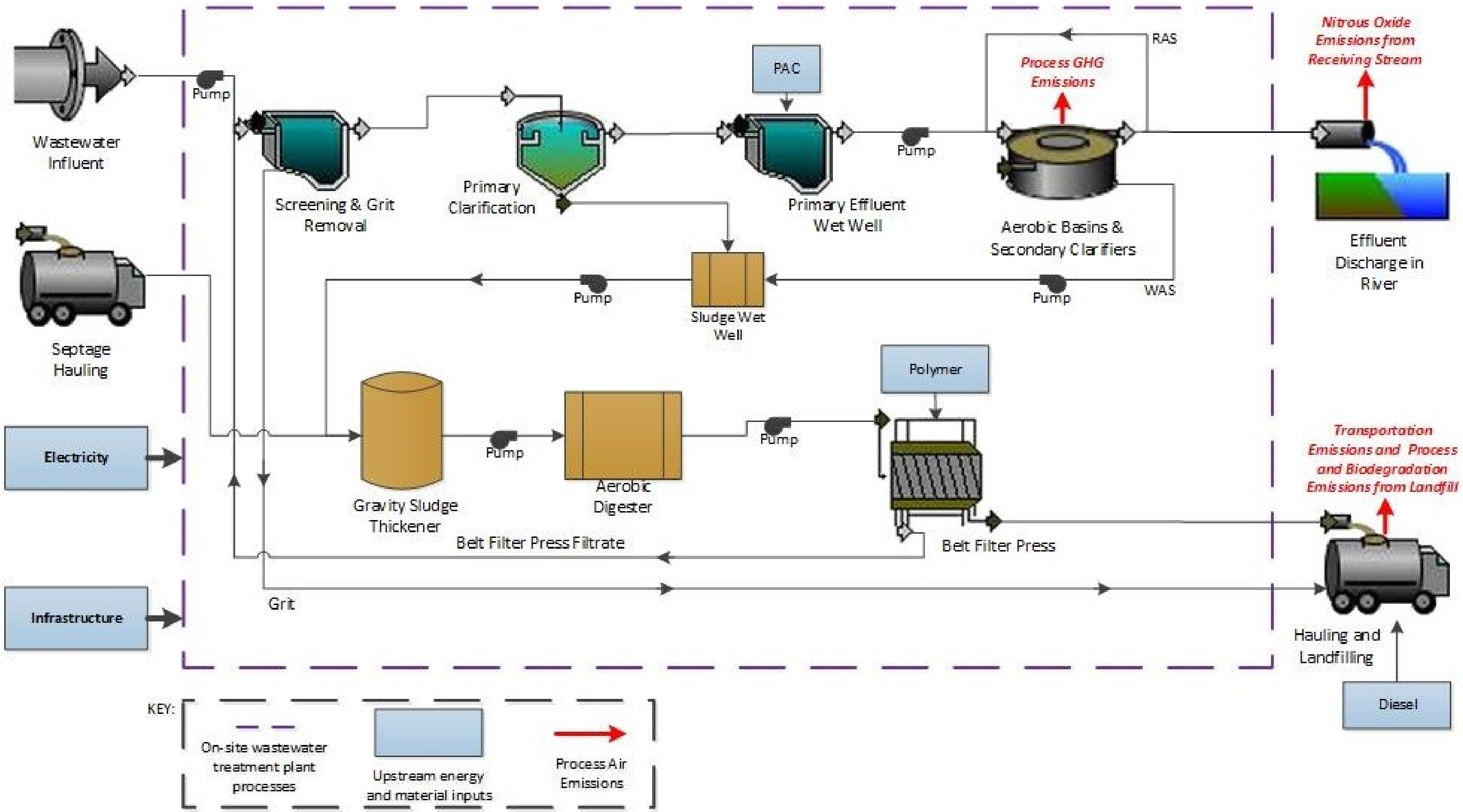

Figure S1. Legacy, conventional activated sludge treatment system diagram

Figure S2 presents a process diagram of the upgraded WRRF showing internal flows, system inputs, and sources of process GHG emissions.

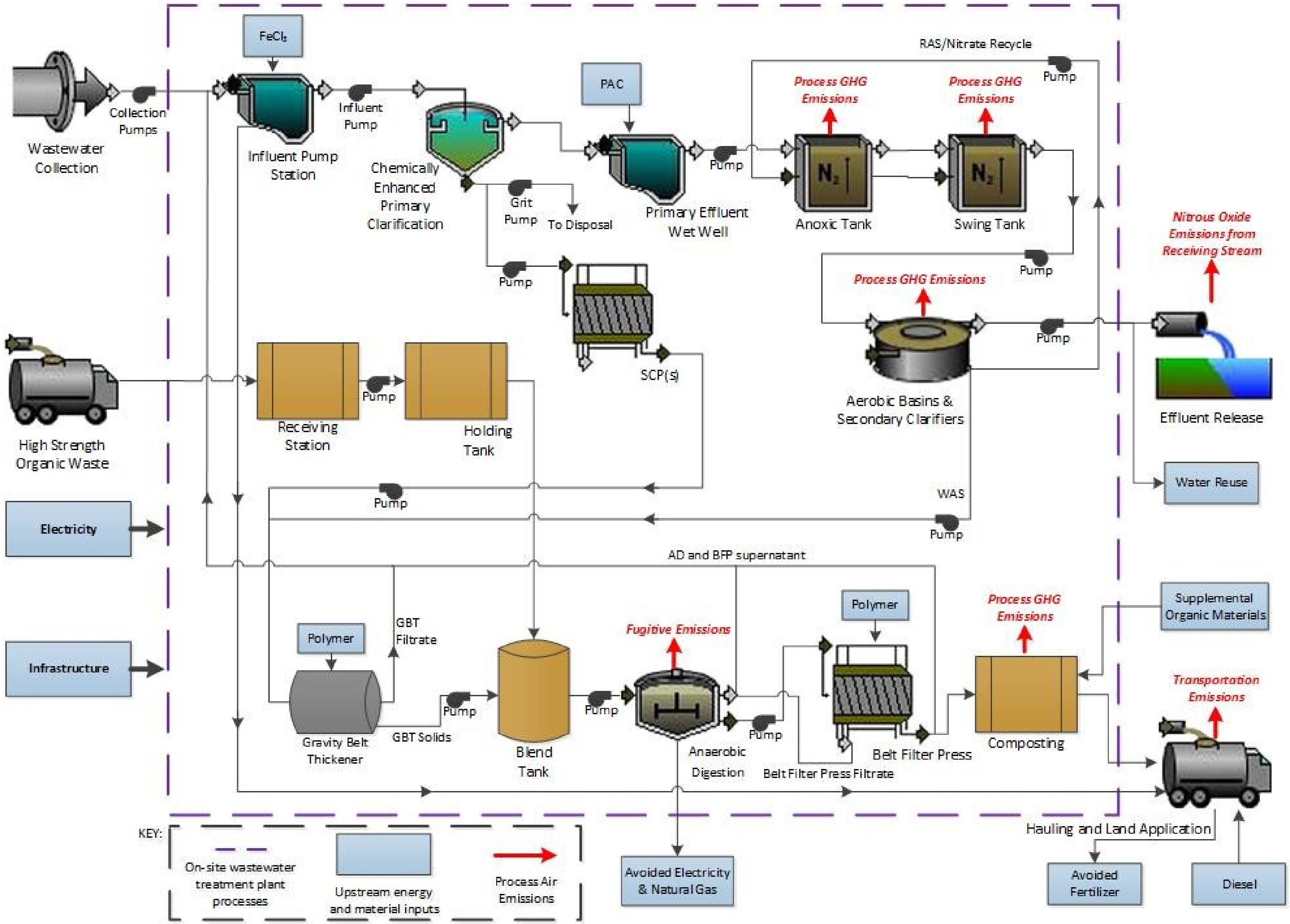

Figure S2. Upgraded WRRF, enhanced primary clarification, Modified-Ludzack Ettinger, and anaerobic digestion system diagram

S1.2. LCA Scenario Combinations

In total, results were generated for six and 54 scenario combinations for the legacy and upgraded treatment systems, respectively. Table S1 lists the scenario combinations evaluated for the legacy treatment system. Base scenario parameter combinations are highlighted in red. Table S2 lists the scenario combinations evaluated for the upgraded WRRF. The optimized scenario parameter combination, shown in the results figures, is highlighted in dark blue.

Table S1. Legacy Treatment System Scenario Combinations

EOL Emission Scenario	Landfill Scenario
Low	Bath Landfill
	Landfill National
Base[1]	**Bath Landfill[1]**
	Landfill National
High	Bath Landfill
	Landfill National

[1] The highlighted scenario combination defines the legacy base scenario.

Table S2. Upgraded Treatment System Scenario Combinations

Feedstock Scenario	AD Performance Scenario	EOL Emission Scenario	Compost System Scenario
Base	Low	**Low[2]**	**Windrow[1,2]**
	Base		
	High		
Medium	Low		
	Base		
	High		
High	Low		
	Base		
	High		
Base[1]	Low	**Base[1]**	
	Base[1]		
	High		
Medium	Low		
	Base		
	High		
High	Low		
	Base		
	High		
Base	Low	High	
	Base		
	High		
Medium	Low		
	Base		
	High		
High[2]	Low		
	Base		
	High[2]		
Base	Low	Low	Aerated Static Pile

Table S2. Upgraded Treatment System Scenario Combinations

Feedstock Scenario	AD Performance Scenario	EOL Emission Scenario	Compost System Scenario
	Base		
	High		
Medium	Low		
	Base		
	High		
High	Low		
	Base		
	High		
Base	Low	Base	
	Base		
	High		
Medium	Low		
	Base		
	High		
High	Low		
	Base		
	High		
Base	Low	High	
	Base		
	High		
Medium	Low		
	Base		
	High		
High	Low		
	Base		
	High		

[1] This parameter combination defines the upgraded base scenario.

[2] This parameter combination defines the upgraded optimized scenario.

S1.3. High Strength Organic Waste Characteristics and Biogas Yield

Table S3 lists representative feedstock characteristics for municipal solids, septage, and HSOW.

Table S3. Anaerobic Digestion Feedstock Characteristics (prior to dewatering)

Waste Type	Solids Content (% w/w)	Source	Volatile Solids (% of TS)	Source	Total N (mg N/L)	Source	Total P (mg P/L)	Source
Waste Activated Sludge	0.50%	[1]	31%	[2]	190[1]	[3]	120[1]	[3]
Primary Sludge	1.80%	[1]	68%	[2]	453[1]	[3]	127[1]	[3]
Septic Tank Waste	0.10%	[4]	57%	[4]	103	[4]	14	[4]
Portable Toilet Waste	0.30%	[4]	43%	[4]	937	[4]	67.7	[4]

Waste Type	Solids Content (% w/w)	Source	Volatile Solids (% of TS)	Source	Total N (mg N/L)	Source	Total P (mg P/L)	Source
Slaughterhouse Waste	13%	[5]	92%	[5]	1.50E+03[2]	[6,7]	NA[3]	
Winery Waste	3.70%	[8]	60%	[8]	105	[8]	NA[3]	
Cheese Waste	7.80%	[9]	62%	[9]	1.02E+03	[9]	300	[9]

[1] Calculated based on information in the cited references

[2] Between values reported in the cited references

[3] NA - not available

Table S4 lists biogas yield values for each source of solids that are fed into the AD. Assumed biogas yield values for each feedstock vary according to the assumed AD performance scenario. Biogas yield for each AD performance scenario is calculated as a weighted average of a feedstock specific biogas yield values using the feedstocks contribution to AD volatile solids as a weighting factor.

Table S4. Biogas Yield Values Associated with each Feedstock and AD Performance Scenario (m^3 biogas/ kg VS destroyed)

Feedstock	Low AD Scenario		Base AD Scenario		High AD Scenario	
	Value	Reference	Value	Reference	Value	Reference
Primary Sludge	0.7	[10] [1]	0.9	[10]	2.7	[11] [2]
Waste Activated Sludge	0.7	[10] [1]	0.9	[10]	1.1	[10] [3]
Septic Tank Waste	0.7	[10] [1]	0.9	[10]	1.1	[10] [3]
Slaughterhouse Waste	1.1	[12] [4]	1.5	[12] [5]	1.8	[12] [6]
Cheese Waste	0.7	[13] [7]	0.9	[13] [8]	1.0	[13] [9]
Winery Waste, Vinasse	0.6	[14] [10]	0.9	[14] [11]	1.1	[14] [12]
Portable Toilet Waste	0.7	[10] [1]	0.9	[10]	1.1	[10] [2]

[1] 20% decrease relative to base AD scenario value.

[2] Calculated using the biogas production value from GHD Inc. [11], 28.3 m^3 biogas/kg VS. Converted to m^3 biogas/kg VS destroyed using the high AD performance VS reduction value of 65 percent.

[3] 20% increase relative to base AD scenario value.

[4] Calculated using the low biogas production value from Braun and Wellinger [12], 550 m^3 biogas/ton organic solids. Converted to m^3 biogas/kg VS destroyed using the waste characteristics reported in Table S3 and the low AD performance VS reduction value of 45 percent. Calculated value was reduced by 20 percent to represent poor digester performance.

[5] Calculated using the average biogas production value from Braun and Wellinger [12], 825 m^3 biogas/ton organic solids. Converted to m^3 biogas/kg VS destroyed using the waste characteristics reported in Table S3 and the base AD performance VS reduction value of 60 percent.

[6] Calculated using the high biogas production value from Braun and Wellinger [12], 1,100 m^3 biogas/ton organic solids. Converted to m^3 biogas/kg VS destroyed using the waste characteristics reported in Table S3 and the high AD performance VS reduction value of 65 percent.

[7] Calculated using the low methane production value from Rico et al. [13], 337 L CH_4/kg VS. Converted to m^3 biogas/kg VS destroyed using the base AD performance VS reduction value of 60 percent and a biogas methane content of 65 percent. Calculated value was reduced by 20 percent to represent poor digester performance.

[8] Calculated using the average methane production value from Rico et al. [13], 363 L CH_4/kg VS. Converted to m^3 biogas/kg VS destroyed using the base AD performance VS reduction value of 60 percent and a biogas methane content of 65 percent.

[9] Calculated using the high methane production value from Rico et al. [13], 388 L CH_4/kg VS. Converted to m^3 biogas/kg VS destroyed using the base AD performance VS reduction value of 60 percent and a biogas methane content of 65 percent.

[10] Calculated using the low biogas production value from Belhadj et al. [14], 0.35 m^3 biogas/kg VS. Converted to m^3 biogas/kg VS destroyed using the low AD performance VS reduction vale of 45 percent. Calculated value was reduced by 20 percent to represent poor digester performance.

[11] Calculated using the average biogas production value from Belhadj et al. [14], 0.525 m^3 biogas/kg VS. Converted to m^3 biogas/kg VS destroyed using the base AD performance VS reduction value of 60 percent.

[12] Calculated using the high biogas production value from Belhadj et al. [14], 0.70 m^3 biogas/kg VS. Converted to m^3 biogas/kg VS destroyed using the high AD performance VS reduction vale of 65 percent.

Table Acronyms: AD – anaerobic digestion, VS – volatile solids

S1.4. Bath Electrical Grid Mix

We used the Bath, NY regional electrical grid mix, Table S5, to estimate the environmental impact of purchased electricity and the environmental benefit of avoided electricity production.

Table S5. Bath, NY Regional Electrical Grid Mix [15,16]

Fuel Source	Electrical Grid Mix (%)[1, 2]
Biomass	3.1%
Wind	1.9%
Solar	0.4%
Hydro	29%
Nuclear	29%
Gas	31%
Coal	5.5%
Total	100%

S1.5. Electricity Calculation Methods

Utility records were provided by facility staff for electricity, natural gas, and water use for the years 2014 and 2015. Electricity use for individual treatment processes was calculated on the basis of mechanical equipment horsepower (HP) or recorded voltage (V) and current (A) readings for each piece of equipment according to Equation S1 and Equation S2.

Electricity Use (kWh) = Unit HP x (0.746 kw/HP) x annual operation (hr)

Equation S1

Electricity Use (kWh) = (Amps x Volts)/1000 x annual operation (hr)

Equation S2

Table S6 lists the scaling factors used to adjust upgraded WRRF electricity consumption for unit process equipment expected to be affected by increases in solids flow associated with the medium and high feedstock scenarios. The low AD performance scenario has lower biogas production and decreased degradation leading to increased solids production. The high AD scenario is associated with lower solids production relative to the base AD scenario.

Table S6. Electricity Scaling Factors for Units Affected by Feedstock-AD Scenarios

	Base Feedstock Scenario*			Medium Feedstock Scenario			High Feedstock Scenario		
Equipment	**Low AD**	**Base AD***	**High AD**	**Low AD**	**Base AD**	**High AD**	**Low AD**	**Base AD**	**High AD**
Swing Tank, aeration	1.00	1.00	1.00	1.02	1.02	1.02	1.05	1.05	1.05
Sludge Pump (1)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sludge Pump (2)	1.00	1.00	1.00	1.25	1.25	1.25	1.50	1.50	1.50
Sludge Pump (3)	1.00	1.00	1.00	1.25	1.25	1.25	1.50	1.50	1.50
Raw Sludge Transfer Pump	1.00	1.00	1.00	1.04	1.04	1.04	1.07	1.07	1.07
GBT Air compressor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Gravity Belt Thickener	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
GBT Booster Pump	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Chemical Feed - Polymer BFP	1.11	1.00	0.960	1.56	1.38	1.32	2.18	1.89	1.79
Chemical Feed - Polymer GBT	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Blend Tank Mixer	1.00	1.00	1.00	1.04	1.04	1.04	1.07	1.07	1.07
Coarse Bubble Diffused Aeration	1.00	1.00	1.00	1.25	1.25	1.25	1.50	1.50	1.50
BFP Feed Pump No. 1	1.11	1.00	0.960	1.56	1.38	1.32	2.18	1.89	1.79
Drum Drive	1.11	1.00	0.960	1.56	1.38	1.32	2.18	1.89	1.79
Belt Drive	1.11	1.00	0.960	1.56	1.38	1.32	2.18	1.89	1.79
Spray Pump	1.11	1.00	0.960	1.56	1.38	1.32	2.18	1.89	1.79
Screw Conveyor Drive	1.11	1.00	0.960	1.56	1.38	1.32	2.18	1.89	1.79
Belt Conveyor Drive	1.11	1.00	0.960	1.56	1.38	1.32	2.18	1.89	1.79
Digested Sludge Transfer Pump	1.11	1.00	0.960	1.56	1.38	1.32	2.18	1.89	1.79

* The base feedstock-base AD performance scenario represents system parameters that are associated with the original electricity consumption estimates (i.e. 1.00).
Table Acronyms: AD – anaerobic digestion, BFP – belt filter press, GBT – gravity belt thickener

S1.6. Chemical Use Calculations

The quantities of chemical inputs were provided by facility staff (in English Units) and values were adjusted in the LCA model to account for the increased flow rate of the study system as compared to the current average flow rate. Chemical additions for the upgraded treatment plant were provided by the engineering design team of GHD Inc. Engineering for chemically enhanced primary clarification and Modified-Ludzack Ettinger (MLE) advanced secondary treatment.

S1.6.1. Legacy Clarifier Polyaluminum Chloride Use (PAC)

Facility staff reported that 114,000 gallons of PAC were used annually in the legacy primary clarifier. The calculation in Equation S3 determines the resulting LCI quantity:

$$\text{PAC (kg/m}^3\text{)} = 114{,}000 \text{ gal/year} \div 264 \text{ gal/m}^3 \times (1.18 \text{ (specific gravity)} \times 1000 \text{ kg/m}^3) \div (1{,}381{,}676 \text{ m}^3\text{/yr} \times 0.67 \text{ MGD}) = 0.55 \text{ kg/m}^3 \text{ wastewater}$$

Equation S3

S1.6.2. Legacy Belt Filter Press Polymer Use

It was reported that 23,000 gallons of polymer solution were used annually. The calculation in Equation S4 determines the resulting LCI quantity:

$$\text{polymer (kg/m}^3\text{)} = 24{,}000 \text{ gal/year} \div 264 \text{ gal/m}^3 \times (1.14 \text{ (specific gravity)} \times 1000 \text{ kg/m}^3) \div (1{,}381{,}676 \text{ m}^3\text{/yr} \times 0.67 \text{ MGD}) = 0.11 \text{ kg/m}^3 \text{ of } 0.5\% \text{ polymer solution}$$

$$\text{polymer quantity} = 0.11\text{kg/m}^3 * (0.5/100) = 5.36\text{E-}6 \text{ kg/m}^3 \text{ wastewater}$$

$$\text{water quantity} = 0.11 - 5.36\text{E-}6 = 0.107 \text{ kg/m}^3 \text{ wastewater}$$

Equation S4

S1.6.3. Upgraded WRRF Clarifier Ferric Chloride Use

The reported ferric chloride addition was 30 mg/L of influent wastewater. The calculation in Equation S5 determines the ferric chloride addition used in the LCI:

$$FeCl_3 \text{ addition} = 30 \text{ mg/L} \times (1{,}381{,}676 \text{ m}^3\text{/yr} \times 1000 \text{ L/m}^3) \div 1\text{E}6 \text{ mg/kg} = 41{,}450 \text{ kg/yr}$$

$$41{,}450 \text{ kg/yr} \div 1{,}381{,}676 \text{ m}^3\text{/yr} = 0.03 \text{ kg } FeCl_3\text{/m}^3 \text{ wastewater}$$

Equation S5

S1.6.4. Upgraded WRRF Wet Well PAC Addition

It was reported that 27 pounds of PAC was used per day at a flow rate of 0.67 MGD. The calculation in Equation S6 determines the PAC addition in the LCI:

$$\text{PAC addition} = 27 \text{ lb/day} \div 0.67 \text{ MGD} \div 2.2 \text{ lb/kg} \times 365 \text{ days/yr} \div 1{,}381{,}676 \text{ m}^3\text{/yr}$$

$$= 0.0048 \text{ kg/m}^3 \text{ wastewater}$$

Equation S6

S1.6.5. Upgraded WRRF Belt Filter Press Polymer Addition

A dosage of 8 lb active polymer ingredient was required per dry short ton of solids processed by the BFP (Table S7) to aid dewatering [11], which is determined according to the feedstock-AD scenario. We assumed that a similar dosage was required for the gravity belt thickener. The calculation in Equation S7 determines the polymer LCI addition for each scenario (Table S8), using values from the base feedstock-base AD scenario as an example:

Polymer Addition (kg/m^3) = 8 lb/short ton x 2.14 short ton/day ÷ 2.2 lb/kg x 365 day/yr ÷ 1,381,676 m^3/yr = 0.0021 kg/m^3 wastewater

Equation S7

Table S7. Dry Short tons of AD Sludge to BFP

Feedstock Scenario	AD Scenario (dry metric ton sludge/day)		
	AD Low	AD Base	AD High
Base	2.16	1.94	1.87
Medium	3.03	2.68	2.57
High	4.23	3.67	3.48

Table S8. Polymer Additions for the BFP by Feedstock and AD Scenario

Feedstock Scenario	Polymer Addition (kg/m^3)		
	AD Low	AD Base	AD High
Base	0.0023	0.0021	0.002
Medium	0.0032	0.0028	0.0027
High	0.0045	0.0039	0.0037

S1.6.6. Upgraded WRRF Gravity Belt Thickener Polymer Addition

The gravity belt thickener (GBT) processes the same quantity of dry solids each day regardless of feedstock scenario as the high strength organic waste was assumed to bypass this unit, leading to a constant polymer addition of 0.003 kg/m^3 as shown in Equation S8.

Polymer Addition (kg/m^3) = 8 lb/ short ton x 3.09 short ton/day ÷ 2.2 lb/kg x 365 day/yr ÷ 1,381,676 m^3/yr = 0.003 kg/m^3 wastewater

Equation S8

S1.7. Greenhous Gas Emission Calculations

Process based GHG emissions were calculated for biological treatment, aerobic and anaerobic digestion unit processes, landfilling, composting, and effluent release. In each of these processes, some portion of influent carbon and nitrogen in wastewater or sludge is released to the atmosphere in the form of carbon dioxide (CO_2), methane (CH_4), or nitrous oxide (N_2O). CO_2 releases were assumed to be biogenic in origin, and therefore do not contribute to global climate change potential impacts. Calculation of CO_2 process emissions were, therefore, not included in this study. The following sections describe calculation procedures used to estimate process based GHG emissions in this analysis.

S1.7.1. Nitrous Oxide Emissions from Biological Treatment

The methodology for calculating N_2O emissions associated with wastewater treatment is based on emission estimates reported in the literature. The procedure provided in the IPCC Guidelines for National Inventories [17] does not provide a sufficient basis to distinguish N_2O emissions from varying types of WRRF configurations, particularly related to biological nutrient removal. More recent research has highlighted the fact that emissions from these systems can be highly variable based on operational conditions, specific treatment configurations, and other factors [18]. Emission factors used to estimate N_2O process emissions for the legacy and upgraded WRRFs are 0.035 [19] and 0.16 [18] percent, respectively. The calculation in Equation S9 is used to determine the N_2O LCI quantity. An example calculation is included for the upgraded WRRF and the base feedstock scenario.

$$N_2O \text{ Process Emissions} = \text{TKN (mg/L)} \times \text{Flow (gpd)} \times 3.785 \text{ L/gal} \times 365.25 \text{ days/yr} \times 1\text{x}10^{-6} \text{ kg/mg} \times (EF_{\%}/100) \times 44/28 \div 1{,}381{,}676 \text{ m}^3\text{/yr}$$

$$45 \text{ mg/L} \times 1\text{x}10^{6} \text{ gpd} \times 3.785 \text{ L/gal} \times 365.25 \text{ days/yr} \times 1\times10^{-6} \text{ kg/mg} \times (0.16/100) \times 44/28 \div 1{,}381{,}676 \text{ m}^3\text{/yr} = 1.13\text{E-}4 \text{ kg } N_2O\text{/m}^3 \text{ wastewater}$$

Equation S9

where:
N_2O Process Emissions = N_2O emissions from the biological treatment process (kg N_2O /yr)
TKN = Concentration of TKN entering biological treatment process (mg/L)
Flow = Wastewater treatment flow entering biological treatment process (gpd)
$EF_{\%}$ = average measured % of TKN emitted as N_2O, %
44/28 = molecular weight conversion of N_2O to N

S1.7.2. Methane Emissions from Biological Treatment

The methodology for calculating CH_4 emissions associated with the WRRF configurations evaluated as part of this study is generally based on the guidance provided in the IPCC Guidelines for National Inventories [17]. CH_4 emissions were estimated based on the amount of organic material (i.e., BOD) entering the unit operations that may exhibit anaerobic activity, an estimate of the theoretical maximum amount of methane that can be generated from the organic material (Bo), and a methane correction factor (MCF) that reflects the ability of the treatment system to achieve that theoretical maximum. In general, the IPCC does not estimate CH_4 emissions from well managed centralized aerobic treatment systems. However, there is acknowledgement that some CH_4 can be emitted from pockets of anaerobic activity, and more recent research suggests that dissolved CH_4 in the influent wastewater to the treatment system is emitted when the wastewater is aerated. The upgraded WRRF includes an anoxic zone within the treatment system. MCFs used to estimate CH_4 process emissions for the legacy and upgraded WRRFs are 0.005 [17,20]and 0.05 [21], respectively. The calculation in Equation S10 is used to determine the CH_4 LCI quantity. An example calculation is included for the upgraded WRRF and the base feedstock scenario. GHG emissions are scaled for the medium and high feedstock scenarios based on the expected increase in TKN and BOD influent concentration attributable to the BFP supernatant return flow.

$$CH_4 \text{ Process Emissions} = \text{BOD (mg/L)} \times \text{Flow (gpd)} \times 3.785 \text{ L/gal} \times 365.25 \text{ days/yr} \times 1\text{x}10^{-6} \text{ kg/mg} \times \text{Bo} \times \text{MCF} \div 1{,}381{,}676 \text{ m}^3\text{/yr}$$

$$=177 \text{ mg/L} \times 1\text{x}10^{6} \text{ gpd} \times 3.785 \text{ L/gal} \times 365.25 \text{ days/yr} \times 1\times10^{-6} \text{ kg/mg} \times 0.6 \times 0.05 \div 1{,}381{,}676 \text{ m}^3\text{/yr}$$

$$= 5.33\text{E-}3 \text{ kg } CH_4\text{/m}^3 \text{ wastewater}$$

Equation S10

where:
CH_4 Process Emissions = CH_4 emissions from the biological treatment process (kg CH_4 /yr)
BOD = Concentration of BOD entering biological treatment process (mg/L)
Flow = Wastewater treatment flow entering biological treatment process (gpd)
Bo = maximum CH_4 producing capacity, kg CH_4/kg BOD
MCF = methane correction factor (fraction)

S1.7.3. Nitrous Oxide Emissions from Effluent Release

The methodology for calculating N_2O emissions associated with effluent discharge is based on the guidance provided in the IPCC Guidelines for national inventories [17]. N_2O emissions from receiving streams were estimated based on the amount of nitrogen discharged to aquatic environments from each WRRF configurations, which accounts for nitrogen removed with sewage sludge (Equation S11).

$N_2O_{EFFLUENT}$ = $N_{EFFLUENT}$ (mg/L) × Flow × 3.785 L/gal × 365.25 days/yr × 1x10-6 kg/mg × EF × 44/28 ÷ 1,381,676 m^3/yr

Equation S11

where:
$N_2O_{EFFLUENT}$ = N_2O emissions from wastewater effluent discharged to aquatic environments (kg N_2O/yr)
$N_{EFFLUENT}$ = N in wastewater discharged to receiving stream, mg/L
Flow = Effluent flow (gpd)
EF = Emission factor (0.005 kg N_2O -N/kg sewage-N produced)
44/28 = Molecular weight ratio of N_2O to N

S1.7.4. Methane Emissions from Landfilling

The methodology for calculating CH_4 emissions associated with landfill disposal are based on a first-order decay model adapted from an RTI methodology developed for EPA [22]. The quantity of degradable carbon that remains after 100 years (i.e. is sequestered) was calculated using Equation S12. An initial fraction of the degradable carbon that ultimately decomposes is applied to the total quantity of degradable carbon prior to the use of this equation. Equation parameters corresponding to the low, base, and high EOL emissions scenarios are listed in the main article.

Degradable Carbon Remaining (metric tons) = Ct = C_0*e(-k*t)

Equation S12

where:
C_t = Degradable carbon remaining at time t
C_0 = Degradable carbon remaining at time 0
k = Degradation rate constant
t = time elapsed

Fifty percent of carbon was assumed to degrade to CH_4 with the remainder degrading to CO_2. Under base EOL scenario assumptions, 41 percent of degradable carbon breaks down in the first 3 years. The method assumes that this methane is lost to the atmosphere, contributing to global climate change potential, because the gas capture system takes time to be installed following the closure of a landfill cell. After the initial three years, the gas capture statistics associated with the Bath regional landfill or the national average landfill were applied to determine the methane emissions released from the landfill. Non-degradable carbon and the quantity of degradable carbon that does not break down in 100 years generates a carbon sequestration credit.

S1.8. Landfill Methane Capture Performance

Table S9 lists the methane capture performance assumptions for the Bath regional landfill and the 2013 national average landfill.

Table S9. Methane Capture Performance of Bath and National Average Landfills

Parameter	**Bath NY Landfill (base)** [23]	**National Average Landfill** [24]
Percentage of methane released w/o treatment	4.50%	29%
Percentage of methane captured for energy recovery	95%	57%
Percentage of methane flared	0%	11%
Percentage of methane oxidized to CO_2	0.50%	3.80%

S1.9. Anaerobic Digestion Biogas LCI Values

Table S10 lists biogas production per cubic meter of wastewater treated for each feedstock-AD scenario. Table S11 lists the electricity production per cubic meter of wastewater treated for each feedstock-AD scenario. Electricity production considers performance of the combined heat and power (CHP) system as reported in the main journal article.

Table **S12** lists the maximum heat generated by the CHP system, and Table S13 shows the quantity of recovered heat that is used within the upgraded WRRF contributing to avoided natural gas production. Table S14 lists the quantity of natural gas that is required in addition to the heat provided to the facility by the CHP system. For scenarios where CHP heat production exceeds facility heat demand the quantity of natural gas required is zero. Table S14. Required Heat from Natural Gas by Feedstock and AD Scenario

Feedstock Scenario	**AD Scenario (MJ/m3 treated water)**		
	AD Low	**AD Base**	**AD High**
Base	2.87	1.63	-
Medium	2.42	0.114	-
High	1.31	-	-

Table S15 and Table S16 list methane losses from the AD units and the CHP system, respectively. A one percent loss rate was assumed for both the AD units and the CHP system.

Table S10. Biogas Production by Feedstock and AD Scenario

Feedstock Scenario	**AD Scenario (m^3 biogas/m^3 wastewater treated)**		
	AD Low	**AD Base**	**AD High**
Base	0.13	0.21	0.53
Medium	0.22	0.38	0.74
High	0.4	0.71	1.17

Table S11. Electricity Production from Biogas by Feedstock and AD Scenario

Feedstock Scenario	**AD Scenario (kwh/m^3 wastewater treated)**		
	AD Low	**AD Base**	**AD High**
Base	0.21	0.45	1.34
Medium	0.35	0.8	1.87
High	0.64	1.5	2.95

Table S12. Potential Heat Production from Biogas by Feedstock and AD Scenario

Feedstock Scenario	AD Scenario (MJ/m^3 wastewater treated)		
	AD Low	AD Base	AD High
Base	1.01	2.24	4.92
Medium	1.74	4.05	6.89
High	3.14	7.56	10.9

Table S13. Modeled Avoided Heat from Natural Gas by Feedstock and AD Scenario

Feedstock Scenario	AD Scenario (MJ/m^3 wastewater treated)		
	AD Low	AD Base	AD High
Base	1.01	2.24	3.01
Medium	1.74	4.05	3.3
High	3.14	4.45	3.59

Table S14. Required Heat from Natural Gas by Feedstock and AD Scenario

Feedstock Scenario	AD Scenario (MJ/m^3 treated water)		
	AD Low	AD Base	AD High
Base	2.87	1.63	-
Medium	2.42	0.114	-
High	1.31	-	-

Table S15. Methane Losses from Digester by Feedstock and AD Scenario

Feedstock Scenario	AD Scenario (kg CH_4/m^3 wastewater treated)		
	AD Low	AD Base	AD High
Base	5.00E-04	9.03E-04	2.43E-03
Medium	8.61E-04	1.63E-03	3.40E-03
High	1.56E-03	3.04E-03	5.38E-03

Table S16. Methane Losses from CHP by Feedstock and AD Scenario

Feedstock Scenario	AD Scenario (kg CH_4/m^3 wastewater treated)		
	AD Low	AD Base	AD High
Base	4.95E-04	8.94E-04	2.41E-03
Medium	8.52E-04	1.61E-03	3.37E-03
High	1.54E-03	3.01E-03	5.32E-03

S1.10. Life Cycle Impact Assessment Methods

Table S17 lists all the impact assessment methods that were run as part of the full analysis. Complete LCIA results are available in an excel-based SI file: Bath WRRF Results File.

Table S17. Life Cycle Impact Assessment Methods

Metric	Method	Unit
Global Warming Potential	TRACI 2.1 [25,26]	kg CO_2-eq.
Eutrophication Potential	TRACI 2.1 [25,26]	kg N-eq.
Particulate Matter Formation Potential	TRACI 2.1 [25,26]	kg $PM_{2.5}$-eq.
Smog Formation Potential	TRACI 2.1 [25,26]	kg O_3-eq.
Acidification Potential	TRACI 2.1 [25,26]	kg SO_2-eq.
Water Use	ReCiPe [27]	m^3
Fossil Depletion Potential	ReCiPe [27]	kg oil-eq.
Cumulative Energy Demand	Ecoinvent [28]	MJ-eq.

S1.11. Life Cycle Cost Assessment Methods and Calculations

S1.11.1. LCCA Scenario Parameter Values

Table S18 lists the LCCA parameters that correspond to the low, base, and high cost scenario estimates. The low cost scenario reflects parameter values that will lead to a lower system NPV, while the high cost scenario reflects parameter values that will tend to yield a higher system NPV.

Table S18. Parameter Values Varied in the Low, Base, and High Cost Scenarios

Parameter Value	**Low Cost Scenario**	**Base Cost Scenario**	**High Cost Scenario**
Planning Period (years)	30	30	30
Real Discount Rate (%)	6%	5%	3%
Interest Rate (%) [11]	0%	0%	0%
Electricity Cost ($/kWh) [11]	0.077	0.051	0.077
Electricity Revenue ($/kWh)	0.077	0.051	0.051
Diesel Cost ($/gal)	2	2.7	3.5
Natural Gas Cost ($/MCF)	4.5	3.84	3.84
Septage Disposal Fee ($/gallon)	0.01	7.00E-03	7.00E-03
High Strength Organic Waste ($/gallon) [29]	0.15	0.06	0.03
Compost Revenue ($/$yd^3$) [30]	10	5	-
Landfill Tipping Fee ($/wet ton) [11]	50.84	50.84	50.84
Fraction of Biogas Heat Valued	Total Heat Potential	Facility Use	Facility Use
Material and Maintenance Escalation	2%	3%	4%
Labor Escalation	1%	2%	3%
Taxes/Salvage Escalation	0%	0%	0%
Operations General Escalation	1%	2%	3%
Fee Escalation	1%	2%	2%
Energy Escalation	2%	2%	3%

S1.11.2. Total Capital Costs

Total capital costs include purchased equipment, direct, and indirect costs. Direct costs are costs incurred as a direct result of installing the WRRF. Direct costs include mobilization, site preparation, site electrical, yard piping, instrumentation and control, and lab and administration building. Indirect costs include land, miscellaneous items, legal costs, engineering design fee, inspection costs, contingency, technical, interest during construction, and profit. Both direct and indirect costs were determined using cost factors based on purchased equipment pricing. Total capital costs are calculated using Equation S13.

$$\text{Total Capital Costs} = \text{Purchased Equipment Costs} + \text{Direct Costs} + \text{Indirect Costs}$$

Equation S13

where:
Total Capital Cost (2014 $) = Total capital costs
Purchased Equipment Costs (2014 $) = Costs to purchase the equipment for the WRRF
Direct Costs (2014 $) = Costs incurred as a direct result of installing WRRF equipment

Indirect Costs (2014 $) = All non-direct costs incurred as a result of installing WRRF equipment

A base escalation factor of 3 percent was applied to all purchased inputs. Escalation factor describes an estimated increase in the price of purchased inputs beyond the rate of inflation. Escalation factors were applied using Equation S14. Escalation factors for various facility costs are varied within the LCCA scenarios as described in Section S1.11.1. .

$$Cost_x = Cost_0\,(1+ESC)^x$$

Equation S14

where:
$Cost_x$ = Cost in future year x
$Cost_0$ = cost in year zero, 2014
ESC = escalation rate, 3% in base cost scenario
x = number of years in the future

S1.11.3. Direct Costs

Direct costs include mobilization, site preparation, site electrical, yard piping, instrumentation and control, and lab and administration building construction.

Table S19 lists the direct cost factors used for this project. The full list of direct costs applies to the newly constructed primary treatment process as well as AD. For retrofitted units, such as the anoxic-swing tank, it was assumed that mobilization, instrumentation and control costs, and one-half of the new construction direct costs for site electrical and yard piping apply. This works out to a total direct cost factor of 27 percent of equipment purchase price. An additional 50 percent factor was applied for the estimated cost of labor for equipment installation.

When a piece of equipment is replaced it was assumed that direct cost factors for mobilization and control and instrumentation apply, which yields a total direct cost factor for material replacement of 13 percent of the purchased equipment price. It was assumed that labor costs for material replacement are 40 percent of the equipment purchase price. Direct cost factors for site preparation and lab and administration building were assumed not to apply for plant renovations and equipment replacement. Equation S15 demonstrates the basic method used to calculate direct costs from purchased equipment prices.

$$\text{Direct Cost Factor} = \frac{\text{Level 1 Direct Cost}}{\text{Level 1 Purchased Equipment Cost}}$$

Equation S15

where:
Direct Cost Factor (%) = Direct cost factor for each direct cost element, see Table S19 below
Level 1 Purchased Equipment Cost (2014 $) = Equipment price paid by the WRRF
Level 1 Direct Cost (2014 $) = Direct cost in excess of purchased equipment price

Table S19. Direct Cost Factors [10]

Direct Cost Elements	Direct Cost Factor (% of Purchased Equipment Cost)
Mobilization	5%
Site Preparation	7%
Site Electrical	15%
Yard Piping	10%

Table S19. Direct Cost Factors [10]

Direct Cost Elements	Direct Cost Factor (% of Purchased Equipment Cost)
Instrumentation and Control	8%
Lab and Administration Building	12%

S1.11.4. Indirect Costs

Indirect costs typically include land costs, legal costs, engineering design fee, inspection, contingency, technical costs, interest during construction, and profit. Table S20 lists indirect cost factors as reported by CAPDETWorks™ engineering cost estimation software [10]. Land costs and interest during construction do not apply to this project and were excluded from the analysis. The upgraded facility will be located completely within the boundaries of lands currently held by the utility provider. The upgrades are set to be funded through a combination of grants and zero interest loans made available by New York State, and consequently no interest is included in the calculation of system NPV. Total indirect costs are the sum of all individual indirect costs as calculated in Equation S16. Indirect cost factors were applied to the sum of purchase price and direct costs. Indirect costs were assumed to apply both to the construction of new units and major renovation and upgrade projects. No indirect costs were assumed to be associated with material replacement.

$$\text{Remaining Indirect Costs} = \text{Indirect Cost Factor} \times (\text{Purchased Equipment Cost} + \text{Direct Cost}) \quad \text{Equation S16}$$

where:
Remaining Indirect Cost (2014 $) = Indirect costs associated with miscellaneous costs, legal costs, engineering design fee, inspection costs, contingency, technical, and profit
Indirect Cost Factor (%) = Indirect cost factor for each indirect cost element, see Table S20 below
Purchased Equipment Cost = Total purchased equipment cost
Direct Cost (2014 $) = Total direct costs

Table S20. Indirect Cost Factors [10]

Indirect Cost Elements	Indirect Cost Factor (% of purchased equipment cost)
Miscellaneous Costs	5%
Legal Costs	2%
Engineering Design Fee	15%
Inspection Costs	2%
Contingency	10%
Technical	2%
Profit	15%

S1.11.5. Total Annual Costs

The total annual costs include the operation and maintenance labor, materials, chemicals, and energy. Total annual costs are calculated using Equation S17.

$$\text{Total Annual Costs} = \text{Operation Costs} + \text{Replacement Labor Costs} + \text{Material Costs} + \text{Chemical Costs} + \text{Energy Costs} \quad \text{Equation S17}$$

where:
Total Annual Costs (2014 $/year) = Total annual operation and maintenance costs
Operation Costs (2014 $/year) = Labor costs for manual labor required to operate the WRRF for a year, including operation, administrative, laboratory labor, and routine equipment maintenance
Replacement Labor Costs (2014 $/year) = Contract labor costs required to replace equipment over the WRRF lifespan
Materials Costs (2014 $/year) = Materials costs for operation and maintenance of the WRRF for a year, including equipment replacement
Chemical Costs (2014 $/year) = Chemical costs for chemicals required for WRRF operation (e.g., PAC, polymer) for a year
Energy Costs (2014 $/year) = Electricity costs to run the WRRF for a year

Operational labor cost associated with primary and secondary treatment remain the same for the upgraded treatment plant with additional personnel requirements for both the AD and composting unit. Regular plant maintenance was assumed to be carried out by facility personnel, and as such does not require additional labor costs beyond their annual salary and benefits. Labor for equipment replacement was assumed to require contractor labor. Maintenance costs per unit, as calculated by GHD Inc., are the primary source of maintenance cost data used in this analysis. GHD's original maintenance costs include labor. This analysis used actual plant labor costs as the source of maintenance labor costs, and therefore only 50 percent of the original GHD maintenance costs were included to approximate the material portion of maintenance costs.

S1.11.6. Net Present Value

Equation S18 shows the calculation used to estimate NPV of the upgraded WRRF.

$$\text{Net Present Value} = \Sigma(\text{Cost}_x/(1+i)^x)$$

Equation S18

where:
NPV (2014 $) = Net present value of all costs and revenues necessary to construct and operate the WRRF
Cost_x = Cost in future year x
i (%) = Real discount rate
x = number of years in the future

A standard payback period was calculated using Equation S19 for both the composting facility and the AD unit. In determining payback, the value of avoided energy production is attributed to the AD. Compost value is attributed to the composting facility. A payback period will only exist if unit annual revenue exceeds annual costs.

$$\text{Payback Period} = \text{Cost}_{\text{const}}/\text{Revenue}_{\text{annual}}$$

Equation S19

S1.12. LCA and LCC Results Presentation

Table S21 shows the association of WRRF unit processes to treatment stages that are used in the presentation of results in the main journal article.

Table S21. Assignment of Unit Processes to Treatment Stage for Results Presentation

Treatment Stage	Unit Process Name	Legacy System	Upgraded System
Preliminary/Primary	Wastewater collection; operation and infrastructure	X	X
Preliminary/Primary	Influent pump station		X
Preliminary/Primary	Screening and grit removal	X	
Preliminary/Primary	Chemically enhanced primary clarification		X
Preliminary/Primary	Primary clarifier	X	
Sludge Handling and Treatment	Screen compaction press		X
Preliminary/Primary	Wet well and sump station	X[1]	X
Biological Treatment	Pre-anoxic & swing tank		X
Biological Treatment	Aeration tanks	X	X
Sludge Handling and Treatment	Waste receiving and holding		X
Sludge Handling and Treatment	Gravity belt thickener		X
Sludge Handling and Treatment	Gravity thickener	X	
Sludge Handling and Treatment	Blend tank		X
Sludge Handling and Treatment	Anaerobic digestion		X
Sludge Handling and Treatment	Combined heat and power		X
Sludge Handling and Treatment	Aerobic digester	X	
Sludge Handling and Treatment	Belt filter press	X	X
Sludge Handling and Treatment	Biosolids composting		X
Sludge Disposal	Land application of compost		X
Sludge Disposal	Sludge disposal in landfill	X	
Effluent Release	Effluent release; to surface water	X	X
Facilities	Control building	X	X

[1] Impact results grouped with the primary clarifier for the legacy system

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