Environmental Life Cycle Assessment and Cost Analysis of Bath, NY Wastewater Treatment Plant: Potential Upgrade Implications

Technical Report · October 2017

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EPA/600/R-17/207 | June 2017 | www.epa.gov/research

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Office of Research and Development
Washington, D.C.

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June 21, 2017

EPA Contract No. EP-C-12-021
Work Assignment 3-41
and
EPA Contract No. EP-C-16-0015
Task Order 0003

This U.S. Environmental Protection Agency (U.S. EPA) report was developed under Contract Nos. EP-C-12-021 and EP-C-16-015 awarded by the U.S. EPA. This document has been reviewed in accordance with U.S. EPA policy and approved for publication. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.

ACKNOWLEDGEMENTS

This research was part of the U.S. Environmental Protection Agency (U.S. EPA) Office of Research and Development's Safe and Sustainable Water Resources (SSWR) Program. The research was supported by U.S. EPA contracts EP-C-12-021 and EP-C-16-0015. Kim Miller and Guy Hallgren provided primary data on the Bath, NY wastewater treatment plant operations and infrastructure for both the legacy and upgraded systems investigated. Engineering design of treatment plant upgrades was performed by personnel from Conestoga-Rovers & Associates, now a division of GHD Inc. Lauren Fillmore and Lori Stone of Water Environment & Reuse Foundation (WE&RF) as well as Pradeep Jangbari of New York State Department of Environmental Conservation provided technical review comments. Jason Turgeon and Michael Nye of U.S. EPA helped develop the initial project scope. Janet Mosely and Jessica Gray of Eastern Research Group provided technical input and review of the life cycle inventory and cost analysis.

ABSTRACT

Many municipalities are facing the call to increase nutrient removal performance of their wastewater treatment plants to limit the impacts of eutrophication on waterbodies receiving the treated effluent. The associated upgrades often demand investment in new technologies and increases in energy and chemical use, which create the potential for environmental trade-offs. The main goal of this study is to quantify these trade-offs for a case study community from an environmental and cost perspective by performing a life cycle assessment and cost analysis. The impacts of a conventional activated sludge treatment process are compared against an upgraded system incorporating chemically enhanced primary settling, Modified Ludzack-Ettinger secondary treatment, and anaerobic digestion (AD). The sensitivity analysis explores the effect of composting emission assumptions, AD operational performance, and the use of excess AD capacity for the processing of high strength organic waste on environmental impact and cost per cubic meter of wastewater treated.

Results show that eutrophication potential impacts decrease by approximately 40 percent following treatment plant upgrades, and that this reduction remains relatively consistent within the sensitivity analysis. Most other impact categories register an increase in impact results of between 5 and 31 percent with the plant upgrades under base case scenario assumptions. The water use category shows an environmental benefit of switching to the upgraded system in all study scenarios, and receives environmental credits in this category from wastewater reuse and avoided fertilizer production from land application of biosolids. Impact results in the remaining categories such as global warming potential and cumulative energy demand are strongly affected by AD and composting emission scenarios. High operational performance of the AD in combination with acceptance of high strength organic waste produces reductions in environmental impact relative to the legacy wastewater treatment system and even net environment benefits. These environmental benefits are attributable to the avoided burdens of grid electricity and natural gas production from recovered AD biogas. Additional benefits are realized as a result of avoided fertilizer production, attributable to land application of composted biosolids. Achievement of net environmental benefits by the upgraded treatment plant are possible for 7 of 8 assessed impact categories. Eutrophication potential is the sole exception where impact results remain positive, although eutrophication potential is still reduced in respect to the legacy system. For global warming potential, the realization of benefits is dependent on the performance of the composting system. In a worst-case scenario, the acceptance of additional feedstock for AD can lead to a near 200 percent increase in global warming potential impact if paired with a poorly managed windrow composting system, emphasizing the importance of selecting the appropriate composting system with proper system maintenance.

Life cycle costs were calculated for the upgraded system, which was found to have a net present value of 37.1 million dollars under the base cost scenario. Several cost scenarios were explored in this study, with assumptions regarding discount rate having a significant effect on project net present value. Whether the AD unit process additions could generate annual revenue, and thus a reasonable payback period, was found to depend on AD performance and the feedstock scenario. Holding cost and AD performance assumptions constant, the AD is shown to reduce project net present value by approximately 13 percent relative to the base case when the full capacity of the AD unit is made available for the processing of high strength waste.

The results show that improvements in environmental performance are available to communities that undertake a similar approach to treatment plant upgrades. Improved environmental performance is largely due to the inclusion of AD, and the avoided electricity and heat production that is a result of energy recovery from biogas. This study revealed that plant level impact results are sensitive to AD operational performance and greenhouse gas emissions associated with composting, indicating the importance of sound management of these unit processes if improvements are to be realized across environmental impact categories.

LIST OF ACRONYMS

A	Current, amps
AD	Anaerobic digester
ASP	Aerated Static Pile
BEAM	Biosolids Emissions Assessment Model
BEGWS	Bath Electric, Gas & Water Systems
BFP	Belt filter press
BNR	Biological nutrient removal
BOD	Biological oxygen demand
CAS	Conventional activated sludge
cBOD	Carbonaceous biological oxygen demand
CHP	Combined heat and power
C:N	Carbon to nitrogen ratio
COD	Chemical oxygen demand
EOL	End-of-life
EPA	Environmental Protection Agency (U.S.)
ERG	Eastern Research Group, Inc.
GBT	Gravity belt thickener
GHG	Greenhouse gas
GPD	Gallons per day
HP	Horsepower
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standardization Organization
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MCF	Methane correction factor
MGD	Million gallons per day
MLE	Modified Ludzack-Ettinger
N	Nitrogen
NMVOC	Non-methane volatile organic compounds
NPV	Net present value
NYDEC	New York Department of Environmental Conservation
P	Phosphorus
PAC	Polyaluminum chloride
QAPP	Quality Assurance Project Plan
RAS	Return activated sludge
RDT	Rotary drum thickener
SCP	Screen compaction press
SPDES	State pollution discharge elimination system
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TP	Total phosphorus
TRACI	Tool for the Reduction and Assessment of Chemical and Environmental Impacts
TSS	Total suspended solids

US LCI	United States Life Cycle Inventory Database
V	Voltage
VFA	Volatile fatty acids
VS	Volatile solids
WAS	Waste activated sludge
WWT	Wastewater treatment
WWTP	Wastewater treatment plant

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1. INTRODUCTION AND STUDY GOAL

The impacts of eutrophication and pollutants on waterbodies in the United States has been a driving factor in the movement towards enhanced effluent quality standards leading to more stringent permitting of municipal wastewater treatment systems. At the same time, municipalities are faced with pressure to minimize the increases in capital and operational expenditures associated with wastewater treatment. As understandings of the environmental and financial resources at stake in this process have been increased, the U.S. Environmental Protection Agency (U.S. EPA) is looked to by municipalities for guidance on how best to meet a set of goals that often seem at odds. Communities and experts have rightly pointed out the potential trade-offs in environmental impact associated with increased standards for nutrient removal as nutrient load reductions are achieved often at the expense of increases in energy use, chemical inputs, and system costs.

The objective of this project is to help the community of Bath New York (hereafter referred to as "Bath") work through these considerations by quantifying the system-wide environmental impacts and monetary costs associated between the legacy and upgraded wastewater treatment plants (WWTP). This work will serve as a case study to provide guidance to other communities as they approach similar questions regarding process upgrades and system analyses.

Bath Electric, Gas, & Water Systems (BEGWS), uniquely having electricity, gas and water services under one utility entity, has implemented a system upgrade for enhanced nutrient removal by way of a Modified Ludzack-Ettinger (MLE) biological treatment step to reach a summer time permit limit of 3.6 mg/L ammonia nitrogen. BEGWS staff is considering the installation of a chemically enhanced primary clarification unit. Both completed and planned improvements are made in part through the construction of new units as well as through the repurposing of existing infrastructure. This approach to upgrades is common among municipalities looking to improve and retrofit their existing municipal wastewater process. BEGWS staff is also considering the implementation of anaerobic digestion (AD) and biosolids composting to improve solids handling, while creating an opportunity for resource recovery. This system will be referred to collectively throughout the report as the "upgraded WWTP" or "upgraded system." This system replaces the conventional activated sludge (CAS) treatment process that was in place prior to 2016, and includes upgrades such as the recently installed MLE treatment process and the treatment steps of AD and composting.

System upgrades look not only to improve plant operations, expand services available to the region for hauled-in waste, and potentially reduce environmental impact, but also eventually to transform the WWTP into a resource recovery hub for the community. AD produces useful biogas for energy recovery, and in combination with composting helps to stabilize biosolids, providing a beneficial amendment for agricultural fields to reduce chemical fertilizer production and use.

Pursuit of the upgrades outlined above involve economic, environmental, and social costs and benefits, which aim to address issues at the center of the sustainability debate. The balance of economic and environmental costs and benefits can be assessed using holistic approaches such as life cycle assessment (LCA) and life cycle cost analysis (LCCA). LCAs is a widely-accepted technique to assess the environmental aspects and potential impacts associated with products, processes, or services. It provides a "cradle-to-grave" analysis of environmental impacts and benefits that can better inform and assist in selecting the most environmentally preferable choice among various options. The steps for conducting an LCA include (1) identifying goal and scope, (2) compiling a life cycle inventory (LCI) of relevant energy and material inputs and environmental releases, (3) evaluating the potential environmental impacts associated with identified inputs and releases, and (4) interpreting the results to help make a more informed decision.

LCCA is a complementary process to LCA for evaluating the total economic costs of an asset by analyzing initial costs and discounted future expenditures over the life cycle of an asset (Varnier 2004). It is used to evaluate differences in cost and the timing of costs between alternative projects.

This study prepares a cost estimate for the upgraded treatment plant and compares environmental impacts associated with Bath's legacy CAS system and the upgraded treatment plant. Bath's CAS system is referred to as the "legacy WWTP" or "legacy system" throughout this report. Applying holistic approaches such as LCA and LCCA to decision making provides the opportunity to optimize environmental and cost benefits without unknowingly shifting burdens between categories of impact. This approach does not eliminate the existence of trade-offs, but it does facilitate a rational, informed decision-making process. Specifically, the study addresses the following objectives:

- Calculate the environmental benefits and burdens of CAS wastewater treatment for a typical small community;
- Quantify the comparative environment benefits and burdens associated with enhanced nutrient removal for a small community wastewater treatment facility, processing 1 million gallons per day (MGD) of wastewater;
- Determine the energy recovery potential of AD, and evaluate the environmental and cost benefits of offsetting external electricity and heat generation;
- Evaluate the co-digestion of industrial food wastes for enhanced energy recovery; and
- Determine the life cycle costs associated with the upgraded treatment plant over a 30-year timespan.

The metrics planned for use in this assessment are cost and a suite of LCA-related impact categories in addition to the traditional suite of wastewater quality parameters. The life cycle impact assessment (LCIA) categories cover global warming potential, eutrophication potential, particulate matter formation potential, smog formation potential, acidification potential, and fossil depletion potential. Water use and cumulative energy demand are incorporated LCI categories. The specific impact categories and associated methods considered are introduced in more detail in Section 2.5.

2. STUDY SCOPE

This study design follows the guidelines for LCA provided by ISO 14044 (ISO 2006). The following subsections describe the scope of the study based on the treatment system configurations selected and the functional unit used for comparison, as well as the system boundaries, LCIA methods, and datasets used in this study.

2.1 Functional Unit

A functional unit provides the basis for comparing results in a LCA. The key consideration in selecting a functional unit is to ensure the treatment system configurations are compared on a fair and transparent basis and provide an equivalent end service to the community. The functional unit for this study is the treatment of one cubic meter of municipal wastewater with the influent wastewater characteristics shown in Table 3-1. Impact results are normalized per cubic meter of the 1 MGD permitted flowrate (approximately 1.4 million cubic meters per year). The quantity of waste treated by the facility varies slightly depending upon the investigated scenario. The legacy system accepts trucked in septage waste, while the upgraded treatment plant accepts both septage and industrial high strength organic wastes. The quantities of accepted septage plus industrial high strength organic waste vary between 8,000 and 24,000 gallons per day (GPD, 0.8 and 2.4 percent of 1 MGD flowrate) depending upon the scenario considered. The basis of normalization for the functional unit is not varied to account for this, and instead the additional burdens of treating septage and high strength organic waste are allocated equally to the permitted 1 MGD flowrate of the facility. Composting amendment is also processed by the upgraded facility and is treated in the same manner as trucked in organic wastes. The main results section presents results per cubic meter of wastewater. LCIA results are also presented on an annual basis for all sensitivity scenarios in Section 6.2.

It is important to note that the composition of effluent resulting from the treatment system configurations is not part of the definition of the functional unit. Rather the level of performance in terms of nitrogen and phosphorus effluent concentration is a key differentiator of the two systems. Differences in effluent composition are captured in the estimation of impacts associated with effluent discharge for each system. Effluent quality values for the two treatment systems are presented in Table 3-2.

The AD sensitivity analysis explores the effect of accepting increased quantities of high strength organic waste to boost volatile solids (VS) available for biogas generation. Composting of yard waste is included in the AD scenarios, as it is necessary to achieve appropriate moisture and nutrient balances for the composting process. As such, the quantity of waste treated by the upgraded system is greater than the legacy system, and it is recommended that the avoided burdens of alternative pathways for treating this waste be examined in future phases of this project to achieve the fairest possible comparison.

2.2 System Definition and Boundaries

The boundary for each wastewater treatment system configuration includes all on-site wastewater and sludge treatment processes necessary to treat the maximum daily flowrate of 1 MGD of municipal wastewater, starting from receiving wastewater influent to the WWTP, operation of the treatment train, and ending in final discharge of the treated effluent and disposal of sludge in a landfill or through land application after conversion to compost. A general system diagram for both systems is presented in Figure 2-1.

WWTPs include electricity and chemical use as well as select infrastructure elements. Concrete, rebar, inter-unit piping, excavation, and sub-grade coarse aggregate are included to represent plant infrastructure. All included infrastructure components are expected to have a useful lifespan that extends beyond the 40-year study timeframe, which eliminates the need to consider material replacement of infrastructure in the environmental analysis. Pumps, electronics, other in-unit mechanical equipment, engineering services, and end-of life (EOL) disposal of plant infrastructure are excluded from the system boundary. Other studies have shown that for activated sludge systems infrastructure and EOL demolition contributions to life cycle energy demand are low as compared to the operational phase (Emmerson et al. 1995), which provides justification for the simplified treatment of infrastructure elements. The electrical grid mix for the Bath region is used in the analysis and is depicted in Table 2-1. Process greenhouse gas (GHG) emissions resulting from biological treatment, fugitive methane releases from AD and landfill disposal and agricultural emissions are estimated and included in the calculation of impacts.

Table 2-1. Bath Electrical Grid Mix

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%

References:
[1] U.S. EPA 2016
[2] ISO-NE 2016

Avoided electricity and heat production associated with methane capture and avoided fertilizer production associated with biosolids land application are considered, and lead to the generation of environmental credits, thereby decreasing the environmental impact of treatment units for which this is applicable. Figure 2-1 shows that production of the constituents that make up the wastewater such as treated drinking water and human and industrial sources of organic material are excluded from the system boundary. The environmental impact of generating these materials is not attributable to wastewater treatment.

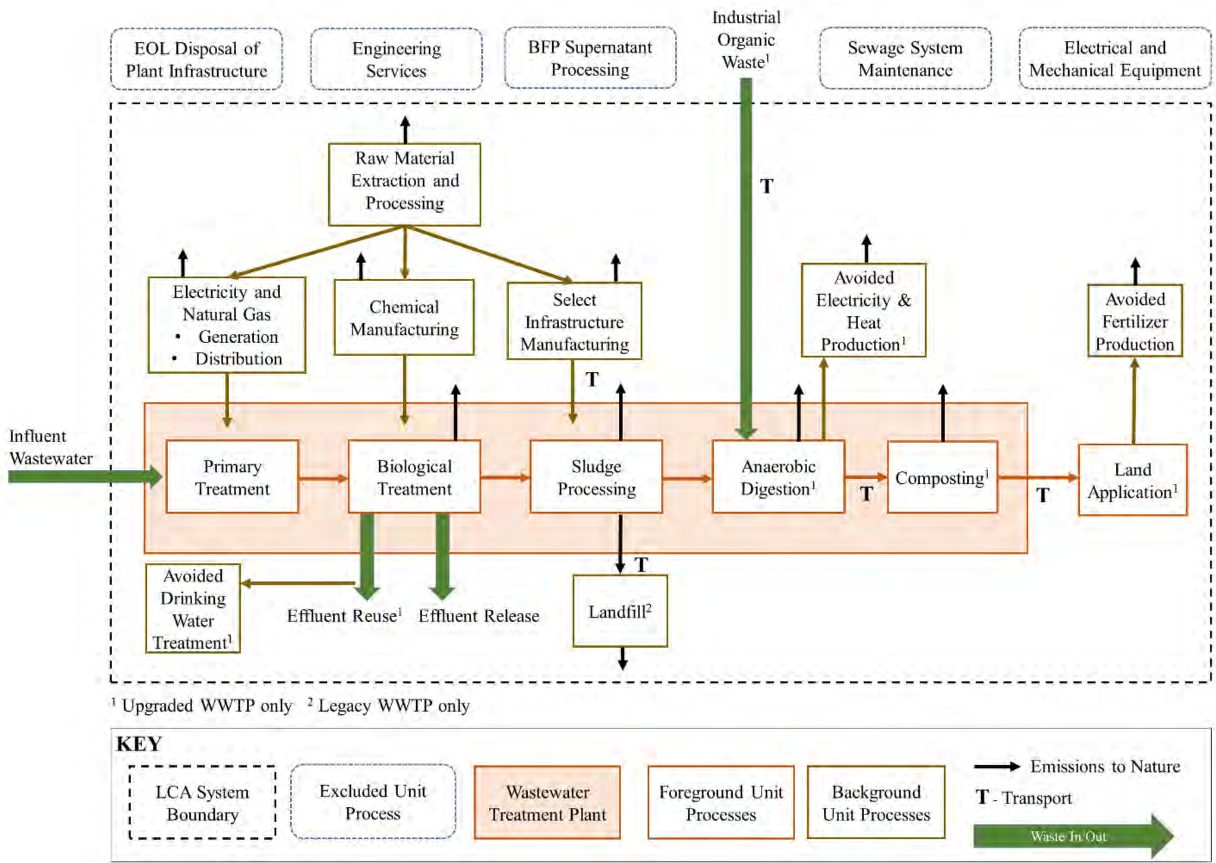

Figure 2-1. General system diagram for both legacy and proposed upgraded systems.

2.3 Study Site Description

This section provides a basic description of the study site, treatment systems considered, and main unit process options. This description is meant to convey what is included in the analysis and to provide an overview of the systems analyzed.

The Village of Bath is in the Finger Lakes district of southwestern New York, and has a population of 5,600. The wastewater treatment facility, operated by BEGWS was originally constructed in 1935, and underwent significant upgrades in both 1972 and 1993.The WWTP currently has the capacity to treat 1 MGD of wastewater and this permitted volume remains consistent for the upgraded system. Analysis of the legacy, CAS system is based on the treatment process that had been in place since the 1993 upgrades. In 2016, the plant finished renovating the CAS system into a MLE biological treatment process. The plant discharges effluent into the nearby Cohocton River, which is part of the Susquehanna River basin that ultimately discharges into the Chesapeake Bay. A map of the region showing Bath and the discharge location is included in Figure 2-2.

Bath's position within the Chesapeake Bay watershed is a contributing factor in their motivation to minimize nutrient loads in their effluent due to the Chesapeake Bay Cleanup Initiative. A new State Pollutant Discharge Elimination System (SPDES) permit from New York

Department of Environmental Conservation (NYDEC) was issued in 2014 to reflect the regulatory effort. The Chesapeake is an important ecological, cultural, and economic feature that has suffered over the years from the effects of upstream development and industry. It is home to renowned shell fishing beds and provides a point of entry to spawning grounds for several migratory fish species such as the American Shad (CBF 2016a/b). More stringent requirements necessary to protect this resource are expected in the future.

Figure 2-2. Regional map of Bath, NY and discharge location.

BEGWS is exploring the option of chemically enhanced primary settling in combination with the existing MLE biological treatment system as a means of consistently achieving effluent quality standards that limit summertime ammonia concentrations to 3.6 mg/L. A list of permitted effluent quality standards is included in Table 2-2.

Table 2-2. Bath NY Permitted Effluent Quality Standards

Wastewater Characteristic[1]	Value	Units
Flow	1	MGD
cBOD	25	mg/L monthly average
TSS	30	mg/L monthly average
Ammonia N (as NH_3)	3.6	mg/L summer
Ammonia N (as NH_3)	8.4	mg/L winter
Total Nitrogen	61,000	lb/year[2]
Phosphorus	1,960	lb/year[2]

Notes & References:

[1] SPDES permit #NY0021431, effective 9/1/2014-8/31/2019

[2] No concentration requirement (i.e. mg/L)

The plant is designed primarily to process residential wastewater and hauled-in septage. The plant has also historically serviced several commercial and industrial customers, and the acceptance of this waste is reflected in the reported influent quality values. BEGWS is exploring the option of expanding its receipt of residential septage and high strength organic waste for processing in the proposed AD, and this option is considered within the sensitivity analysis for this study.

Detailed descriptions of each treatment system along with separate descriptions of the AD, composting, and land application unit processes are included in the following sections.

2.3.1 Legacy WWTP: Conventional Activated Sludge

The legacy treatment system is a standard example of CAS treatment as deployed by many communities around the country. Preliminary treatment consists of a mechanical bar screen, comminutors, and a grit well. These elements are arrayed around a Parshall Flume, which is used to monitor the influent flow rate. Wastewater then moves into a two-chambered primary settling tank for the removal of settleable solids. Solids move on to a gravity thickener, while wastewater flows to a primary wet well for polyaluminum chloride (PAC) addition prior to being pumped into a bank of three aeration basins. Aeration and secondary clarification are carried out in concentric regions of circular tank units with clarification occurring in the interior region. A return activated sludge (RAS) flow is utilized to seed the aeration basins with the appropriate microbial biomass. Following clarification, wastewater is discharged to the Cohocton River. No disinfection step is required at this time. Waste activated sludge (WAS) is separately pumped to the thickener wet well, where it is combined with primary sludge prior to entering the gravity thickener. Thickened sludge is sent to a series of four concrete basins for aerobic digestion of solids. Digested sludge is sent to a belt filter press (BFP) with polymer addition for further dewatering before it is trucked to a local landfill for disposal (CRA 2015). A simplified depiction of this treatment process, showing relevant material and energy flows, is included in Figure 2-3.

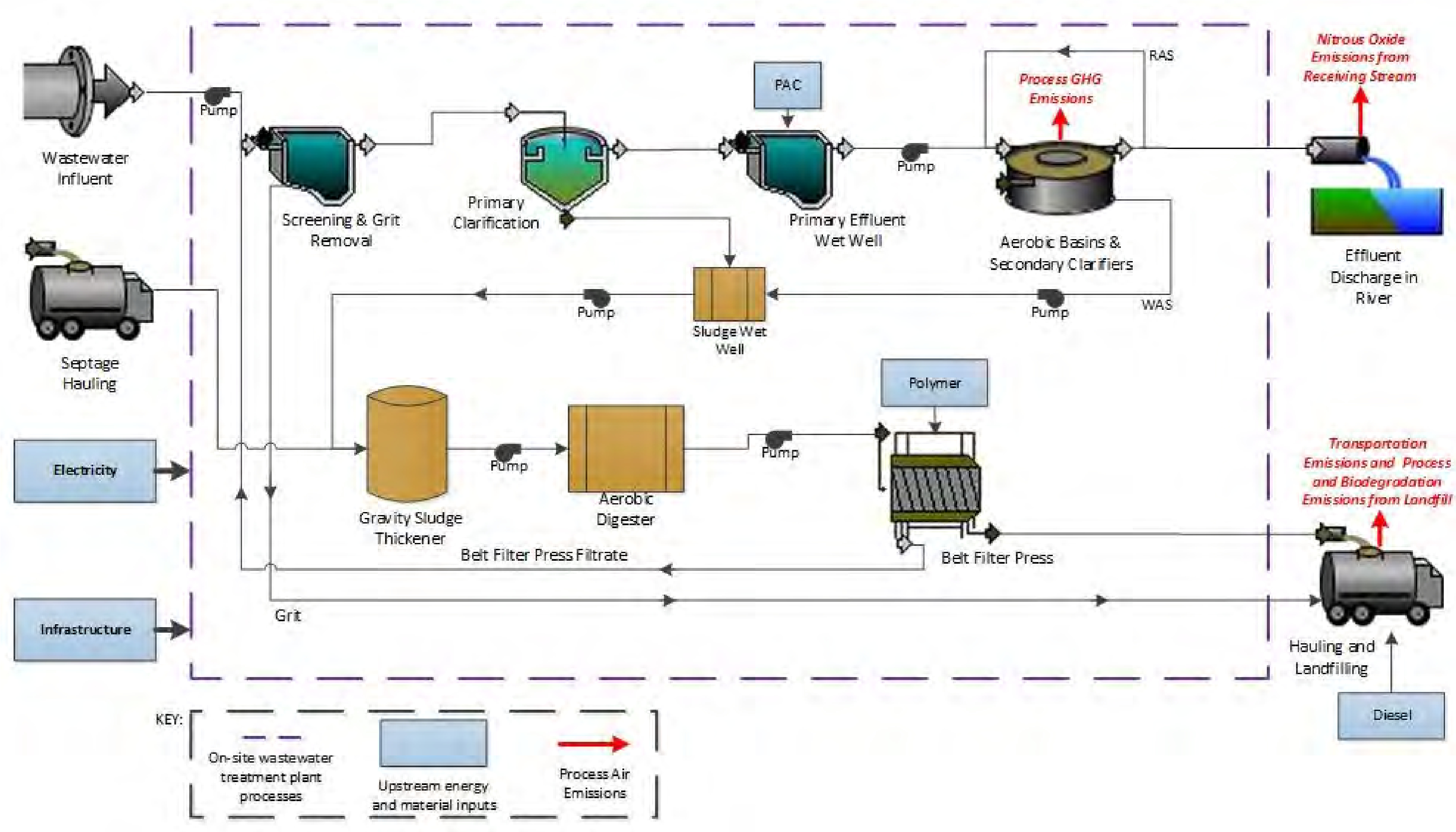

Figure 2-3. Legacy, CAS treatment system diagram.

2.3.2 Upgraded WWTP: Chemically Enhanced Primary Clarification with MLE

The proposed treatment system upgrade is an example of enhanced primary clarification in combination with a MLE biological treatment process for nitrogen removal, as described later in this Section (depicted in Figure 2-4). Ferric chloride is added to the wastewater at the influent pump station prior to entering the chemically enhanced primary clarification tank. Following primary clarification, a screen compaction press (SCP) is used to remove grit from the primary sludge before it moves on to a gravity belt thickener (GBT) where solids concentration is increased to 6 percent. Wastewater flows from primary clarification to a wet well for the addition of PAC before being pumped to the MLE unit. A pre-anoxic tank is the first stage in the MLE process and provides for the removal of nitrogen as N_2 gas via denitrification. A swing tank, which can be operated either as an aerobic or anaerobic unit can be adjusted to provide either nitrification or denitrification as dictated by influent wastewater quality and weather related demands on treatment. The anoxic and swing tank repurpose cells of the existing aerobic digester with the addition of new mixing units. Water exiting these tanks is pumped into the existing bank of three aeration basins. Aeration and secondary clarification are carried out in concentric regions of circular units with clarification occurring in the interior region as in Legacy system. Separate RAS and nitrate recycle flows are utilized to seed the MLE process with the appropriate microbes and boost nitrogen removal rates, respectively. Treated effluent is either discharged to the Cohocton River or is pumped to a local golf course for reuse as irrigation water. The upgraded plant includes a receiving station for acceptance of high strength organic waste, which is to be processed in the AD. The remaining cells of the aerobic digester are to be used as a holding tank for the high strength organic waste. No thickening step is required for the organic waste feedstocks included in this analysis. The high strength organic waste is combined with primary and waste activated sludge in a blend tank prior to entering the AD. Digested sludge is pumped to the BFP, which is used as a final dewatering step with polymer addition prior to composting. Compost is land applied for use as an agricultural amendment.

2.3.2.1 Anaerobic Digestion

AD is to be used as the main sludge processing step within the upgraded treatment plant, and is set to replace the aerobic digestion system currently in use. AD uses a methanogenic process to break down volatile suspended solids contained within the sludge. Biogas is produced as a result of this degradation process. The biogas is comprised mostly of methane and carbon dioxide gas. An example of a typical biogas composition is shown in Table 2-3. Feedstocks for AD include primary solids, WAS, residential septage, and industrial organic wastes such as animal renderings, cheese whey, and winery waste.

The AD system is an example of conventional two-stage mesophilic digestion, and is accomplished in cylindrical primary and secondary vessels operated in series. Both units have a maximum capacity of approximately 300,000 gallons solids/sludge with a diameter of 45 feet and a 23.5-foot side water depth. The primary vessel runs at a constant temperature of 95°F. The secondary vessel is unheated and unmixed (CRA 2015). Sludge influent to the ADs is heated to match the reactor temperature prior to introduction into the primary vessel. Dual membrane covers are used for gas storage, and a combined heat and power (CHP) system is used to convert biogas into electricity and heat energy. Heat energy is used to provide process heat for AD and the on-site control buildings, thereby off-setting natural gas usage. It is assumed that any additional heat energy is wasted as there are no current plans for the distribution system which would be required to utilize this energy. Additional on-site uses of excess heat energy such as to heat wastewater in the colder months or for thermal processing of compost are possibilities, however no benefits to this effect are quantified in the analysis.

Table 2-3. Typical Biogas Composition for Residential Waste

Biogas Component	Expected Range[1]
Methane (CH_4) – dry basis, by volume	60-70%
Carbon Dioxide (CO_2) – dry basis, by volume	30-45%
Nitrogen (N_2) – dry basis, by volume	0.2-2.5%
Hydrogen (H_2) – dry basis, by volume	0-0.5%
Hydrogen Sulfide (H_2S) - ppm	200-3500
Water Vapor (H_2O) – wet basis, by volume	5.9-15.3%

Notes & References:
[1] Reproduced from Wiser et al. 2010

2.3.2.2 Composting

Thickened solids exiting the AD are trucked 0.8 km to a composting facility located adjacent to the Bath WWTP. An active windrow system is modeled as the composting method in the baseline scenario, which utilizes locally available sources of yard waste organic material as bulking agent and to achieve the desired carbon to nitrogen (C:N) ratio. The composting process is designed to achieve a target moisture content of between 55 and 60 percent. Digested solids are trucked to the composting site and unloaded into windrows. Additional organic material is placed next to the digested solids. Material mixing and the necessary water addition are accomplished using a self-propelled compost windrow turner. A minimum of five turnings are assumed during the active composting phase with up to two during compost curing. The turnings should be timed to maintain an average windrow temperature of 55°C for a period of 15 days for vector control and pathogen reduction (U.S. EPA 1994). Finished compost is screened prior to the curing stage, and is loaded into transport vehicles via a front-end loader for hauling to the site of land application. A sensitivity analysis is included that examines the effect on environmental impacts when an aerated static pile composting system is used in place of the windrow facility.

2.3.2.3 Land Application

Finished compost is assumed to be applied to local agricultural fields as both a soil amendment and source of essential plant nutrients. A transport distance of 25 km is assumed. Compost is spread on agricultural fields at typical agronomic rates (U.S. EPA 2013). Avoided fertilizer production is calculated based on compost application at the specified rates.

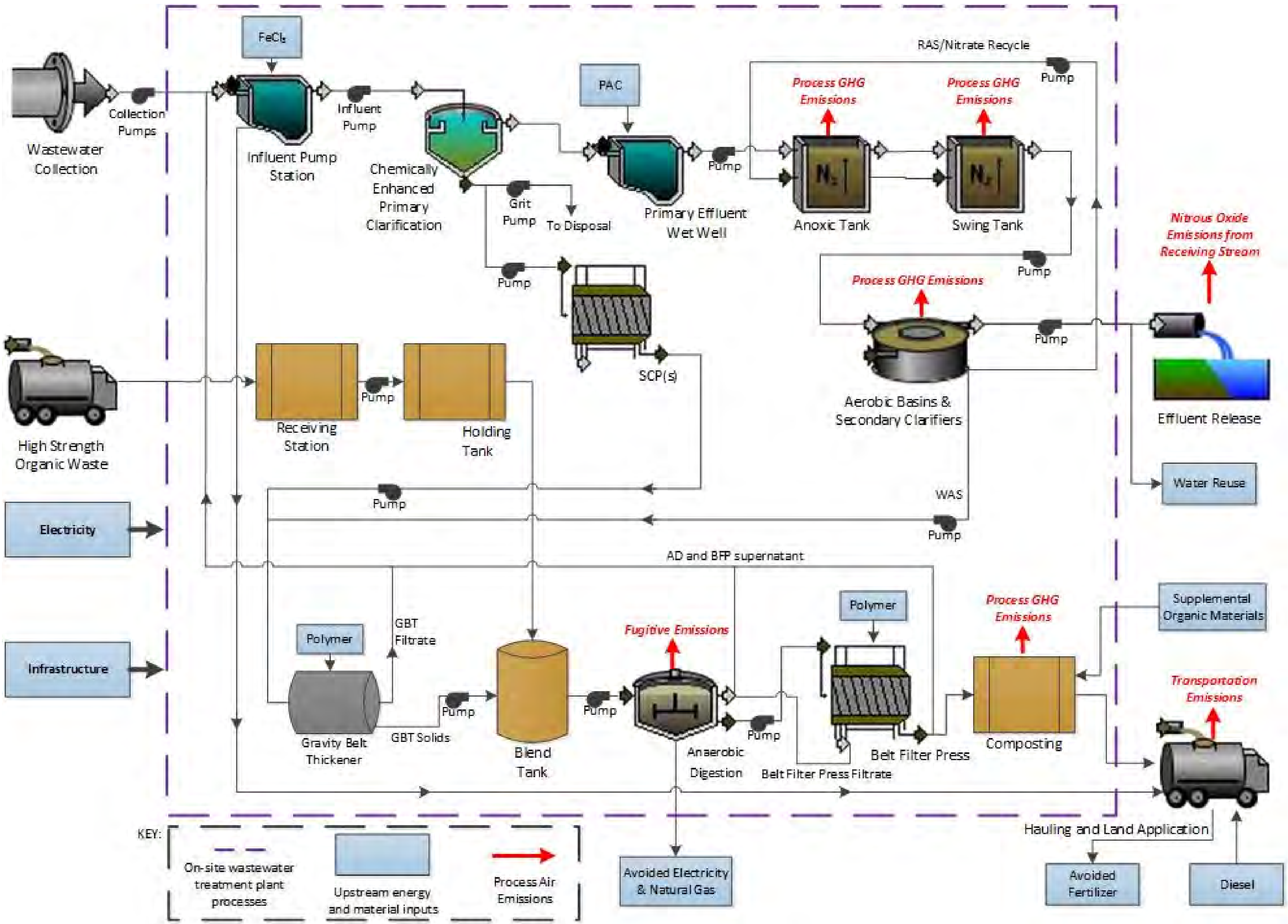

Figure 2-4. Upgraded WWTP, enhanced primary clarification, MLE and AD system diagram.

2.4 Background LCI Databases

In addition to the primary data sources described in the preceding sections, several background LCI databases have been used to provide information on upstream processes such as electricity inputs, transportation and manufacturing of chemical and material inputs. Ecoinvent 2.2 serves as the basis for most of the upstream infrastructure inputs and chemical and avoided fertilizer manufacturing (Frischknecht et al. 2005). The U.S. Life Cycle Inventory (U.S. LCI) database is used to represent the manufacture of some chemical and energy inputs in cases where applicable U.S. specific processes are available in the database (U.S. LCI 2012). A U.S. EPA LCI database is also used for electricity and transportation processes, and a number of infrastructure elements (U.S. EPA 2015a).

2.5 Metrics and Life Cycle Impact Assessment (LCIA) Scope

Table 2-4 summarizes the metrics calculated for each treatment system option, together with the method and units used to characterize each. The cost of the upgraded system configuration is estimated using standard approaches for LCCA, with more detail on the costing methodology provided in Section 4. Most of the LCIA metrics are estimated using the Tool for the Reduction and Assessment of Chemical and Environmental Impacts (TRACI), version 2.1 (Bare et al. 2003, Bare 2011). TRACI is an LCIA method developed by the U.S. EPA. It includes a compilation of methods representing current best practice for estimating human health and ecosystem impacts based on U.S. conditions and emissions information provided by LCI models. Global warming potential is estimated using the 100-year characterization factors provided by the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report, which are the global warming potentials currently used for international reporting (Myhre et al. 2013). In addition to TRACI, the ReCiPe LCIA method is used to characterize water use and fossil depletion potential (Goedkoop et al. 2009), impacts which are not included in the current version of TRACI. To provide another perspective on energy, cumulative energy demand including the energy content of all non-renewable and renewable energy resources extracted throughout the supply chains associated with each configuration is estimated using a method adapted from one provided by the Ecoinvent Centre (Ecoinvent Centre 2010). Table 2-5 includes a description of each impact category.

Table 2-4. Environmental Impact and Cost Metrics

Metric	Method	Unit
Cost	LCCA	USD 2014
Global Warming Potential	TRACI 2.1	kg CO_2-eq.
Eutrophication Potential	TRACI 2.1	kg N-eq.
Particulate Matter Formation Potential	TRACI 2.1	kg $PM_{2.5}$-eq.
Smog Formation Potential	TRACI 2.1	kg O_3-eq.
Acidification Potential	TRACI 2.1	kg SO_2-eq.
Water Use	ReCiPe	m^3
Fossil Depletion Potential	ReCiPe	kg oil-eq.
Cumulative Energy Demand	Ecoinvent	MJ-eq.

Table 2-5. Description of LCA Impact Categories

Impact/Inventory Category	**Description**	**Unit**
Eutrophication Potential	Eutrophication assesses the potential impacts from excessive loading of macro-nutrients to the environment and eventual deposition in waterbodies. Excessive macrophyte growth resulting from increased nutrient availability can directly affect species composition or lead to reductions in oxygen availability that harm aquatic ecosystems. Pollutants covered in this category are phosphorus and nitrogen based chemical species. The method used is from TRACI 2.1, which is a general eutrophication method that characterizes limiting nutrients in both freshwater and marine environments, phosphorus and nitrogen respectively, and reports a combined impact result.	kg N eq
Global Warming Potential	The global warming potential impact category represents the heat trapping capacity of GHGs over a 100-year time horizon. All GHGs are characterized as kg CO_2 equivalents using the TRACI 2.1 impact assessment method. TRACI GHG characterization factors align with the IPCC 4th Assessment Report for a 100-year time horizon.	kg CO_2 eq
Cumulative Energy Demand	The cumulative energy demand indicator accounts for the total usage of non-renewable fuels (natural gas, petroleum, coal, and nuclear) and renewable fuels (such as biomass and hydro). Energy is tracked based on the heating value of the fuel utilized from point of extraction, with all energy values summed together and reported on a MJ basis.	MJ
Water Use	Water use results are based on the volume of fresh water inputs to the life cycle of products within the WWTP supply-chain. Water use is an inventory category, and does not characterize the relative water stress related to water withdrawals. This category has been adapted from the water depletion category in the ReCiPe impact assessment method.	m^3
Particulate Matter Formation Potential	Particulate matter formation results in health impacts such as effects on breathing and respiratory systems, damage to lung tissue, cancer, and premature death. Primary pollutants (including PM2.5) and secondary pollutants (e.g., SOx and NOx) leading to particulate matter formation are characterized here as kg $PM_{2.5}$ eq based on the TRACI 2.1 impact assessment method.	kg $PM_{2.5}$ eq

Table 2-5. Description of LCA Impact Categories

Impact/Inventory Category	Description	Unit
Acidification Potential	Acidification potential quantifies the acidifying effect of substances on their environment. Acidification can damage or shift sensitive plant and animal populations and lead to damaging effects on human infrastructure (i.e. acid rain) (Norris 2003). Important emissions leading to terrestrial acidification include SO_2, NOx, and NH_3. Results are characterized as kg SO_2 eq according to the TRACI 2.1 impact assessment method.	kg SO_2 eq
Smog Formation Potential	Smog formation potential results determine the formation of reactive substances that cause harm to human respiratory health and can lead to reduced photosynthesis and vegetative growth (Norris 2003). Results are characterized here to kg of ozone (O_3) eq according to the TRACI 2.1 impact assessment method. Some key emissions leading to smog formation potential include CO, methane (CH_4), NOx, non-methane volatile organic compounds (NMVOCs), and SOx.	kg O_3 eq
Fossil Fuel Depletion	Fossil fuel depletion captures the consumption of fossil fuels, primarily coal, natural gas, and crude oil. All fuels are normalized to kg oil eq based on the heating value of the fossil fuel and according to the ReCiPe impact assessment method.	kg oil eq

LCIA results are grouped according to treatment stage for results presentation in all LCIA impact categories. Table 2-6 shows the assignment of unit processes to treatment stage categories for both the legacy and upgraded system. The 'X' indicates that a unit process is included in the referenced system.

Table 2-6. 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

Table 2-6. Assignment of Unit Processes to Treatment Stage for Results Presentation

Treatment Stage	Unit Process Name	Legacy System	Upgraded System
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

Results are also presented according to process categories for eutrophication potential, global warming potential, and cumulative energy demand. All unit processes in the LCA model are assigned to the process categories listed in Table 2-7.

Table 2-7. Process Categories for Results Presentation

Process Categories
Electricity
Natural Gas
Chemicals
Unit Process Emissions
Effluent Release
Transport
Landfill
Composting
Land Application
Avoided Products
Infrastructure
Diesel

3. LCA METHODOLOGY

This chapter covers the data sources, assumptions, and parameters used to establish the LCI values used in this study.

3.1 Water Quality and Organic Feedstock Characteristics

The characteristics associated with the influent municipal wastewater are the same for both the legacy and the upgraded treatment systems (Table 3-1). Wastewater influent to the Bath treatment facility is mixture of residential sewage and local industrial wastewater generators including a hospital, leachate treatment facility, and an airport (CRA 2015). Suspended solids concentrations are higher than those observed for typical domestic wastewater, while biological oxygen demand (BOD), nitrogen, and phosphorus values all fall within the expected range (Tchobanoglous et al. 2014). The temperature of influent and effluent wastewater varies between 8 and 20 degrees Centigrade depending upon the season. Influent wastewater characteristics for this study are set equal to the average observed influent values over the period from October 2011 to November 2015 (BEGWS 2016). Records of influent and effluent wastewater quality during this period are reported in the Appendix. The reported influent values include loadings from the permitted commercial and industrial sources which discharge to the Bath sewer system.

Table 3-1. Average Influent Composition of Bath, NY Wastewater Treatment Plant

Characteristic	Value	Unit	Reference(s)
Suspended Solids	437	mg/L	BEGWS 2016
Volatile Solids	51	%	calculated
Carbonaceous Biological Oxygen Demand (cBOD)[1]	279	mg/L	BEGWS 2016
Biological Oxygen Demand	323	mg/L	calculated, Brake 2007
Total Kjeldahl Nitrogen (TKN)	56	mg/L N	BEGWS 2016
Ammonia	32	mg/L N	BEGWS 2016
Total Phosphorus (TP)	8	mg/L P	Miller 2016
Nitrite	<1	mg/L N	Cunningham 2016
Nitrate	<1	mg/L N	Cunningham 2016
Organic Nitrogen	29	mg/L N	Miller 2016
Temperature	8-23	ºC, seasonal	BEGWS 2016

Notes & References:
[1] Assumes BOD/cBOD ratio of 1.16 (Brake 2007)

Effluent characteristics for the two systems are a key differentiating factor in this study. Effluent values used in this study are reported in Table 3-2 and are presented next to the effluent criteria values from the SPDES permit for the Bath WWTP. The effluent standards, which became effective in September 2014, require a treatment system upgrade to be met consistently. Effluent values for the legacy system are the average of recorded effluent test values over the period from October 2011 to November 2014 (BEGWS 2016). Expected effluent values for the upgraded treatment system are taken from engineering documents associated with the upgraded treatment system (CRA 2015).

Table 3-2. Effluent Composition of Two Bath, NY Wastewater Treatment Configurations

Characteristic	Legacy	Upgraded[1]	SPDES Permit Standard[3]	Unit	Reference (Legacy; Upgraded)
Suspended Solids	7.9	5.0	30	mg/L	BEGWS 2016; CRA 2015, fig. 5.4
Biological Oxygen Demand[2]	8.5	2.3	25[5]	mg/L	BEGWS 2016; CRA 2015, fig. 5.4
Total Kjeldahl Nitrogen	16	4.4	n.a.[4]	mg/L N	BEGWS 2016; CRA 2015, fig. 5.4
Ammonia	6.7	3.6	3.6	mg/L NH_3	BEGWS 2016; CRA 2015, fig. 5.4
Total Phosphorus	0.7	0.6	1,960	lb/yr P	BEGWS 2016; CRA 2015, fig. 5.4
Nitrite	2.8	0.8	n.a.[4]	mg/L N	BEGWS 2016; calculated
Nitrate	13	14	n.a.[4]	mg/L N	BEGWS 2016; Cunningham 2016
Organic Nitrogen	9	0.8	n.a.[4]	mg/L N	calculated
Total Nitrogen	31	20	61,000	lb/yr N	BEGWS 2016; CRA 2015, fig. 5.4

Notes & References:

[1] Upgraded system accepts a quantity of septage and organic waste not covered under current permit

[2] Assumes BOD/cBOD ratio of 1.16 (Brake 2007)

[3] SPDES 2014

[4] n.a. – not applicable

[5] Permit is specific to $cBOD_5$

Characteristics of waste destined for treatment via AD affect both plant operation and biogas production. Table 3-3 lists basic feedstock characteristics that describe waste as it is received by the Bath treatment facility, or in the case of primary and WAS, as it exists prior to thickening or blending. Both residential septic tank and portable toilet waste are treated within the WWTP alongside municipal sewage waste, which is to say that they are subject to both primary and secondary treatment. Septic tank and portable toilet waste are referred to collectively as septage throughout this report. Primary and WAS are collected via primary and secondary clarification, respectively, and will include solids derived from both forms of septage waste. The quantity of septage waste is limited to 8,000 GPD in the legacy treatment system. The quantity of accepted septage waste is limited to 16,000 GPD in the upgraded treatment plant as is specified in the engineering planning documents (CRA 2015). The loadings associated with septage waste are considered in both the legacy and upgraded effluent values. Septage is distinguished from high strength organic waste for the purposes of this study.

The high strength organic wastes considered in this study include slaughterhouse, winery, and cheese waste. High strength organic wastes skip primary and secondary treatment and are introduced directly into the AD following blending with thickened primary and waste activated sludge. The high solids content of these wastes allows them to bypass gravity belt thickening. This serves several purposes, including maximization of loading to the ADs, which in turn increases the potential for methane generation. This decision also eliminates a source of increased pollutant loading to primary and secondary treatment, which would result from the need to process supernatant from the avoided thickening step. The high strength organic waste feedstock scenarios analyzed in the sensitivity analysis are presented in Section 1.1 and the supplemental organic amendments for composting are listed in Section 3.3.

Table 3-3. Waste Characteristics of AD Feedstock

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	0.5%	1	31%	7	190	2	120	2
Primary Sludge	1.8%	1	68%	7	453	2	127	2
Septic Tank Waste	0.1%	3	57%	3	103	3	14.0	3
Portable Toilet Waste	0.3%	3	43%	3	937	3	67.7	3
Slaughterhouse Waste	13%	4	92%	4	1.50E+3	9	NA	8
Winery Waste	3.7%	5	60%	5	105	5	NA	8
Cheese Waste	7.8%	6	62%	6	1.02E+3	6	300	6

Notes & References:
[1] GHD Engineering Service 2015
[2] calculated based on Tchobanoglous et al. 2014
[3] ALS 2015
[4] Luste and Luostarinen 2010
[5] Bustamante et al. 2005
[6] Gelegenis et al. 2007
[7] CRA 2015
[8] NA - not available
[9] Between values reported in Palatsi et al. 2011 and Sindt 2006, nitrate/nitrite assumed negligible (De Guardia et al. 2009)

3.2 Legacy WWTP

Data regarding the construction and operation of the legacy system was provided by BEGWS staff. The system as modeled has been in operation since 1993, leaving a detailed record of treatment performance over many years. The secondary treatment system was upgraded to an MLE unit in 2016, replacing the legacy CAS system.

Utility records were provided by BEGWS for electricity, natural gas, and water usage for the years 2014 and 2015. Electricity usage for units is 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 1 and Equation 2. Equation 2, which relies on facility records of equipment V and A draw, is preferred over Equation 1 when this information is available. Natural gas is used for building space conditioning, and is not expected to increase as a result of increasing the flow rate from the current average of 0.67 MGD to the maximum flowrate of 1 MGD, which is used as the basis of this analysis. The energy requirement of treating 8,000 GPD of septage is included in the numbers prior to scaling and the quantity is expected to remain constant, meaning that no further adjustments are required. The quantities of chemical inputs were provided by BEGWS staff, and these values were increased in the LCA model to account for the increased flow rate of the study system as compared to the current average flow rate. Values in electricity use tables throughout this section have been rounded to three significant figures.

$$\text{Electricity Use (kWh/year)} = \text{Unit HP} \times (0.746\ \text{kw/HP}) \times \text{annual operation (hr/yr)}$$

Equation 1

$$\text{Electricity Use (kWh/year)} = (\text{Amps} \times \text{Volts})/1000 \times \text{annual operation (hr/yr)}$$

Equation 2

System dimensions from construction drawings for the 1968 and 1993 plant upgrades were used to estimate the included infrastructure components of each unit. Concrete volume, rebar weight, aggregate weight, piping quantity, and excavation volume comprise the majority of infrastructure included. Example infrastructure calculations are included in Appendix A. Smaller infrastructure components such as pumps, valves, pipe elbows, and internal unit piping are excluded from the analysis. The following units are included in the infrastructure estimate: (1) parshall flume, (2) primary settling tank, (3) wet well, (4) aeration basins, (5) aerobic digester, (6) sludge thickener, (7) inter-unit piping, (8) control buildings, and (9) collection system piping.

Process based GHG emissions and those emanating from receiving waters were calculated based on the methods introduced in the following unit descriptions, and described in detail in the Appendix A. The following subsections provide the detailed operational LCI developed for the legacy WWTP by unit process on an annual basis. Annual inputs and outputs are allocated to the functional unit by dividing annual input and output quantities by the number of cubic meters of wastewater treated at the plant per year.

3.2.1 Screening and Grit Removal

This unit includes the drive motor for the mechanical bar screen and the equipment involved in grit removal as well as flow sensor and transmitter equipment associated with the operation of the Parshall flume (Table 3-4). No chemical use is associated with this unit.

Table 3-4. Screening and Grit Removal – Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Electricity Use (kWh/yr)
Drive Motor	1.50	2.60	460	8,740	10,400
Grit Feed Pump Motor	5.00	8.10	460	2,900	10,900
Screw Drive Motor	1.00	1.60	460	8,740	6,430
Vacuum Pump	0.50	0.90	115	728	75.3
Air Compressor	0.50	0.90	115	728	75.3
Flow Sensor	0.50	0.90	24.0	8,740	189
Flow Transmitter	0.50	0.90	115	8,740	904

3.2.2 Primary Clarifier

As shown in Table 3-5, the primary clarifier unit process includes the mechanical equipment required to collect primary sludge. Electricity use for the primary effluent pump and PAC feed pump are also included in this unit in the LCA results. The primary effluent pump moves wastewater from the primary clarifier to the aeration basins.

Table 3-5. Clarifier – Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Electricity Use (kWh/yr)
Longitudinal Collector 1	0.50	0.90	460	8,740	3,620
Longitudinal Collector 2	0.50	0.90	460	8,740	3,620
Cross Collector Drive	0.50	0.90	460	8,740	3,620
Scum Pump	5.00	8.10	460	728	2,710
Wet Well Level Sensor	0.50	0.90	24.0	8,740	189
Primary Effluent Pump No. 1	20.0	27.5	460	8,740	111,000
Primary Effluent Pump No. 2[1]	20.0	27.5	460	-	-
PAC Feed Pump	1.00	1.60	110	8,740	1,540

Note:
[1] Auxiliary pump

It was reported that 114,000 gallons of PAC are used annually. The calculation in Equation 3 determines the resulting LCI quantity:

$$\text{PAC (kg/m3)} = 114{,}000 \text{ gal/year} \div 264 \text{ gal/m}^3 \text{ x } (1.18 \text{ (specific gravity) x } 1000 \text{ kg/m}^3) \div (1{,}381{,}676 \text{ m}^3\text{/yr x } 0.67 \text{ MGD}) \boxed{= 0.55 \text{ kg/m}^3}$$

Equation 3

3.2.3 Aeration Tanks and Secondary Clarification

A bank of three aeration tanks forms the secondary treatment system, which includes integrated secondary clarification, and the blowers and mechanical equipment required to run these units. Electricity use calculations for these aeration tanks and integrated secondary clarification are provided in Table 3-6. PAC, which aids flocculation in this unit, is added in the primary effluent wet well, and its impacts are included with the primary clarifier.

Table 3-6. Aeration Tanks – Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Electricity Use (kWh/yr)
Multi-Stage Centrifugal Blower No. 1	50.0	61.0	460	8,740	245,000
Multi-Stage Centrifugal Blower No. 2	50.0	61.0	460	8,740	245,000
Multi-Stage Centrifugal Blower No. 3[1]	50.0	61.0	460	-	-
Clarifier Drive No. 1	0.50	1.00	460	8,740	4,020
Clarifier Drive No. 2	0.50	1.00	460	8,740	4,020
Clarifier Drive No. 3	0.50	1.00	460	8,740	4,020
WAS System	0.50	0.90	110	2,910	288

Note:
[1] Auxiliary blower

GHG emissions from the aerobic tanks are calculated based on influent TKN and BOD concentrations. For a CAS system, it is assumed that 0.035 percent of influent nitrogen is released as nitrous oxide (Czepiel 1995). Methane emissions from the aeration tanks are calculated using a theoretical maximum methane generation rate of 0.6 kg CH_4/kg influent BOD, which is adjusted downwards using a methane correction factor of 0.005 (Czepiel 1993) as demonstrated in the Appendix.

3.2.4 Sludge Thickening

The sludge thickening unit process includes electricity requirements for pumping from the sludge well to the thickener unit and the thickener drive motor (Table 3-7). No chemicals are used for gravity sludge thickening.

Table 3-7. Sludge Thickening – Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Electricity Use (kWh/yr)
Thickener Feed Pump No. 1	7.50	9.50	460	364	1,590
Thickener Feed Pump No. 2[1]	7.50	9.50	460	-	-
Thickener Drive Motor	1.00	1.60	110	8,740	1,540

Note:
[1] Auxiliary pump

3.2.5 Aerobic Digestion

Aerobic digestion includes electricity use for the operation of two digester feed pumps and four positive displacement blowers for aeration of the thickened sludge (Table 3-8).

Table 3-8. Aerobic Digester – Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Electricity Use (kWh/yr)
Digester Feed Pump No. 1	3.00	4.40	460	364	737
Digester Feed Pump No. 2[1]	3.00	4.40	460	--	--
Positive Displacement Blower No. 1	25.0	32.0	460	8,740	129,000
Positive Displacement Blower No. 2	25.0	32.0	460	8,740	129,000
Positive Displacement Blower No. 3	25.0	32.0	460	8,740	129,000
Positive Displacement Blower No. 4	25.0	32.0	460	8,740	129,000
Positive Displacement Blower No. 5[1]	25.0	32.0	460	--	--

Note:
[1] Auxiliary pump and blower

GHG emissions from the aerobic digester are calculated based on influent TKN and BOD concentrations. It is assumed that 0.035 percent of influent nitrogen is released as nitrous oxide (Czepiel 1995). Methane emissions from the tanks are calculated using a theoretical maximum methane generation rate of 0.6 kg CH_4/kg influent BOD, which is adjusted downwards using a methane correction factor of 0.005 (Czepiel 1993) as demonstrated in the Appendix.

3.2.6 Belt Filter Press

The BFP includes all equipment required for sludge dewatering. Associated electricity use calculations for the BFP are presented in Table 3-9.

Table 3-9. Belt Filter Press – Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Electricity Use (kWh/yr)
BFP Feed Pump No. 1	5.00	6.60	460	2,080	6,310
BFP Feed Pump No. 2	5.00	6.60	460	-	-
Drum Drive	1.00	1.60	460	2,080	1,530
Belt Drive	1.50	2.80	460	2,080	2,680
Spray Pump	7.50	9.40	460	2,080	8,990
Screw Conveyor Drive	1.00	1.60	460	2,080	1,530
Belt Conveyor Drive	1.00	1.60	460	2,080	1,530
Polymer Feed Pump	1.00	1.60	110	8,740	1,540

It is reported that 23,000 gallons of polymer solution are used annually. The following calculation in Equation 4 was performed to determine the resulting LCI quantity:

$$\text{polymer (kg/m3)} = 23{,}000\ \text{gal/year} \div 264\ \text{gal/m3} \times (1.14\ \text{(specific gravity)} \times 1000\ \text{kg/m3}) \div (1{,}381{,}676\ \text{m3/yr} \times 0.67\ \text{MGD}) = 0.11\ \text{kg/m}^3\ \text{of 0.5\% polymer solution}$$

$$\text{polymer quantity} = 0.11\text{kg/m}^3 * (0.5/100)\ \boxed{= 5.36\text{E-4 kg/m}^3}$$

$$\text{water quantity} = 0.11 - 5.36\text{E-4}\ \boxed{= 0.107\ \text{kg/m}^3}$$

Equation 4

3.2.7 Sludge Landfilling

Landfilling of biosolids following aerobic digestion is the EOL approach for the legacy plant. This can be compared to composting and land application, which is the EOL reuse option applied to the upgraded system. Preliminary screening of results indicated the importance of EOL disposal routes, particularly composting, to GHG impacts per cubic meter of wastewater.

Three methane emission scenarios were developed for the landfill emissions sensitivity analysis using parameters listed in Table 3-10. The method first calculates the fraction of degradable carbon. A first-order decay equation is used to calculate the portion of degradable carbon that degrades each year over a 100-year timespan. Fifty percent of carbon that degrades is assumed to produce methane, with the remainder producing biogenic CO_2. Emissions occurring within the first 3 years are assumed to be released to the atmosphere as it takes time to put a methane capture system in place. Carbon sequestration is estimated as the fraction of non-degradable carbon plus the fraction of degradable carbon that does not degrade over the 100-year time horizon.

Table 3-10. Methane Emission Calculation Parameters for the Low, Base, and High Emission Scenarios

	Low Emission		Base Emission		High Emission	
Parameter	**Value**	**Source**	**Value**	**Source**	**Value**	**Source**
Wet Weight of Solids Landfilled Annually	2,636	1	2,636	1	2,636	1
Moisture Content of Biosolids	20	2	20	2	20	2
Dry Weight of Solids	527	calculated	527	calculated	527	calculated
Carbon Content of Dry Solids	39%	3	48%	average	57%	4
Incoming C, Annual (metric tons)	206	calculated	253	calculated	300	calculated
Carbon, % of wet mass	8%	calculated	10%	calculated	11%	calculated
Non-degradable Carbon, % of wet mass	3%	calculated	5%	calculated	6%	calculated
Degradable Organic Carbon, % of wet mass	5%	5	5%	5	5%	5
Fraction of Degradable Carbon Decomposed	50%	3	65%	average	80%	3
Fraction of Degraded Carbon Turning to CH_4	50%	3,5	50%	3,5	50%	3,5
Fraction of Methane Oxidized to CO_2 in landfill cover	25%	3	10%	3	3%	3
MCF (methane conversion factor)	1	3,5	1	3,5	1	3,5
K	0.1	3,5	0.175	3,5	0.225	3

Notes & References:
[1] Bath Sludge Report to EPA
[2] Hydromantis 2014
[3] SYLVIS 2011
[4] Maulini-Duran 2013
[5] RTI 2010

Two scenarios were evaluated to determine the impact of methane fate on life cycle impacts: (1) bath landfill and (2) national average landfill. Table 3-11 shows the methane capture performance of the landfill scenarios. The Steuben County landfill that services the Town of Bath was retrofitted with a modern gas capture system in 2010 that is designed to capture 95 percent of methane produced in the facility. Ten percent of the methane released without treatment is assumed to oxidize to CO_2 as it moves upwards through the landfill prior to emission. Of methane produced in the national average landfill, 28.8 percent is assumed to be lost to the atmosphere, 3.8 percent is oxidized to CO_2 within the landfill, 10.6 percent is flared, and 56.8 percent is recovered and used for energy production (U.S. EPA 2015b).

Table 3-11. Methane Capture Performance of Bath and National Average Landfills

Parameter	Bath NY Landfill (baseline)	National Average Landfill
Percentage of landfilled C that produces methane	50%	50%
Percentage of methane released w/o treatment	4.5%	29%
Percentage of methane captured for energy recovery	95%	57%
Percentage of methane flared	0%	11%
Percentage of methane oxidized to CO_2	0.5%	3.8%

The potential range of nitrous oxide (N_2O) emissions that could be expected from landfilling of sludge was determined through a review of published emission factors. All estimates of landfill nitrous oxide emissions are in the form of mass N_2O emitted per m^2 of landfill area per hour during active landfilling. Only one study was found that deals specifically with nitrous oxide emissions of landfilled sludge, and this is in the context of daily cover for the landfill (Borjesson and Svensson 1997).

Low, medium, and high estimates of potential landfill N_2O emissions were taken from the literature (Rinne et al. 2005, Barton and Atwater 2002, Borjesson and Svensson 1997). Table 3-12 shows reasonable, low, medium, and high estimates of N_2O emission rates during active landfilling. The ratio of landfilled waste to landfill area from Rinne et al. 2005 was used to transform N_2O emission rates ($mg/m^2/hr$) into kg N_2O emitted per kg of waste landfilled. These values are used to calculate the N_2O emission factors used in the LCI and displayed in Table 3-13. The work of Barton and Atwater indicates that N_2O emissions after landfill closure will be negligible in comparison to the values found for the active phase of the landfill's lifetime. The base N_2O emission factor is equivalent to a 1.65 percent loss of nitrogen content as N_2O (Barton and Atwater 2002), which is like estimates for land application.

Transport requirements were calculated by multiplying the weight of dewatered sludge by an estimated average transport distance to the landfill of 24 km (15 miles), one way.

Table 3-12. N_2O Emission Rates During Active Landfilling

Parameter	Value	Unit	Source
Low N_2O emission factor during active landfilling	1.70	mg $N_2O/m^2/hr$	Borjesson and Svensson 1997
Medium N_2O emission factor during active landfilling	4.20	mg $N_2O/m^2/hr$	Rinne et al. 2005
High N_2O emissions during active landfilling	56.1	mg $N_2O/m^2/hr$	Borjesson and Svensson 1997

Table 3-13. Landfill N_2O Emission Factors per Cubic Meter of Wastewater

Parameter	Value	Units
N_2O emission factor, low	4.01E-05	kg N_2O/m^3
N_2O emission factor, base	6.14E-04	kg N_2O/m^3
N_2O emission factor, high	1.34E-03	kg N_2O/m^3

3.2.8 Effluent Release

Nitrous oxide emissions from receiving streams are calculated based on the IPCC guideline that 0.005 kg of N_2O-N are emitted per kg of nitrogen discharged to the aquatic environment. Details of that calculation are presented in the Appendix.

3.3 Upgraded WWTP

Data concerning the upgraded wastewater treatment facility was also provided by BEGWS staff. Most of the original values the study is based upon were generated by GHD Engineering as part of the facility design process (CRA 2015).

Estimates of unit electricity use are based on the assumed daily flowrate of 1 MGD. Electricity usage for units is calculated based on mechanical equipment horsepower or recorded voltage and current readings for each piece of equipment according to Equation 1 and Equation 2, respectively. Equation 2, which relies on facility records of equipment V and A draw, is preferred over Equation 1 when this information is available. Electricity use of appropriate units is scaled for the medium and high feedstock scenarios to account for additional solids processing. Values in electricity use tables throughout this section have been rounded to three significant figures. Annual estimates of chemical usage for each unit were determined by GHD Engineering based on the assumed influent wastewater characteristics presented in Table 3-1. When necessary, chemical use was adjusted upwards to account for the difference between GHD's assumed average annual flow rate of 0.67 MGD to the maximum daily flowrate of 1 MGD.

The following units are included in the infrastructure estimate for the upgraded system: (1) chemically enhanced primary clarification, (2) wet well, (3) anoxic and swing tanks, (4) aeration basins, (5) waste holding and receiving tanks, (6) blend tank, (7) primary and secondary AD, (8) inter-unit piping, and (9) collection system piping. The chemically enhanced primary clarification unit, receiving station, and ADs all require new infrastructure. Other units are re-purposed. Basic dimensions for the enhanced primary settling tank and the waste receiving station were provided by BEGWS staff assuming the same basic construction methods as employed by all other units for tank walls, slab, rebar, excavation, and foundation gravel. Infrastructure estimates for the primary and secondary digesters were calculated using CAPDETWorks™ engineering design and costing software (Hydromantis 2014).

Process based GHG emissions and those emanating from receiving waters were calculated based on the methods introduced in the following unit descriptions, and described in detail in the Appendix. The following subsections provide the detailed operational LCI developed for the upgraded WWTP by unit process on an annual basis. Annual inputs and outputs are allocated to the functional unit by dividing annual input and output quantities by the number of cubic meters of wastewater treated per year. Environmental benefits and burdens, including those generated due to treatment of additional high strength organic waste, are normalized to the maximum facility flow capacity of 1 MGD.

3.3.1 Sludge Receiving and Holding

Electricity use for the sludge receiving and holding unit process includes the operation of sludge pumps (2) and (3) and an estimate of aeration energy required for odor control during sludge holding before blending and introduction into the ADs (Table 3-14). Electricity usage is scaled up for the medium and high feedstock scenarios to account for additional pumping and aeration energy requirements based on the additional volume of organic waste accepted at the receiving station. No chemical use is required for this unit process.

Table 3-14. Sludge Receiving and Holding – Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Annual Electricity Use (kWh)
Sludge Pump (2)	7.50	-	-	2,190	12,300
Sludge Pump (3)	7.50	-	-	2,080	11,600
Coarse Bubble Diffused Aeration	25.0	32.0	460	2,920	43,000

Truck transport energy of incoming high strength organic waste is also included in the analysis and is calculated for each feedstock scenario (Table 3-15). An incoming transport distance of 25 km is assumed.

Table 3-15. Transport Calculations for Incoming High Strength Organic Waste and Septage

Feedstock Scenario	Waste Volume (gal)	Waste Mass (metric ton/yr)	transit (t-km)[1]	tkm/m^3
Base	16,000	22,120	553,000	0.40
Medium	20,000	27,820	695,000	0.50
High	24,000	33,590	840,000	0.61

Note:
[1] t-km = metric ton*kilometer

3.3.2 Chemically Enhanced Primary Clarification

As illustrated in Table 3-16, electricity use for enhanced primary clarification in the LCA results included operation of the influent pump, SCP and grit equipment, and the ferric chloride feed equipment. Electricity requirements for primary clarification remain constant across the scenarios due to a minimal, less than 0.5 percent, increase in flow rate at the headworks due to supernatant recycling from the AD and BFP.

Table 3-16. Enhanced Primary Clarification – Annual Equipment Electricity Use

Equipment	Unit Quantity	Units On	HP	Run Time (hr/yr)	Annual Electricity Use (kWh)
Influent Pumps	2	1	40.0	2,340	69,700
Lift Drives	8	2	5.00	8,760	65,300
Air Scour Blowers	8	3	1.20	8,760	23,500
Backwash Booster Pump	1	1	5.00	8,760	32,700
Actuator Valves	41	20	0.25	730	2,720
SCP Pumps	2	1	15.0	4,380	49,000
SCP	2	1	3.00	4,380	9,800
Grit Pumps	2	1	15.0	1,460	16,300
Chemical Feed - $FeCl_3$	2	1	0.10	8,760	653

The reported ferric chloride addition was 30 mg/L of influent wastewater. The following calculation in Equation 5 was performed to determine the ferric chloride addition used in the LCI:

$$FeCl_3 \text{ addition} = 30 \text{ mg/L x } (1{,}381{,}676 \text{ m}^3\text{/yr x } 1000 \text{ L/m}^3) \div 1E6 \text{ mg/kg} \div 1{,}381{,}676 \text{ m}^3\text{/yr} = 41{,}450 \text{ kg/yr} \div 1{,}381{,}676 \text{ m}^3\text{/yr} \boxed{= 0.03 \text{ kg } FeCl_3/m^3 \text{ Wastewater}}$$

Equation 5

3.3.3 Primary Effluent Wet Well

As shown in Table 3-17, the primary effluent wet well includes pumping energy required to move wastewater from primary to secondary treatment in addition to the energy required for PAC addition.

Table 3-17. Primary Effluent Wet Well – Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Annual Electricity Use (kWh)
Primary Effluent Pump No. 1	20.0	27.5	460	8,740	130,000
Primary Effluent Pump No. 2	0.0	27.5	460	-	-
Primary Effluent Wet Well Level Sensor	0.50	0.90	24.0	8,760	189
CHEM FEED - PAC	1.00	1.60	110	8,760	1,540

It is reported that 27 pounds of PAC is used per day at a flow rate of 0.67 MGD. The following calculation in Equation 6 is used to determine the PAC addition used in the LCI:

$$\text{PAC addition} = 27 \text{ lb/day} \div 0.67 \text{ MGD} \div 2.2 \text{ lb/kg} \times 365 \text{ days/yr} \div 1{,}381{,}676 \text{ m}^3\text{/yr wastewater} \boxed{= 0.0048 \text{ kg/m}^3 \text{ wastewater}}$$

Equation 6

3.3.4 Anoxic and Swing Tank

Electricity consumption includes tank mixers, aeration for the swing tank, and pump energy required to move wastewater to the aeration basins (Table 3-18). Electricity use of the swing tank aerators is increased for the medium and high feedstock scenarios based on the percent increase in BOD and total nitrogen (TN) attributable to supernatant return flows. No chemical use is required for the anoxic or swing tanks. The use of a carbon source to aid denitrification is possible, but is not anticipated to be necessary. GHG emissions from this unit are included with the aeration and secondary clarification unit process.

Table 3-18. Anoxic and Swing Tank – Annual Equipment Electricity Use

Equipment	Units On	HP	Run Time (hr/day)	Electricity Use (kWh/yr)
Pre-Anox and Swing Tank Submersible Mixers	1	8.30	3.60	8,140
Swing Tank, Aeration	1	25.0	4.00	27,200
Pump, to Aeration Tank	1	20.0	24.0	131,000

3.3.5 Aeration and Secondary Clarification

Electricity consumption for this unit includes aeration and clarifier drive energy, nitrate and RAS pumping, and movement of WAS to the sludge well (Table 3-19). Electricity use is not scaled for aeration and secondary clarification due to the minimal effect of supernatant return flows on flowrate and the assumption that unit equipment is operating at a fixed capacity. The PAC addition which aids flocculation in this unit is added in the primary effluent wet well.

Table 3-19. Aeration and Secondary Clarification – Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Electricity Use (kWh/yr)
RAS Pumps	3.00	-	-	8,760	19,600
RAS Pumps	3.00	-	-	8,760	19,600
RAS Pumps	3.00	-	-	8,760	19,600
WAS Pumps[1]	0.50	0.90	110	2,910	1,090
Nitrate Recycle Pumps	5.00	-	-	8,760	32,700
Nitrate Recycle Pumps	5.00	-	-	8,760	32,700
Nitrate Recycle Pumps	5.00	-	-	8,760	32,700
Multi-Stage Centrifugal Blower No. 1	50.0	61.0	460	8,740	245,000
Multi-Stage Centrifugal Blower No. 2	50.0	61.0	460	8,740	245,000

Table 3-19. Aeration and Secondary Clarification – Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Electricity Use (kWh/yr)
Clarifier Drive No. 1	0.50	1.00	460	8,740	4,020
Clarifier Drive No. 2	0.50	1.00	460	8,740	4,020
Clarifier Drive No. 3	0.50	1.00	460	8,740	4,020

Note:
[1] Equation 1 was used to calculate electricity use of the WAS pump, which yields a higher estimate of electricity consumption than Equation 2. While this approach is inconsistent with the preference for use of Equation 2 when electrical load information is available, the effect is negligible at a process unit and treatment system level.

GHG emissions from the aerobic tanks are calculated based on influent TKN and BOD concentrations. For a MLE system with zones for both nitrification and denitrification it is assumed that 0.16 percent of influent nitrogen is lost as nitrous oxide (Chandran 2012). Methane emissions from the upgraded secondary treatment system are calculated using a theoretical maximum methane generation rate of 0.6 kg CH_4/kg influent BOD, which is adjusted downwards using a methane correction factor of 0.05 (Daelman et al. 2013) as demonstrated in Appendix A.

3.3.6 Belt Filter Press

Electricity use includes the operation of pumps and drive motors for the BFP and energy required for chemical additions (Table 3-20). Baseline electricity requirements for all BFP equipment are scaled based on the increase in waste processed for each Feedstock-AD scenario relative to the baseline. Scaling factors are recorded in the Appendix.

Table 3-20. Belt Filter Press – Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Annual Electricity Use (kWh)
Chemical Feed - Polymer BFP	1.00	-	-	4,380	3,270
BFP Feed Pump No. 1	5.00	6.60	460	2,080	6,320
Drum Drive	1.00	1.60	460	2,080	1,530
Belt Drive	1.50	2.80	460	2,080	2,680
Spray Pump	7.50	9.40	460	2,080	8,990
Screw Conveyor Drive	1.00	1.60	460	2,080	1,530
Belt Conveyor Drive	1.00	1.60	460	2,080	1,530

A dosage of 8 lb active polymer ingredient is required per dry ton of solids processed by the BFP to aid dewatering (GHD 2016, pg. 32), which is determined according to the Feedstock-AD scenarios introduced in Section 3.3.9. It is assumed that a similar dosage is required for the gravity belt thickener. The following calculation in Equation 7 is performed to determine the polymer LCI addition for each scenario (Table 3-21), using values from the Base Feedstock-Base AD scenario as an example:

Polymer Addition (kg/m^3) = 8 lb/ short ton x 2.3 short ton/day ÷ 2.2 lb/kg x 365 day/yr ÷ 1,381,676 m^3/yr = 0.0022 kg/m^3

Equation 7

Table 3-21. 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	0.0020
Medium	0.0032	0.0028	0.0027
High	0.0045	0.0039	0.0037

3.3.7 Gravity Belt Thickening

Electricity use for the GBT includes pumping energy from the sludge well, and operation of drive motors, pumps, and compressors as well as energy required for polymer addition (Table 3-22).

Table 3-22. Gravity Belt Thickener – Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Annual Electricity Use (kWh)
Sludge Pump (1)	7.50	-	-	2,080	11,600
GBT Air compressor	1.00	-	-	1,460	1,090
Gravity Belt Thickener	1.00	-	-	2,080	1,550
GBT Booster Pump	5.00	-	-	2,080	7,760
Chemical Feed- Polymer GBT	1.00	-	-	4,380	3,270

The GBT processes the same quantity of dry solids each day regardless of feedstock scenario as the high strength organic waste is assumed to bypass this unit, leading to a constant polymer addition of 0.003 kg/m^3 as shown in Equation 8.

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

Equation 8

3.3.8 Blend Tank

Blend tank operation and pumping energy to the primary digester comprise equipment energy use for the blend tank (Table 3-23). Baseline electricity requirements for the blend tank are scaled based on the increase in waste processed for each Feedstock-AD scenario relative to the baseline. Scaling factors are recorded in Appendix A. No chemical additions are required for the blend tank.

Table 3-23. Blend Tank – Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Annual Electricity Use (kWh)
Raw Sludge Transfer Pump	7.50	-	-	2,080	11,600
Blend Tank Mixer	8.30	-	-	1,310	8,140

3.3.9 Anaerobic Digestion

AD electricity consumption includes unit mixing, sludge transfer, and biogas cleaning energy (Table 3-24). Baseline electricity requirements for the digested sludge transfer pump are scaled based on the increase in waste processed for each Feedstock-AD scenario relative to the baseline. Scaling factors are recorded in the Appendix. The gas cleaning system runs 24 hours a day regardless of gas production, with the assumption that electricity consumption remains constant. No chemical additions are required for this unit.

Table 3-24. Anaerobic Digestion – Annual Equipment Electricity Use

Equipment	HP	Run Time (hr/yr)	Annual Electricity Use (kwh)
Digester Mixing Pump	25.0	8,760	163,000
Digested Sludge Transfer Pump	7.50	2,080	11,600
Gas Cleaning System Booster Pump	30.0	8,760	196,000

AD operational parameters were calculated using the approach developed for implementation in the CAPDETWorks™ WWTP design and costing software (Hydromantis 2014). The base scenario incorporates sludge quantities associated with operating the treatment plant at its full capacity of 1 MGD, plus the acceptance of an additional 16,000 GPD of septic and portable toilet waste (GHD 2016). The medium and high feedstock scenarios have been developed assuming additional acceptance of high strength organic wastes as reflected in Table 3-25, leading to a maximum acceptance of 24,000 GPD of trucked in waste in the High feedstock scenario. Quantities of accepted waste were determined by the size of the ADs and a reasonable range of targeted loading rates of between 130 and 205 lb VS/1000 ft^3/day at a retention time of 15 days (Tchobanoglous et al. 2014). The quantities included in Table 3-25 are prior to dewatering in the GBT. Actual daily flow to the AD is just below 20,100 gal/day in the high feedstock scenario, which is below the maximum flow capacity of 21,000 gal/day (CRA 2015). The characteristics of each feedstock are included in Table 3-3.

Table 3-25. Feedstock Scenarios for AD Sensitivity Scenarios (prior to dewatering)

Waste Type[1]	Base (gal/day)	Medium (gal/day)	High (gal/day)
Primary Sludge	17,654	17,654	17,654

Table 3-25. Feedstock Scenarios for AD Sensitivity Scenarios (prior to dewatering)

Waste Type[1]	Base (gal/day)	Medium (gal/day)	High (gal/day)
Waste Activated Sludge	75,557	75,557	75,557
Septic Tank Waste	14,000	14,000	14,000
Slaughterhouse Waste	-	1,000	4,000
Cheese Waste	-	2,000	3,000
Winery Waste	-	1,000	1,000
Portable Toilet Waste	2,000	2,000	2,000
Loading (lb VS/1000 ft3/day)	130	158	205

[1] Primary sludge, waste activated sludge, septic, and portable toilet waste are dewatered prior to entering the AD, decreasing volume to within the maximum AD flow capacity. All values shown in this table are for waste quantities prior to dewatering.

Given the uncertainty associated with the co-digestion of novel combinations of industrial and municipal feedstocks a series of three AD operational scenarios have been developed based on the range of operational parameter values as found in the literature, as documented in Table 3-26. Composite biogas yield values were calculated based on the feedstock scenarios outlined in Table 3-25 and the individual biogas yield values found for each feedstock within the literature from Table 3-26. Table 3-27 shows these composite low, base, and high biogas yield estimates assumed for each feedstock.

Table 3-26. Operational Parameters for AD Sensitivity

Parameter Name		AD Low		AD Base		AD High		Units
		Value	Reference	Value	Reference	Value	Reference	
Percent Volatile Solids Reduction		45	1	60	1	65	1	%
Biogas Yield	Base[5]	12.0	calculated	15.0	calculated	34.7	calculated	ft^3/lb VS destroyed
	Medium[5]	12.8	calculated	16.7	calculated	30.0	calculated	ft^3/lb VS destroyed
	High[5]	14.2	calculated	19.2	calculated	29.1	calculated	ft^3/lb VS destroyed
Methane Content of Biogas		60	2	65	2	75	2	% v/v
Biogas Heat Content		0.55	2	0.59	2	0.61	2	MJ/ft^3
Electrical Efficiency		30	2	36	3	42	2	%
Thermal Efficiency		41	2	51	3	43	2	%
Reactor Heat Loss		Northern US	4	Northern US	4	Northern US	4	

Notes & References:

[1] Appleton and Rauch Williams 2017

[2] Wiser et al. 2010

[3] GHD 2016

[4] Hydromantis 2014

[5] Refers to the feedstock scenario

Table 3-27. Biogas Yield for AD Sensitivity (ft^3 biogas/ lb VS destroyed)

Feedstock	AD Low		AD Base		AD High	
	Value	Reference	Value	Reference	Value	Reference
Primary Sludge	12.0	3,1	15.0	1	43.5	2
Waste Activated Sludge	12.0	3,1	15.0	1	18.0	8,1
Septic Tank Waste	12.0	3,1	15.0	1	18.0	8,1
Slaughterhouse Waste	17.0	3,4,5	23.9	3,4,5	29.4	3,4,5
Cheese Waste	11.1	3,7	14.9	3,7	15.9	3,7
Winery Waste, Vinasse	10.0	6	14.0	6	17.3	6
Portable Toilet Waste	12.0	3,1	15.0	1	18.0	8,1

Notes & References:

[1] Hydromantis 2014

[2] GHD 2016,

[3] 20% reduction in biogas yield due to ammonia inhibition (IEA 2009)

[4] Braun and Wellinger 2003

[5] Luste and Luostarinen 2010

[6] Belhadj et al. 2013

[7] Rico et al. 2014

[8] 20% increase, represents general improvement in AD performance. Value is within the range of other referenced increases in biogas yield.

The quantity of biogas generated varies across both feedstock scenarios and AD operational scenarios. As shown in Table 3-28, biogas production varies by a factor of ten between the Base Feedstock-Low AD scenario and the High Feedstock-High AD scenarios.

Table 3-28. Biogas Production by Feedstock and AD Scenario

Feedstock Scenario	AD Scenario (m^3 biogas/m^3 treated water)		
	AD Low	AD Base	AD High
Base	0.13	0.21	0.53
Medium	0.22	0.38	0.74
High	0.40	0.71	1.17

Electricity production varies by a factor of 14 across the scenarios because electrical efficiency of CHP technology increases from the low to high AD scenarios on top of the differences in biogas production (Table 3-29). One hundred percent of electricity produced avoids electrical production via the local grid. Electricity produced by the CHP system is feed into the grid to satisfy local demand. Three perspectives on production and use of heat energy associated with the AD unit are presented in Table 3-30 through Table 3-32. Table 3-30 shows total potential heat production available when the full quantity of biogas is used in CHP. Only the portion of heat required for preheating sludge, AD unit heat, and building heat offsets natural gas production (Table 3-31) in the absence of further technology used to upgrade and distribute the heat product. The difference between heat values reflected in Table 3-30 and Table 3-31 is heat production that is currently not utilized, and therefore does not generate a credit for avoiding natural gas use. Seasonality of heat demand for both the AD and the facility itself are considered within the AD heat loss equation and utility records. Table 3-32 shows the quantity of natural gas that is required for AD operation and building heat on top of the heat provided via biogas combustion. The inclusion of AD at the WWTP is able to satisfy the heat energy requirement of the facility for the High Feedstock-Base AD scenario and all feedstock scenarios under the best-case (High AD) scenario for AD operational performance.

Table 3-29. Electricity Production from Biogas by Feedstock and AD Scenario

	AD Scenario (kwh/m^3 treated water)		
Feedstock Scenario	**AD Low**	**AD Base**	**AD High**
Base	0.21	0.45	1.34
Medium	0.35	0.80	1.87
High	0.64	1.50	2.95

Table 3-30. Potential Heat Production from Biogas by Feedstock and AD Scenario

	AD Scenario (MJ/m^3 treated water)		
Feedstock Scenario	**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 3-31. Modeled Avoided Heat from Natural Gas by Feedstock and AD Scenario

	AD Scenario (MJ/m^3 treated water)		
Feedstock Scenario	**AD Low**	**AD Base**	**AD High**
Base	1.01	2.24	3.01
Medium	1.74	4.05	3.30
High	3.14	4.45	3.59

Table 3-32. Required Heat from Natural Gas by Feedstock and AD Scenario

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

As shown in Table 3-33 and Table 3-34, methane emissions associated with the anaerobic digesters and CHP also increase from the Base Feedstock-Low AD to High Feedstock-High AD scenarios as it is assumed that 1 percent of biogas methane content is lost during each subsequent step.

Table 3-33. Methane Losses from Digester by Feedstock and AD Scenario

Feedstock Scenario	AD Scenario (kg CH4/m^3 treated water)		
	AD Low	AD Base	AD High
Base	5.00E-4	9.03E-4	2.43E-3
Medium	8.61E-4	1.63E-3	3.40E-3
High	1.56E-3	3.04E-3	5.38E-3

Table 3-34. Methane Losses from CHP by Feedstock and AD Scenario

Feedstock Scenario	AD Scenario (kg CH4/m^3 treated water)		
	AD Low	AD Base	AD High
Base	4.95E-4	8.94E-4	2.41E-3
Medium	8.52E-4	1.61E-3	3.37E-3
High	1.54E-3	3.01E-3	5.32E-3

3.3.10 Composting

Both the feedstock scenarios and AD operational parameters affect the quantity of sludge that is influent to the composting system. High operational performance of AD leads to less dry solids production as more of the feedstock is converted to biogas. The composting process is designed to hit a moisture content of approximately 55 percent and a C:N ratio of approximately 30:1. A standard C:N ratio of 12.7:1 is assumed for the digested biosolids (Maulini-Duran et al. 2013). Supplemental organic materials expected to be readily available have been used to adjust the C:N ratio and moisture content of biosolids to match these targets for the feedstock and AD operational scenarios. Loose dry leaves and newsprint serve as the feedstocks of choice in all the analyzed scenarios. Table 3-35 provides feedstock characteristics for a range of materials that are likely to be available in Bath, NY.

Table 3-35. Composting Supplemental Feedstock Characteristics

Feedstock	Moisture (% w/w)[1]	Carbon (% w/w)[1]	Nitrogen (% w/w)[1]	C:N[1]	Density (kg/m3)[2,3]
Leaves Loose, Dry	15%	49%	0.9%	54	388
Grass, Loose	82%	58%	3.4%	17	716
Newsprint	6%	63%	0.1%	625	425
Leaves, Fresh	38%	49%	0.9%	54	590
Food Waste	87%	39%	3.3%	12	866
Chipped Wood	40%	58%	0.1%	641	897

Notes & References:
[1] Richard 2014
[2] CWMI 1990
[3] Harris and Phillips 1986

Digested biosolids are transported by truck a short distance (0.8 km) from the wastewater treatment plant to the composting site. The baseline scenario uses a basic windrow composting system where the piles are turned regularly using a self-propelled compost turner. To be classified as Class A biosolids it is necessary to maintain compost pile temperatures at 55ºC for a minimum period of 15 days with 5 turnings during this time (U.S. EPA 1994). Elevated temperatures within the compost pile are due solely to microbial activity and decomposition. No external source of heat is provided to the compost pile. It is assumed that compost is left on site for a total period of 14 to 16 weeks for curing with an additional two turnings during this time (ROU 2006). Windrows are modeled to be 10 feet wide by 4.5 feet tall (Hao et al. 2001). In addition to regular pile turning, the use of bulking agents is employed to help provide adequate aeration (Malinska et al. 2013). Table 3-36 lists the supplemental organic feedstock mixtures used in the sensitivity analysis. Small quantities of water are required to adjust the initial moisture content of the compost pile, amounting to less than 150 m^3 per year (less than 0.1 percent of treated wastewater). Compost is assumed to be screened prior to being sold as an agricultural soil amendment. Electricity and diesel consumption factors of 0.13 kWh and 5.02 liters/ton of incoming material are used to account for grinding, windrow turning, and screening energy consumption (ROU 2006).

Table 3-36. Organic Compost Additions by Feedstock-AD Scenario (Metric Tons/Year)

Feedstock	Base-Low	Base-Base	Base-High	Medium-Low	Medium-Base	Medium-High	High-Low	High-Base	High-High
Leaves Loose, Dry	2,500	2,250	2,100	3,400	3,100	3,000	4,700	4,300	4,000
Newsprint	15	15	10	25	25	20	35	35	25

Opinions on the emission of methane and nitrous oxide during the composting process range widely within the published literature. Some authors indicate that no methane is released (ROU 2006), while other authors indicated that up to 2.5% of incoming carbon content in the composting feedstock can be liberated as methane during the composting process (SYLVIS 2011). The 2006 IPCC Guidelines for National GHG Inventories suggest a range of less than one percent to a few percent of incoming carbon content can be released as methane. The range is even wider for nitrous oxide with a potential emission range of 0.5 to 5 percent of initial nitrogen content being released as N_2O-N (IPCC 2006).

A range of GHG emissions from composting are available within the literature and given the many parameters that can vary within a study there is a large uncertainty as to which values most closely apply to our proposed management system. The above management practices are expected to minimize GHG production, but even a well-managed composting system can be expected to produce some emissions of methane and nitrous oxide. Given these considerations, three sets of emission factors are applied during the sensitivity analysis to test their effect on system level environmental impacts. Ammonia, non-methane volatile organic compounds (NMVOC), and carbon monoxide emissions are also included in the inventory. The emission of CO_2 is not included in the analysis as it is biogenic in origin, and therefore carbon neutral. Table 3-37 shows emission factors for the Base Feedstock-Base AD scenario used in the sensitivity analysis. A table detailing compost emission factors for all scenarios is included in Appendix A.

Emission factors vary across scenarios due to the variable quantity of carbon and nitrogen present in the compost mixtures as specified.

A sensitivity analysis is also employed to quantify the potential benefits and burdens associated with the use of an aerated static pile (ASP) composting system in place of the windrow system. The Biosolids Emissions Assessment Model (BEAM) composting emissions suggest that ASP systems can eliminate methane emissions if paired with an effective biofilter (SYLVIS 2011). The ASP biofilter reduces NH_3 and NMVOC emissions by 95% relative to a non-filtered system (Williams 2009). CO and N_2O emissions are the same as those from the windrowing system. Fuel and electricity use for the ASP is set at 2.5 L/wet metric ton and 90 kWh/dry metric ton (Brown et al. 2008).

Table 3-37. Low, Medium, and High Estimates of Potential Composting Emissions for the Base Feedstock-Base AD Scenario

Emission Species	Low Estimate			Medium Estimate			High Estimate		
	Value	Unit	Ref.	Value	Unit	Note	Value	Unit	Ref.
Methane (CH_4)	0.0016	kg CH_4/m^3	1	0.0070	kg CH_4/m^3	Average	0.0246	kg CH_4/m^3	2
Nitrous Oxide (N_2O)	0.0002	kg N_2O/m^3	1	0.0017	kg N_2O/m^3	Average	0.0029	kg N_2O/m^3	3
Ammonia (NH_3)	0.0006	kg NH_3/m^3	4	0.0033	kg NH_3/m^3	Average	0.0062	kg NH_3/m^3	3
Carbon Monoxide	0.0010	kg CO/m^3	1	0.0010	kg CO/m^3	Average	0.0010	kg CO/m^3	1
NMVOC	0.0002	kg NMVOC $/m^3$	4	0.0002	kg NMVO C/m^3	Average	0.0002	kg NMVO C/m^3	4

Notes & References:
[1] Hellmann 1997
[2] Hellebrand 1998
[3] Fukumoto et al. 2003
[4] Maulini-Duran et al. 2013

To best interpret the compost emission values, a description of each study considered is included in Table 3-38. Several variables emerge as being crucial to ultimate emissions from composting: (1) moisture content, (2) carbon and nitrogen content of incoming material, (3) C:N ratio, and (4) composting method. Moisture contents above 60 percent are expected to contribute to the formation of anaerobic zones, and therefore increased methane production (Fukumoto et al. 2003). Low C:N ratio is reported to increase the emission of volatile nitrogen compounds (Brown et al. 2009). Some authors have also reported that methane emissions tend to peak after pile turnings (Hao et al. 2001), however given the requirements for Class A biosolids, the number of pile turnings cannot be reduced without movement to a forced aeration system.

Table 3-38. Compost Emission Study Description

Citation	Study Description
Hellmann 1997	This study is conducted on a full-scale windrow composting system, which utilizes the organic fraction of municipal solid waste and yard waste as feedstocks. The initial moisture content is 60%, with an initial C:N ratio is 26.1:1
Hellebrand 1998	This study is conducted on a full-scale, trapezoidal compost heap, utilizing grass cuttings, soil, and manure as feedstocks. The initial moisture content is not reported, but was 70 percent for a concurrent lab-scale experiment that was run by the authors. Initial C:N ratio was 27:1.
Fukumoto et al. 2003	This study is conducted on a full-scale compost heap using forced aeration. Results from both small and large piles were developed. The feedstock for this study was pig manure amended with sawdust. Initial moisture content of both piles was 68 percent, and while the authors do not report their C:N ratio they note that the value tends to be low for livestock manure.
Maulini-Duran et al. 2013	This is a pilot-scale study testing emissions on forced aerated anaerobic digester sludge. Initial moisture content was 58 percent with an initial C:N ratio of 12.7:1.

The chemical composition of finished compost is used to determine environmental benefits and burdens of land application. Table 3-39 shows typical physical characteristics for finished compost that is produced from a mixture of biosolids and organic plant residues, such as those assumed in this study.

Table 3-39. Physical Characteristics of Finished Compost, Base Feedstock-Base AD Scenario

Parameter	Value	Unit
Moisture Content	45	% w/w
Organic Matter	55-75	% dry matter
Total N	2.9	% dry matter
Total P	0.5	% dry matter
Total K	0.2	% dry matter

Reference:
ROU 2006

3.3.11 Land Application of Composted Biosolids

Composted biosolids are assumed to be transported an average of 25 km to farm fields for application as a fertilizer and soil amendment. Compost is hauled in an 18-ton dump truck, which is assumed to be empty during the back-haul. Compost is loaded into a manure spreader and is surface applied to agricultural fields at the average U.S. application rate. It is assumed that 1.02 liters of diesel fuel are required per ton of compost (ROU 2006). In 2011, an average of 138 pounds of nutrient was applied per acre of agricultural land in the U.S. Nutrient content is calculated in terms of N, P_2O_5, and K_2O, which comprise 59, 20, and 21 percent of total nutrient additions respectively (U.S. EPA 2013). The ratio of elemental nitrogen, phosphorus, and potassium in finished compost is not the same as the typical agricultural application rate. Due to the greater relative presence of phosphorus in finished compost it is assumed that composted biosolids are applied at a rate necessary to achieve the average per acre phosphorus addition of 27.4 lbs P_2O_5/acre/year. If application rates were based on nitrogen or potassium content the corresponding additions of phosphorus would be greater than what is required.

Estimates of avoided fertilizer costs are based on N, P_2O_5, and K_2O in the form of urea, triple phosphate, and potassium sulfate. Inorganic fertilizers tend to have greater plant availability than do organic fertilizers with equivalent nutrient contents. A fertilizer replacement value of 73 percent is assumed for this study when calculating the avoided quantity of mineral fertilizer to produce a conservative estimate of environmental benefit. This value was demonstrated for digested manure over the course of four years (Smith 2007). This study applies the same replacement value for both phosphorus and potassium.

Typical agricultural emissions such as nitrous oxide, ammonia, nitrate, soluble phosphorus, and sediment bound phosphorus have been calculated based on a conservative estimate of the potential net change in agricultural emissions that could occur by replacing inorganic fertilizers with organic alternatives. As with composting emissions, field emissions of nutrients can vary over a wide range depending upon application method and timing, soil type, and a variety of climatic factors. The methods used to estimate field emissions are based on nutrient application rates, and assuming equivalent emissions between organic and inorganic fertilizer types per unit mass of nutrient land applied, this could lead to an increase in field emission of nutrients due to the higher application rate of organic nutrients implied by the 73 percent fertilizer replacement value cited above. A summary of agricultural emission rates, given the assumed application rates are presented in Table 3-40. Impacts based on values calculated in this report should be viewed as a reasonable estimate, however significant variability in these values is expected in practice.

Table 3-40. Emission Rates at National Average Application Rate

Emission Species	Compartment	Emission[1]	Units
Ammonia	air	16.5%	of applied N
Nitrous Oxide	air	1.17%	of applied N
Nitrate	water	10.5%	of applied N
P, sediment	water	10.1%	of applied P
P, soluble	water	3.20%	of applied P
P, soluble	groundwater	0.32%	of applied P
P, sediment	air	2.40%	of applied P

Note:
[1] Emissions are calculated as a function of application rate for nitrate and ammonia.

3.3.12 Effluent Release

One of the goals of the upgraded wastewater treatment system is to produce wastewater that can be put to a variety of reuse applications such as for landscape irrigation. A local golf course has expressed interest in reusing up to 13 million gallons of treated effluent annually for irrigation. It is assumed that this reuse application avoids the need to treat an equivalent quantity of water to fill that need. An estimate of pumping energy to the golf course in addition to the operation of an effluent sampler is included in the study (Table 3-41). No standard set of guidelines specifying target effluent quality for specific reuse applications are available for New York (CDM Smith 2012). However, water reuse projects have occurred within NY State and it is assumed that they are approved on an individual basis.

Table 3-41. Effluent Release - Annual Equipment Electricity Use

Equipment	HP	A	V	Run Time (hr/yr)	Annual Electricity Use (kWh)
Sampler	0.50	0.90	115	1,250	129
Pump to Reuse Location	20.0	27.5	460	3,600	45,500

Nitrous oxide emissions from receiving streams are calculated based on the IPCC guideline that 0.005 kg of N_2O-N are emitted per kg of nitrogen discharged to the aquatic environment. Details of that calculation are presented in the Appendix.

3.4 LCI Limitations & Data Quality

LCI information that falls outside of the system boundary is introduced and discussed in Section 2.2. More general LCI limitations that readers should understand when interpreting the data and findings are as follows:

- **Transferability of Results.** While this study is intended to inform decision-making for WWTPs of similar size and design, the data presented here relates to a specific U.S. WWTP in Bath, NY. Further work is recommended to understand the variability of key parameters across different conditions, system sizes, and configurations.
- **Representativeness of Background Data.** Background processes are representative of either U.S. average data (in the case of data from U.S. EPA LCI or U.S. LCI) or European average (in the case of Ecoinvent) data. In some cases, European Ecoinvent processes were used to represent U.S. inputs to the model (e.g., for chemical inputs) due to lack of available representative U.S. processes for these inputs. The background data, however, met the criteria listed in the project quality assurance project plan (QAPP) for completeness, representativeness, accuracy, and reliability.
- **Data Accuracy and Uncertainty.** In a complex study with literally thousands of numeric entries, the accuracy of the data and how it affects conclusions is truly a difficult subject, and one that does not lend itself to standard error analysis techniques. The reader should keep in mind the uncertainty associated with LCI models when interpreting the results. Comparative conclusions should not be drawn based on small differences in impact results.

4. LCCA METHODOLOGY

This section presents the methodology used to develop life cycle costs for the upgraded WWTP. Forward looking life cycle cost estimates of the legacy system are not appropriate as this system will be superseded in the future. Cost data has been collected and adjusted from several sources as described in Section 4.1. Basic LCCA methods are described in Section 4.3. LCCA results are presented according to three cost scenarios, which cover a reasonable range regarding potential input parameters. Parameter values for the low cost, base, and high cost scenarios are listed in Section 4.3.7.

4.1 LCCA Data Sources

Cost data were obtained from the following sources:

- Primary budget data for the legacy WWTP, budget year 2013-2014.
- GHD Engineering Life Cycle Cost Analysis of Preliminary and Primary Treatment Processes (GHD 2016)
- CAPDETWorks Version 3.0 (Hydromantis 2014)
- RSMeans Building Construction Cost Data (RSMeans 2016)
- Personal communication with BEGWS personnel

4.2 Unit Process Costs

The following sections describes data sources and cost estimation assumptions for individual unit processes.

4.2.1 Collection System

Only operational costs associated with electricity consumption are considered for the collection system.

4.2.2 Chemically Enhanced Primary Clarification

GHD Engineering carried out a LCCA on the costs of installing chemically enhanced primary clarification at the Bath wastewater treatment facility. Cost estimates from that study are used in this analysis. The GHD LCCA was carried out for process upgrades taking place for the preliminary and primary treatment processes (GHD 2016). The GHD analysis uses an average annual flow rate of 0.67 MGD, which necessitates an update of annual operating costs associated with chemical and electricity use. It is assumed that annual maintenance and periodic equipment replacement costs remain the same regardless of flowrate. The equipment specified by GHD is designed to handle the 1 MGD flow rate specified in this analysis.

4.2.3 Anoxic-Swing Tank

The anoxic and swing tank repurposes two cells of the existing aerobic digester. These units require the installation of new aeration devices and mixing units. The direct and indirect costs associated with unit renovation, as described in Section 4.3, are applied to this unit.

4.2.4 Aeration Basins

The three aeration basins will continue to function much as they have during the operation of the legacy system, with the addition of nitrate recycle pumping. As the aeration basins have been in use for a considerable period, it is assumed that all major equipment including the clarifier drive and centrifugal blowers will require replacement during the initial renovation as they are reaching the end of their useful lifespan. Equipment costs have been approximated using estimates from BEGWS personnel or the RSMeans database. Direct and indirect cost assumptions associated with unit renovation are applied as discussed in Sections 4.3.3 and 4.3.4.

4.2.5 Sludge Receiving and Holding

Sludge receiving and holding consists of a mixture of new construction and repurposed units. Two of the existing aerobic digester cells are to be repurposed for temporary storage of incoming high strength organic waste. A new sludge pumping system will be required, as well as the replacement of the existing aeration system for use during temporary storage. The cost of transporting septage and high strength organic waste to the wastewater treatment facility is borne by the waste generator, and is excluded from the analysis. Direct and indirect cost assumptions associated with unit renovation are applied as discussed in Section 4.3.

4.2.6 Gravity Belt Thickening

The GBT is a new unit. Cost estimates for a rotary drum thickener were included in the GHD analysis, and in the absence of better information and remaining uncertainty regarding the type of unit that will ultimately be implemented, these costs have been used to approximate the thickening step. GHD's assumptions regarding direct and indirect costs are included for this unit.

4.2.7 Blend Tank

The existing gravity thickening tank is repurposed to serve as a blend tank for the mixture of high strength organic waste, WAS, and primary sludge prior to AD. The addition of a mixing unit and sludge pump are required. Direct and indirect cost assumptions associated with unit renovation are applied.

4.2.8 Belt Filter Press

The BFP is an existing unit that is housed in the control building. Given the age of this unit it is assumed that all main pieces of equipment are replaced or refurbished during the plants initial renovation and construction period. Indirect costs associated with engineering design and profit are excluded for this unit, which is considered a material replacement as opposed to a renovation or new construction.

4.2.9 Anaerobic Digestion

The costs of unit construction, mechanical equipment, additional personnel, and all other associated direct and indirect costs for AD have been calculated using CAPDETWorks™ engineering costing software. The full suite of direct and indirect costs as listed in Table 4-1 and Table 4-2 are included. Revenue from waste tipping fees, electricity production, and avoided natural gas purchasing are calculated based on LCI input values associated with each Feedstock-AD scenario.

4.2.10 Combined Heat and Power

The costs of unit construction and maintenance were developed based on an EPA report titled *Evaluation of Combined Heat and Power Technologies for Wastewater Facilities* (Wiser 2010). Cost of the engine itself accounts for 14 percent of total costs with gas cleaning, engineering, facility, and installation costs contributing the remainder of the cost. No additional direct and indirect costs apply.

4.2.11 Composting

The composting facility requires the purchase and maintenance of a material grinder, self-propelled pile turner, front end loader, and material screen. Taxes, housing, insurance, and an estimate of salvage value is included for each piece of equipment. Diesel and electricity consumption costs are also included. It is assumed that one full personnel position is required to manage the composting facility with an inclusive annual cost of $100,000. The effect of compost sale price on life cycle costs is examined in the low, base, and high cost scenarios in the results section. No further costs associated with land application are assumed. The facility has an area adjacent to the treatment plant that can be used for the composting facility, which is assumed to be sufficient. If additional land purchases are required these costs would need to be added to the calculation of life cycle costs.

4.3 LCCA Methods

The LCCA, applied to the upgraded system, uses a net present value (NPV) method to consider capital costs and annual or otherwise periodic costs associated with operation, maintenance, and material replacement.

Upgrades to the legacy WWTP include the installation of new unit processes in the case of both AD and chemically enhanced primary clarification. The installation of new units is assumed to incur all costs typically associated with new construction. The upgraded MLE secondary treatment process and other process upgrades such as the conversion of the existing GBT to a sludge blending tank constitute upgrades to existing infrastructure, which eliminates some costs while modifying others. This necessitates the application of different costing methods on a unit-by-unit basis as described in Sections 4.2.1 through 4.2.11. General costing methods used are described below.

4.3.1 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 WWTP. 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 are determined using cost factors based on purchased equipment pricing. Total capital costs are calculated using Equation 9.

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

Equation 9

where:

Total Capital Cost (2014 $) = Total capital costs

Purchased Equipment Costs (2014 $) = Costs to purchase the equipment for the WWTP

Direct Costs (2014 $) = Costs incurred as a direct result of installing the WWTP

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

4.3.2 Purchased Equipment Costs

It was necessary to seek outside sources of cost information for pieces of equipment required in the secondary treatment plant upgrade as well as those pieces of equipment which will require replacement within the 30-year horizon of the LCCA. Sources for this information are described in Section 4.2.

A base escalation factor of 3 percent is applied to all purchased inputs. Escalation factor describes an estimated increase in the price of purchased inputs beyond the rate of inflation. Escalation factors are applied using Equation 10. Escalation factors for various facility costs are varied within the LCCA scenarios as described in Section 4.3.7.

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

Equation 10

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

4.3.3 Direct Costs

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

Table 4-1 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 is 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 is applied for the estimated cost of labor for equipment installation.

When a piece of equipment is replaced it is 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 is 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 are assumed not to apply for plant renovations and equipment replacement. Equation 11 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 11

where:

Direct Cost Factor (%) = Direct cost factor for each direct cost element, see Table 4-1 below

Level 1 Purchased Equipment Cost (2014 $) = Equipment price paid by the WWTP

Level 1 Direct Cost (2014 $) = Direct cost in excess of purchased equipment price

Table 4-1. Direct Cost Factors

Direct Cost Elements	Direct Cost Factor (% of Purchased Equipment Cost)
Mobilization	5%
Site Preparation	7%
Site Electrical	15%
Yard Piping	10%
Instrumentation and Control	8%
Lab and Administration Building	12%

Reference:
CAPDETWorks™

4.3.4 Indirect Costs

Indirect costs typically include land costs, legal costs, engineering design fee, inspection, contingency, technical costs, interest during construction, and profit. Table 4-2 lists indirect cost factors as reported by CAPDETWorks™ engineering cost estimation software. Land costs and interest during construction do not apply to this project and are excluded from the analysis. The upgraded facility will be located completely within the boundaries of lands currently held by BEGWS. The upgrades are set to be funded through a combination of grants and zero interest loans made available by New York State. Total indirect costs are the sum of all individual indirect costs as calculated in Equation 12. Indirect cost factors are applied to the sum of purchase price and direct costs. Indirect costs are assumed to apply both to the construction of new units and major renovation and upgrade projects. No indirect costs are assumed to be associated with material replacement.

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

Equation 12

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 4-2 below

Purchased Equipment Cost = Total purchased equipment cost

Direct Cost (2014 $) = Total direct costs

Table 4-2. Indirect Cost Factors

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%

Reference:
CAPDETWorks™

4.3.5 Total Annual Costs

The total annual costs include the operation and maintenance labor, materials, chemicals, and energy. Total annual costs are calculated using Equation 13.

$$\text{Total Annual Costs} = \text{Operation Costs} + \text{Replacement Labor Costs} + \text{Materials Costs} + \text{Chemical Costs} + \text{Energy Costs}$$

Equation 13

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 WWTP 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 WWTP lifespan

Materials Costs (2014 \$/year) = Materials costs for operation and maintenance of the WWTP for a year, including equipment replacement

Chemical Costs (2014 \$/year) = Chemical costs for chemicals required for WWTP operation (e.g., PAC, polymer) for a year

Energy Costs (2014 \$/year) = Electricity costs to run the WWTP 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 is assumed to be carried out by BEGWS personnel, and as such does not require additional labor costs beyond their annual salary and benefits. Labor for equipment replacement is assumed to require contractor labor. Maintenance costs per unit, as calculated by GHD, are the primary source of maintenance cost data used in this analysis. GHD's original maintenance costs include labor. This analysis uses actual plant labor costs as the source of maintenance labor costs, and therefore only 50 percent of the original GHD maintenance costs are included to approximate the material portion of maintenance costs.

4.3.6 Net Present Value

NPV for the upgraded system is calculated using Equation 14.

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

Equation 14

where:

NPV (2014 \$) = Net present value of all costs and revenues necessary to construct and operate the WWTP

Cost_x = Cost in future year x

i (%) = Real discount rate

x = number of years in the future

A real discount rate of 5 percent is used in the base cost scenario. The planning period of the LCCA is 30 years.

A standard payback period is calculated using Equation 15 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.

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

Equation 15

4.3.7 LCCA Cost Assumption Scenarios

Many assumptions are required to perform an LCCA. These assumed parameter values can have a significant effect on total life cycle costs or the cost performance of any particular unit within the WWTP. Table 4-3 documents assumptions that comprise the low, base, and high cost scenarios covered in the sensitivity analysis. The low cost scenario corresponds to parameter values that will yield a lower system NPV than the base cost scenario, while the high cost scenario corresponds to parameter values that lead to a high estimate of system NPV. The low, base and high cost scenarios define an envelope of expected NPV estimates for the upgraded treatment system.

The study period remains consistent across scenarios, while the real discount rate varies between 3 and 6 percent between the high cost and low cost scenarios. A lower discount rate indicates that a higher value is placed on money in the future, which increases the contribution of future operational costs and material replacement to NPV. The interest rate is assumed to be zero percent across all scenarios given the funding sources that are available for this project. The low cost scenario explores the effect of increased electricity rate, increased disposal fee for high strength organic waste, and a rise in the price of natural gas on plant NPV. The low cost scenario also assumes that a market for all the potential biogas heat output can be found. The base and high cost scenario assume that avoided electricity is valued at the current electricity rate paid by BEGWS, $0.051. In the high cost scenario, diesel fuel costs are assumed to rise to $3.50 per gallon. In both the base and high cost scenarios, only the portion of biogas heat that can be used within the facility is considered to avoid natural gas production. The remainder of biogas heat is wasted until a suitable market can be found, and generates no revenue or avoided value. The fee generated per yard of finished compost increases from 0, to 5, to 10 dollars per cubic yard between the high and low cost scenarios. More compost and biogas revenue are generated in the low cost scenario. The lower section of Table 4-3 lists the assumed escalation factors for various annual and periodic costs.

Table 4-3. 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 (%)[1]	0%	0%	0%
Electricity Cost ($/kWh)[1]	0.077	0.051	0.077
Electricity Revenue ($/kWh)	0.077	0.051	0.051
Diesel Cost ($/gal)	2.00	2.70	3.50
Natural Gas Cost ($/MCF)	4.50	3.84	3.84
Septage Disposal Fee ($/gallon)	0.010	7.00E-3	7.00E-3
High Strength Organic Waste ($/gallon)[2]	0.150	0.060	0.030
Compost Revenue ($/yd^3)[3]	10.0	5.00	-
Landfill Tipping Fee ($/wet ton)[1]	50.8	50.8	50.8
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%

References & Notes:
[1] GHD 2016
[2] Appleton and Rauch-Williams 2017, fee received by WWTP
[3] Williams 2009

5. LCA AND LCCA RESULTS BY TREATMENT STAGE

This section presents comparative LCA results for the legacy and upgraded wastewater treatment systems by impact category.

5.1 Guide to Results Interpretation

Results for this project were calculated for all combinations of the following parameters. Baseline results, presented in Section 5, represent a subset of these parameters, with the full range of results being presented within the sensitivity and scenario analysis of Section 6. While the full range of results is presented within the report, not all possible parameter results' combinations are shown.

Model Parameters varied within the Analysis:

- ***Feedstock Scenarios*** **–** Results are available for the low, base and high feedstock scenarios for the upgraded WWTP, which demonstrates the effect of accepting additional high strength organic wastes on impact potential of the treatment system. Feedstock quantities associated with the scenarios are presented in Table 3-25.
- ***Anaerobic Digestion*** **–** Results are calculated for a set of parameters defining low, base, and high operational performance of the AD units, as presented in Table 3-26.
- ***Composting Method*** **–** Results are calculated assuming either a windrow or ASP composting system. The windrow system is presented as the baseline scenario in Section 5
- ***Landfill Methane Capture System*** - The performance of the methane capture system at the landfill in the Bath region of NY is significantly higher than the national average landfill methane capture system. Results have been calculated for both systems and are presented in Section 6.1. The Bath landfill values are presented as baseline results in Section 5.
- ***Compost Bulking Material*** - The sensitivity analysis explores the effect of including or excluding compost bulking material from the calculation of cumulative potential impacts. Calculation of results including the impact associated with bulking material is presented as the baseline scenario.

The above model parameters are varied over the ranges defined in Section 3 to accurately convey the potential variability in impact results that can be realized by wastewater treatment systems of the types considered in this analysis. The trends observed and the key variables that drive environmental impacts, as described in Sections 5 and 6, can be used by facilities or during the design process to estimate potential impacts and areas for potential improvement by choosing results associated with the parameter combinations that most closely match those of their specific system of interest.

Throughout this section, results calculated at the unit process level have been aggregated by treatment stage, as shown in Table 2-6. Eutrophication potential, global warming potential, and cumulative energy demand also include impact results aggregated according to the process categories listed in Table 2-7. Results presented in Section 5 refer to the base case scenario for feedstock consumption, anaerobic digester operational performance, and composting and landfill emissions. Sensitivity analyses for these scenarios are conducted in Section 6.

The relationship between gross and net impact is presented in Equation 16. Impact contributions from individual treatment stages or processes are calculated relative to gross environmental impact results. This method is preferred such that impact contributions do not exceed 100 percent, and the percent reduction in impact attributable to avoided products is calculated relative to the gross impact that avoided products serve to reduce. This generalized calculation is presented in Equation 17, and an example calculation specific to avoided product contribution for cumulative energy demand of the upgraded WWTP is presented in Equation 18. Percent contributions calculated based on net impact yield higher values, which can exceed 100 percent when environmental credits (i.e., avoided products), are associated with the investigated system. The two calculation methods yield identical values if no environmental credits are associated with an impact category, which is typically not the case in this analysis.

$$\text{Net Impact} = \text{Gross Impact} + (-\text{Avoided Product Credit})$$

Equation 16

$$\text{Process Impact Contribution or Reduction} = \frac{\text{process impact}}{\text{gross impact}}$$

Equation 17

$$\text{Upgraded WWTP CED Avoided Product Impact Reduction} = \frac{\text{avoided product credit}}{\text{gross CED}} = \frac{-6.96\ \text{MJ}}{16.5\ \text{MJ}}$$
$$= -42\ \text{Percent Reduction in Gross CED}$$

Equation 18

Changes in impact between the legacy and upgraded system are calculated relative to the legacy system using Equation 19.

$$\text{Relative Change} = \frac{\text{Upgraded Impact} - \text{Legacy Impact}}{\text{Legacy Impact}}$$

Equation 19

Baseline results for both the legacy and upgraded WWTP include the environmental burdens attributable to 1 MGD of municipal wastewater. The legacy and upgraded WWTPs accept an additional 8,000 and 16,000 GPD of septic and portable toilet waste, respectively. The additional burdens of treating this waste are allocated equally to the 1 MGD of municipal wastewater. No high strength organic waste is associated with either system in the baseline scenario.

5.2 Eutrophication Potential

Given the goal of improving nutrient removal performance, eutrophication is a critical metric for measuring the comparative environmental performance of the legacy and upgraded wastewater treatment systems. Figure 5-1 presents net eutrophication potential results grouped by treatment stage, while Figure 5-2 presents impact results according to process category. Total values in both figures refer to net impact results. Please refer to Table 2-6 for a reminder of which treatment processes contribute to each treatment stage.

Eutrophication impacts are dominated by effluent release for both the legacy and the upgraded system. Effluent release contributes 94 percent to eutrophication impact for the legacy system, and 71 percent to the upgraded system. Nitrogen deposition resulting from fossil fuel combustion for electricity production and emissions to water resulting from land application of composted biosolids are the other main contributors to eutrophication impacts. Additional nutrient removal accomplished with the introduction of the upgraded MLE secondary treatment unit leads to a 37 percent reduction in net eutrophication potential impact per cubic meter of wastewater treated. Avoided fertilizer production from land application of biosolids and avoided energy production from AD biogas recovery reduce gross eutrophication impact for the upgraded treatment system by 2 and 3 percent, respectively. This study assumes no leaching of nutrients to surface or groundwater from the composting facility.

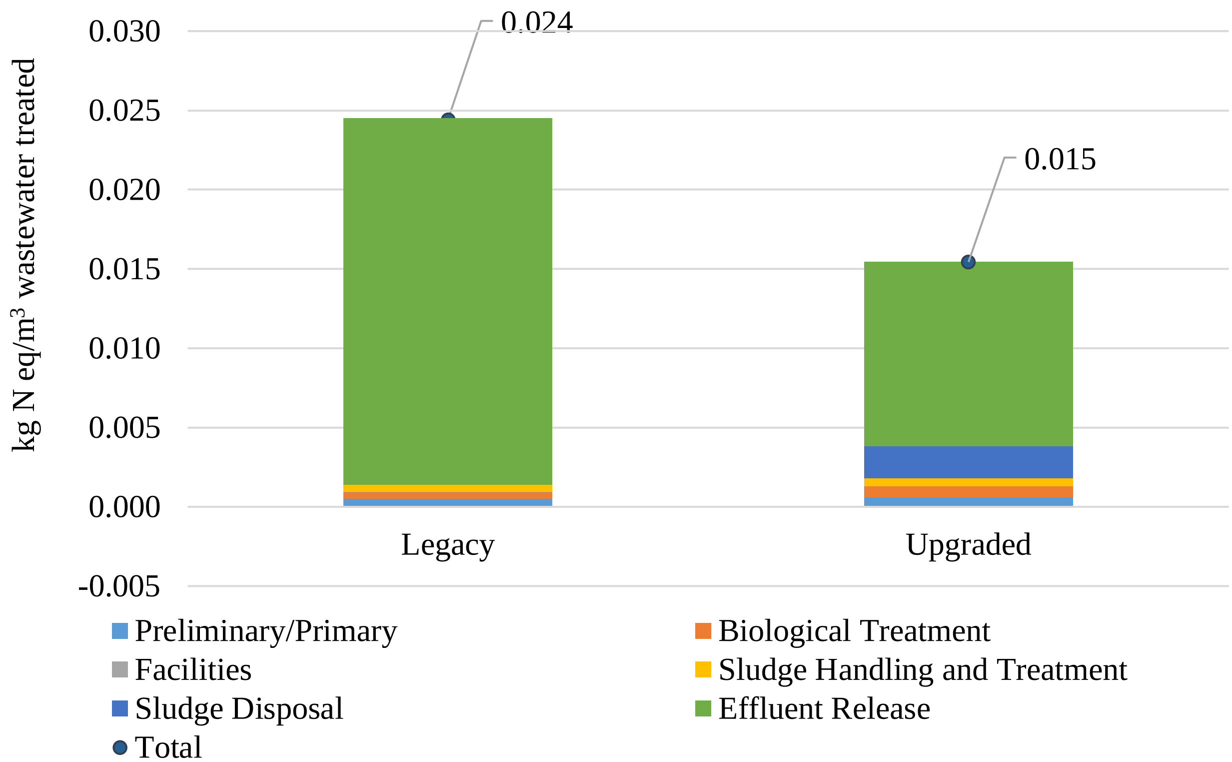

Figure 5-1. Eutrophication potential results by treatment stage.

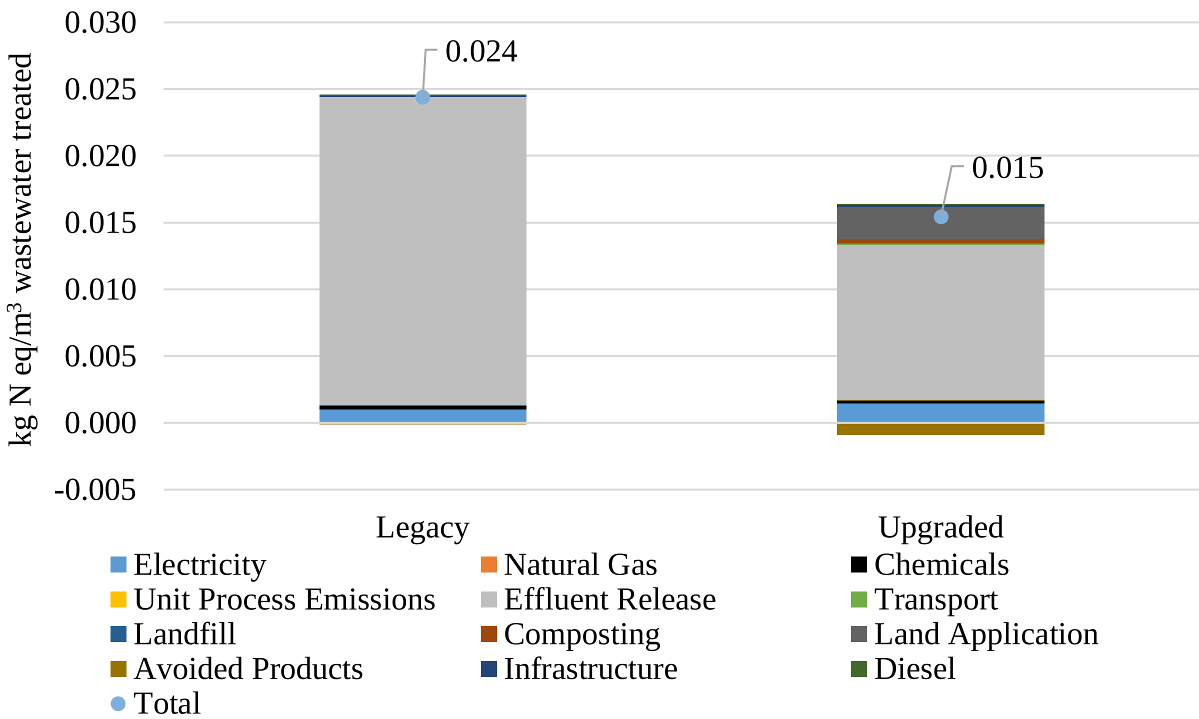

Figure 5-2. Eutrophication potential results by process category.

5.3 <u>Cumulative Energy Demand</u>

Figure 5-3 and Figure 5-4 present cumulative energy demand results grouped according to treatment stage and by process contribution, respectively. Net cumulative energy demand is 5 percent greater for the upgraded system. Electricity use accounts for 66 and 58 percent of cumulative energy demand for the legacy and upgraded WWTPs. Avoided energy and fertilizer production from AD biogas recovery and land application reduce gross cumulative energy demand for the upgraded system by 42 percent. Hauling of incoming high strength organic waste and of digested solids to composting contributes 21 percent of cumulative energy demand for the upgraded system, due to the large water content of these wastes and the associated trucking weight. Natural gas use to provide building and AD unit heat requirements contribute 8 and 12 percent of cumulative energy demand for the legacy and upgraded WWTPs, respectively. Chemical production contributes 12 and 5 percent of cumulative energy demand for the legacy and upgraded WWTPs, respectively.

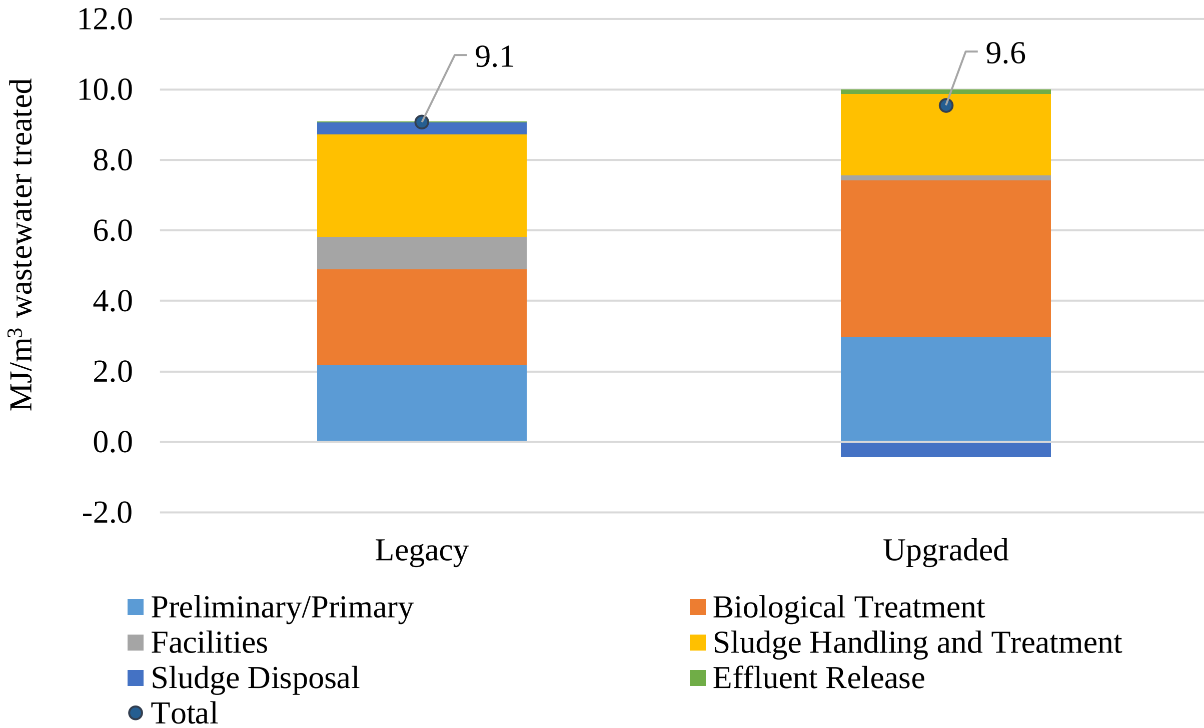

Figure 5-3. Cumulative energy demand results by treatment stage.

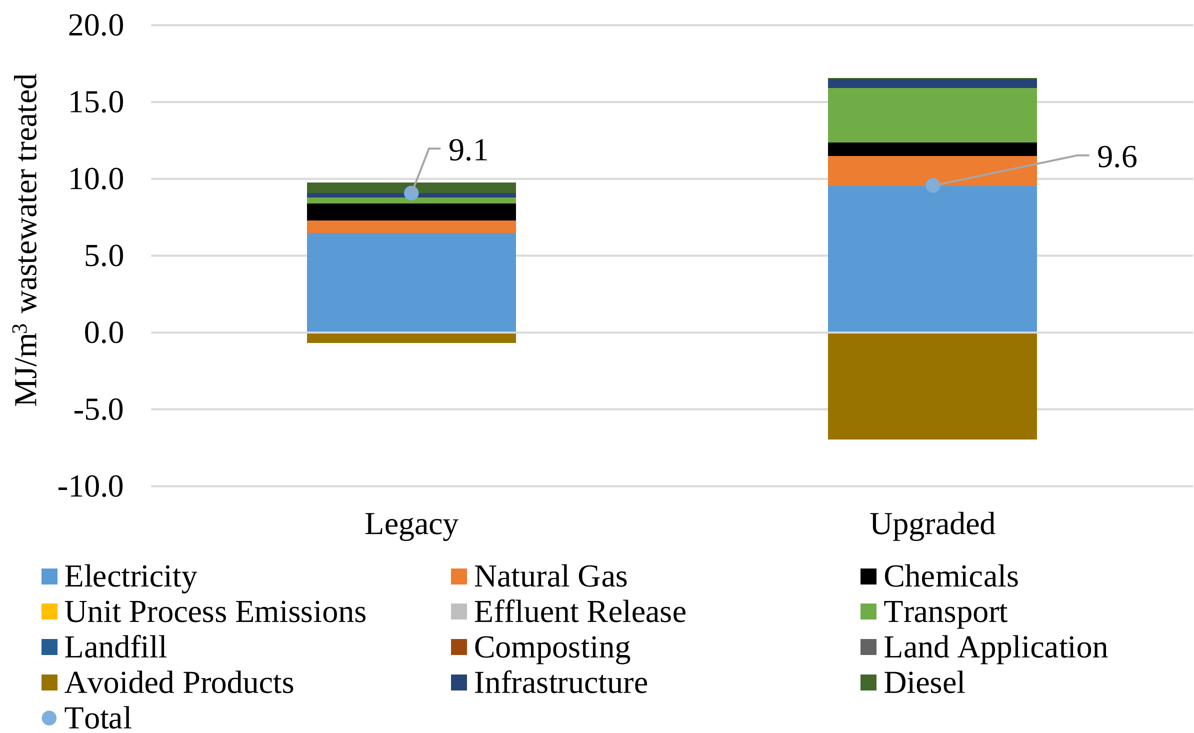

Figure 5-4. Cumulative energy demand results by process category.

5.4 Global Warming Potential

Figure 5-5 presents the global warming potential results grouped according to treatment stage, while Figure 5-6 presents results according to process category. For the base scenario, the upgraded WWTP demonstrates a net global warming potential that is approximately 25 percent greater than that realized by the legacy system. This is despite a 21 percent reduction in gross impact due to avoided electricity, natural gas, and fertilizer consumption from biogas recovery and agricultural reuse of compost. The environmental credit for these avoided products is fully visible in Figure 5-6. The figure also shows the carbon credit that results from carbon storage in soil due to land application of compost that reduces gross global warming potential by 24 percent. Approximately 42 percent of impact is due to composting emissions of methane and nitrous oxide. In the base scenario, 1,500 and 54 metric tons of elemental carbon and nitrogen, respectively, enter the composting facility each year either within the digested sludge or in the supplemental organic materials. The base scenario emission factors assume that 0.82 and 2.7 percent of incoming carbon and nitrogen are lost as methane and nitrous oxide, respectively, which is in the middle of the expected range as reported by the IPCC (2006). Emissions of methane and nitrous oxide from the landfill contribute 17 percent of impact for the legacy system. Due to uncertainty concerning the magnitude of these emissions, and their importance to the overall environmental impact of the system, low and high emissions scenarios are analyzed in the sensitivity analysis to explore the effect on environmental impacts per cubic meter of wastewater.

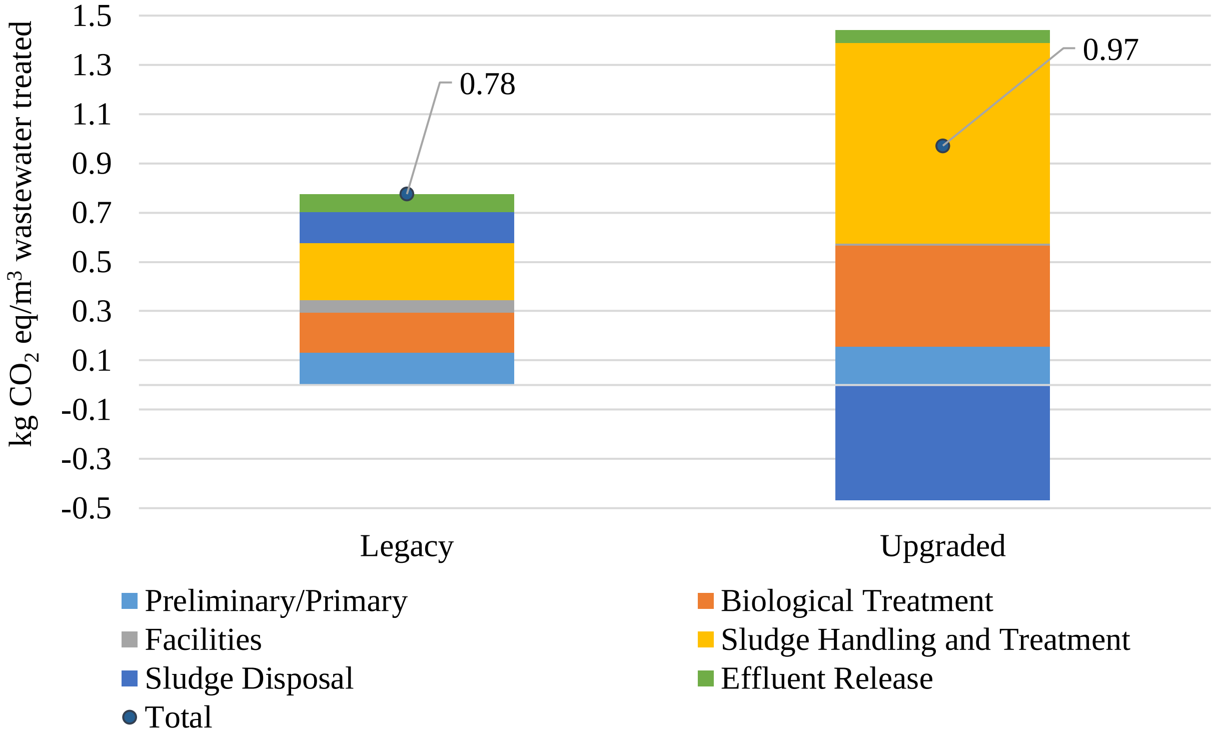

Figure 5-5. Global warming potential results by treatment stage.

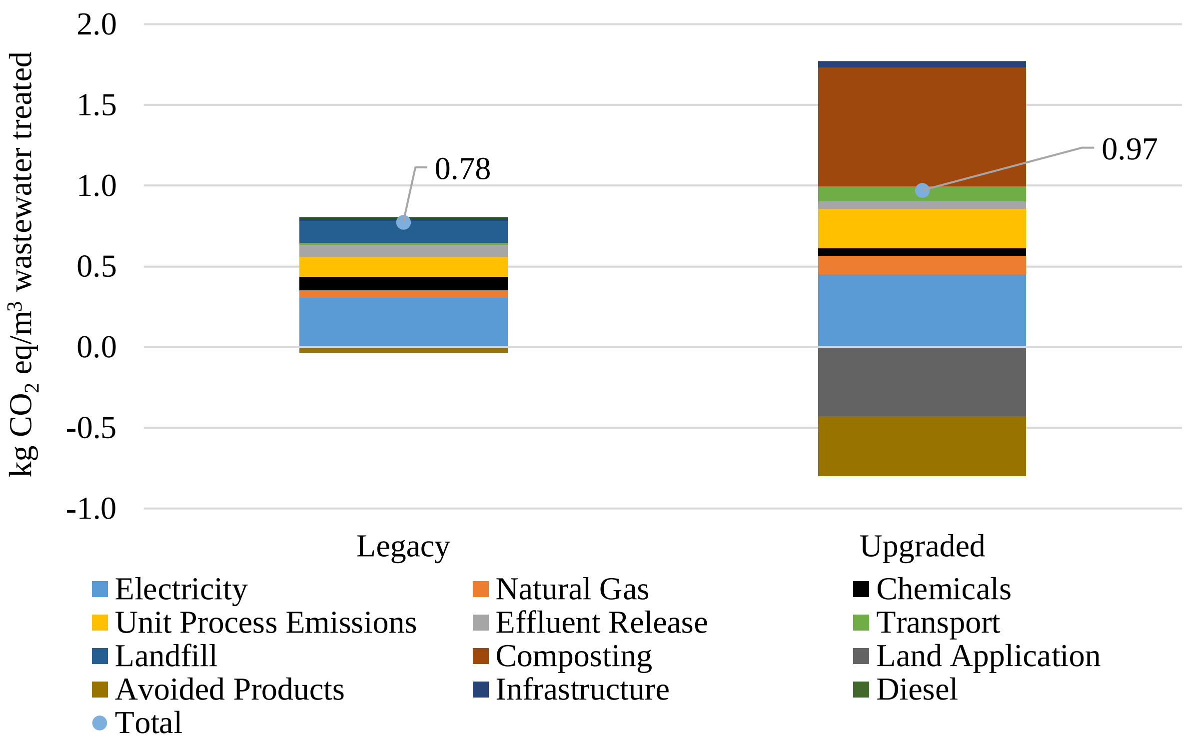

Figure 5-6. Global warming potential results by process category.

Other process based GHG emissions contribute 15 and 14 percent of impact for the legacy and upgraded systems, respectively. Electricity use at the WWTP contributes 38 and 26 percent of global warming potential impact for the legacy and upgraded systems. The Bath region is serviced by a relatively clean electricity grid, with 65 percent of their energy coming from hydropower, nuclear, biomass, and other renewables. Thirty-one percent of the regions electricity comes from natural gas, and only 5.5 percent is from coal. Chemical production contributes 10 percent of global warming potential impact for the legacy system, and only 3 percent of impact for the upgraded plant despite the addition of chemically enhance primary treatment. Hauling of high strength organic waste contributes 5 percent of global warming potential impact for the upgraded system, and both plants see a 2 percent contribution from infrastructure.

5.5 Acidification Potential

Figure 5-7 presents the impact assessment results for acidification potential grouped according to treatment stage. Net acidification potential impacts are approximately 30 percent greater for the upgraded system. Acidification impact is dominated by electricity production, particularly the combustion of coal and biomass. Avoided electricity production from the AD contributes a 14 percent reduction in gross acidification impact for the upgraded plant bringing results for the two systems closer together. Avoided fertilizer production contributes an additional reduction in acidification potential impacts; however, this reduction is less than the increased acidification potential impact of ammonia emissions from land application of the compost.

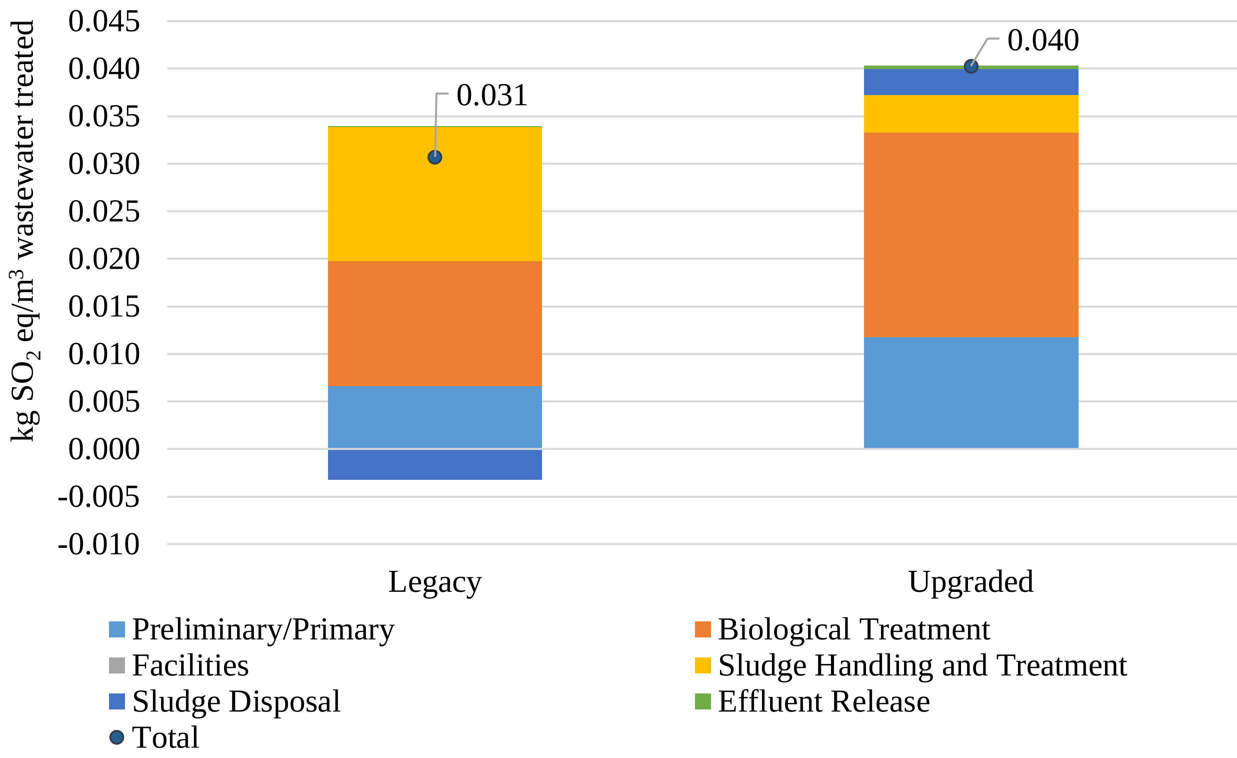

Figure 5-7. Acidification potential results by treatment stage.

5.6 Fossil Depletion Potential

Figure 5-8 presents fossil depletion results grouped according to treatment stage. Net fossil depletion potential is 9 percent greater for the upgraded system. Electricity use contributes over 50 percent of impact for the upgraded system, and over 60 percent for the legacy system. Avoided electricity production from biogas recovery provides an 18 percent reduction in gross fossil depletion potential impact for the upgraded treatment plant with a further 20 percent reduction from avoided natural gas production. Diesel fuel use to haul 16,000 GPD of incoming septage waste contributes 22 percent of impact for the upgraded system. PAC production contributes nearly 10 percent of impact for the legacy system. Trucking and equipment use for sludge landfilling accounts for approximately 13 percent of acidification potential for the legacy system.

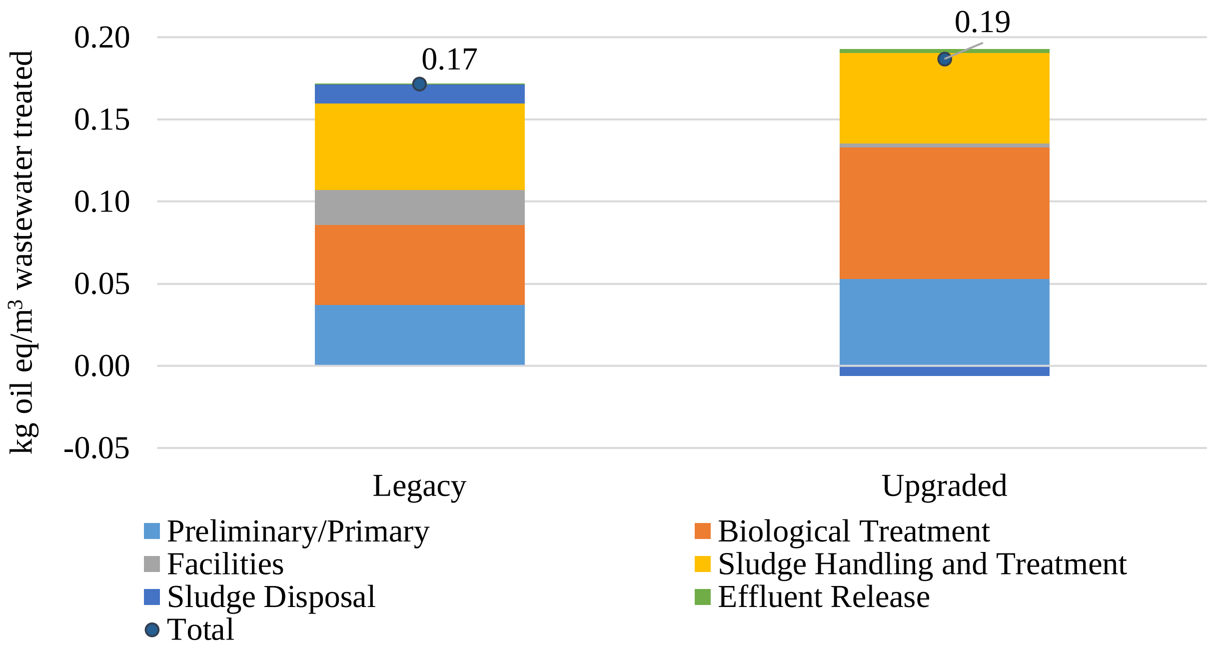

Figure 5-8. Fossil depletion potential results by treatment stage.

5.7 Smog Formation Potential

Figure 5-9 presents net smog formation potential results grouped according to treatment stage. The impact results for net smog formation potential are within 7 percent of one another between the legacy and the upgraded treatment systems. Electricity consumption contributes over 95 percent of assessed impact for both systems. Avoided energy production associated with biogas recovery serves to reduce gross smog formation potential impact of the upgraded system by 33 percent. Truck transport of incoming septage contributes approximately 2 percent of the impact result for the upgraded system. PAC production contributes between 1 and 2 percent of smog formation potential impact for the legacy system.

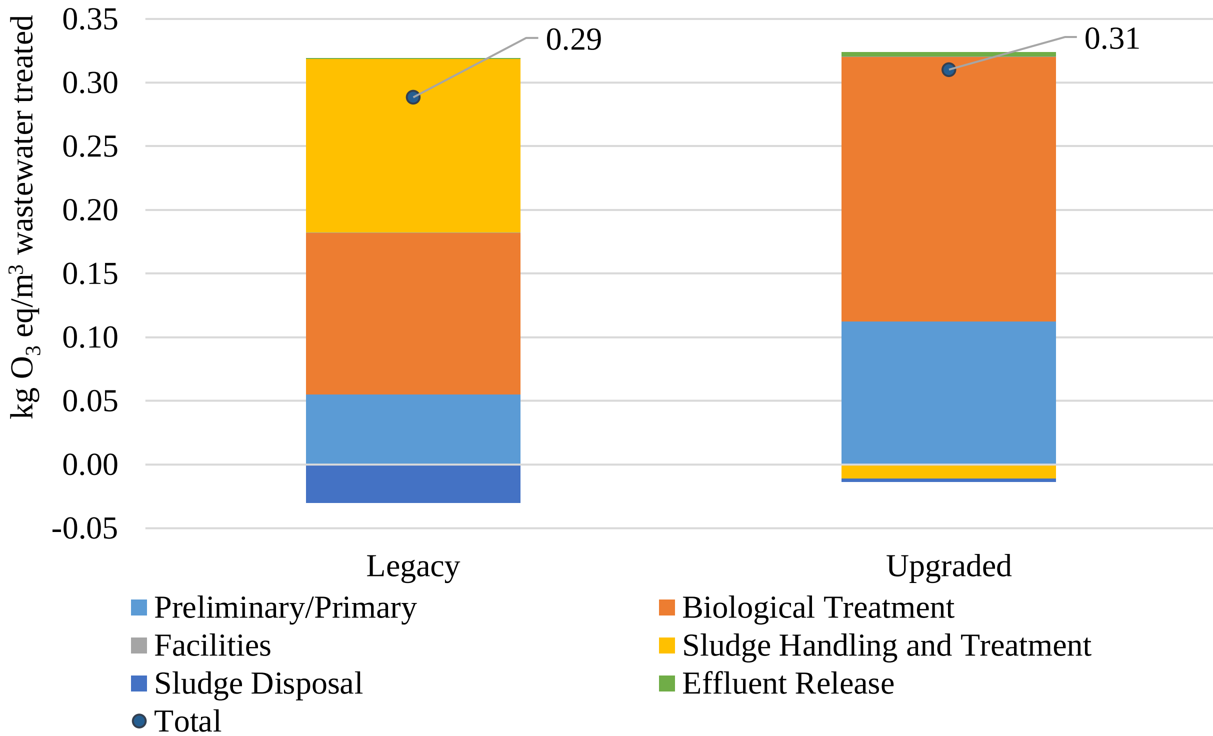

Figure 5-9. Smog formation potential results by treatment stage.

5.8 Particulate Matter Formation Potential

Figure 5-10 presents net particulate matter formation potential results grouped according to treatment stage. Net particulate matter formation potential impact is 11 percent greater for the upgraded treatment system. Electricity consumption contributes over 95 percent of particulate matter formation potential for both systems, and while it is not visible in Figure 5-10, the avoided energy production that results from biogas recovery serves to reduce gross impact of the upgraded system by 32 percent. Avoided fertilizer production from compost land application contributes an additional 1 percent reduction to gross particulate matter formation potential impact. Chemical production contributes between 2 and 3 percent of impact for the legacy system.

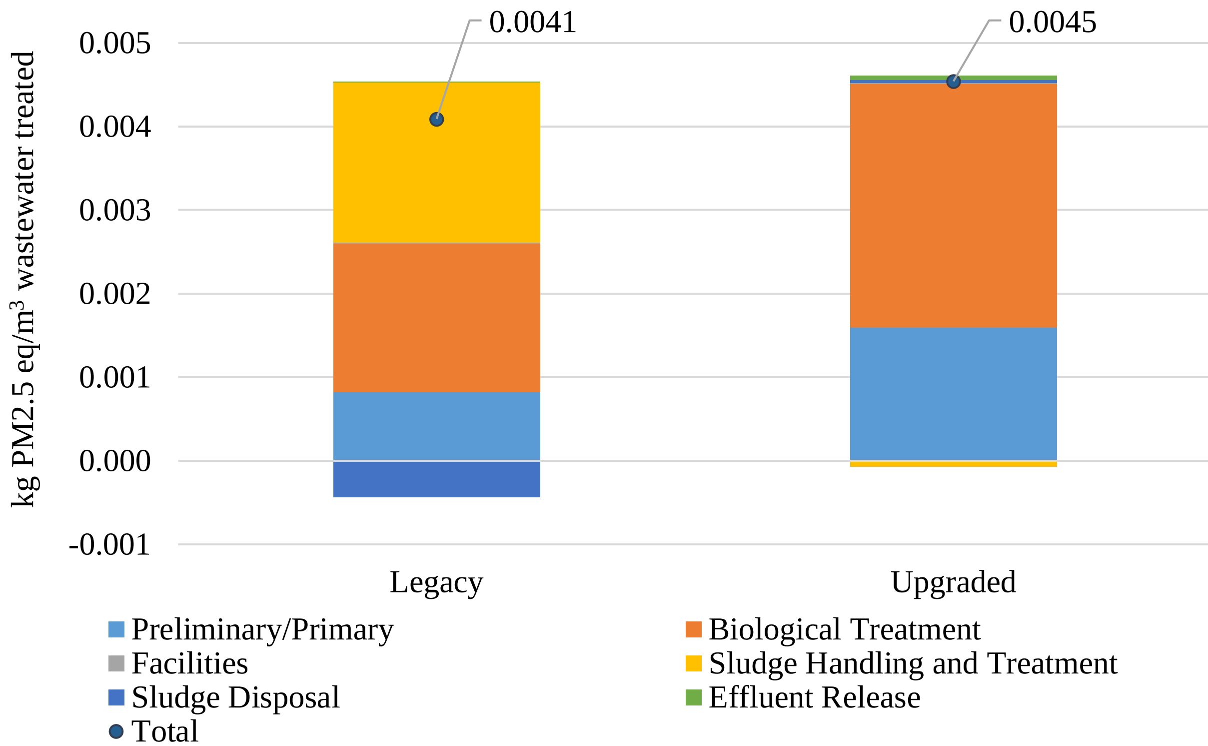

Figure 5-10. Particulate matter formation potential results by treatment stage.

5.9 Water Use

Figure 5-11 presents water use results grouped according to treatment stage. Use of process water for both systems is marginal, and as a result pressure on the freshwater supply from both systems is minimal. In this analysis, a modest quantity of the treated effluent from the upgraded system is reused for landscape irrigation at a local golf course. This is expected to amount to approximately 14 million gallons per year, or the equivalent of 14 days' worth of treated effluent. Avoided drinking water production reduces gross water use of the upgraded system by less than 1 percent. Finding further reuse opportunities for the treated wastewater would further reduce impacts in this category. The net negative effect of avoided fertilizer production from compost land application indicates that the upgraded system yields an environmental benefit in this category, reducing the need for more freshwater than it itself consumes.

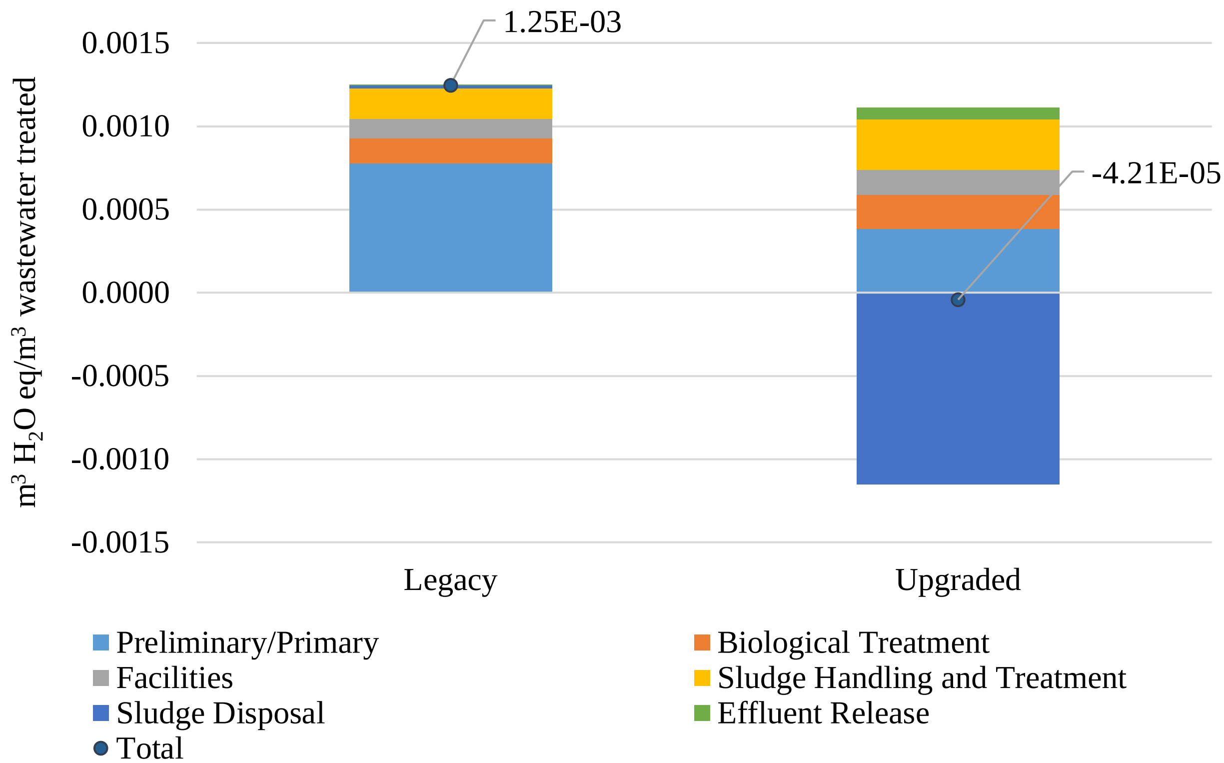

Figure 5-11. Water use results by treatment stage.

5.10 LCCA

Figure 5-12 shows the breakdown of life cycle costs for the upgraded WWTP by cost category. No life cycle costs were calculated for the legacy plant, as this design is going to be superseded moving forwards in order to meet effluent standards specified in Bath's SPDES permit. Total NPV of the upgraded plant for the base feedstock, AD, and cost scenarios is just over 37 million dollars over a 30-year time horizon. Forty-six percent of total NPV is due to construction costs, which total 17.1 million dollars. Construction costs include upgrades to headworks and a new waste receiving station, enhance primary clarification, upgrades to the secondary treatment system, and installation of anaerobic digestion and a composting facility. A further 40 percent are operational costs mostly attributable to wages and other personnel costs such as health insurance. The material cost of replacing and maintaining plant and equipment over the course of 30 years constitutes 6 percent of life cycle costs. Net energy cost is shown in Figure 5-12, which includes energy purchased from the utility and electricity sales from biogas generation. The value of avoided natural gas purchasing is captured through a reduction in the purchase of natural gas. Purchased chemical inputs contribute 3 percent of life cycle costs in the base cost scenario.

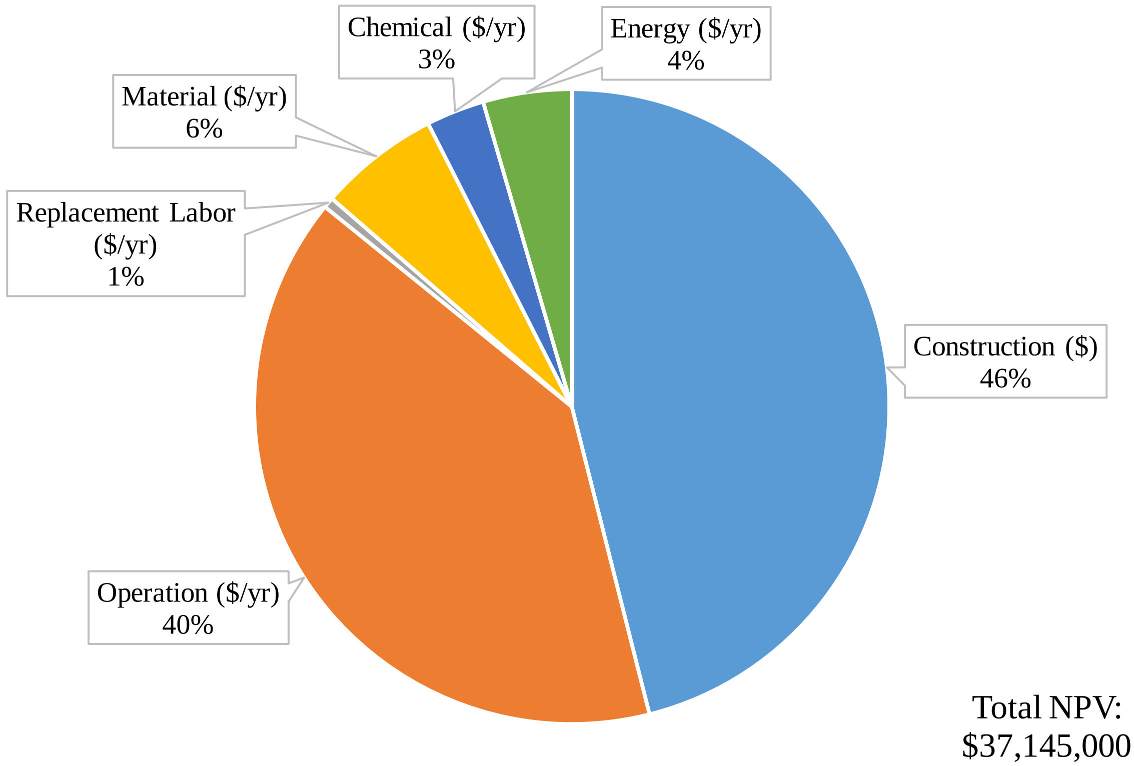

Figure 5-12. Base life cycle costs by cost category for upgraded WWTP.

6. Scenario Sensitivity Analysis

The first section in the sensitivity analysis provides an isolated look at the effect of low, medium (i.e., base), and high estimates of the emission factors for composting and landfilling GHG emissions on global warming potential impact. The second sensitivity analysis is employed to determine the impact of AD and compost feedstock scenarios on life cycle environmental impacts and costs of operating a 1 MGD wastewater treatment system. The analysis highlights the range in environmental impacts that can result from variations in AD feedstock inputs and operational performance as outlined in Section 3.3.9. Figures in Section 1.1 also include the effect of compost and landfill emissions scenarios. Section 6.3 isolates the effects of including or excluding composting amendment material from the system boundaries and the effect that this decision has on cumulative global warming potential impacts of the WWTP. Results of the LCCA scenario assumptions on system costs over 30 years are presented in Section 6.5

6.1 Landfill and Compost Emission Scenarios

Figure 6-1 shows the effect of low, base, and high compost and landfill emission scenarios on total global warming potential impact results for the legacy and upgraded WWTPs. The figure also includes alternative scenarios, utilizing Base Feedstock-Base AD scenario assumptions, that represent the use of national average landfill gas capture rates and an ASP composting system in place of the windrow system and the Bath regional landfill values. The figure shows the contribution of each life cycle stage to net global warming potential impact results for the entire treatment system. For the upgraded treatment system, EOL processes include both composting and land application, while for the legacy treatment plant EOL includes only the landfilling process. The figure highlights the wide range of potential impacts associated with composting emissions, the sensitivity of global warming potential impact to this parameter, and the potential negative impact of a poorly managed composting system. Likewise, the figure highlights the potential environmental benefit that is possible given a well-managed composting operation.

Under the base EOL emissions scenario, the ASP composting system demonstrates the lowest net EOL global warming potential impact given that the carbon credit associated with land application nearly balances out the GHG emissions released during the composting process. The biofilter that is part of the ASP system is assumed to effectively eliminate CH_4 emissions, however the system still produces N_2O. The BEAM model, which can be used to estimate global warming potential impacts associated with wastewater treatment, indicates that N_2O emissions can also be eliminated if the solids content of the composting pile is greater than 55 percent (SYLVIS 2011). However, the recommended moisture content of a composting pile is between 50 and 60 percent, placing 55 percent solids content outside of the moisture range recommended in practice (Pawlowski et al. 2013, Chardoul et al. 2011). CO_2 emissions associated with all systems are assumed to be of biogenic origin, and therefore do not contribute to global warming potential. In the base emissions' scenario, the windrow composting system has impacts that fall between those of the Bath regional landfill and national average landfill. Under the low emissions scenario, the windrowing system demonstrates the lowest net EOL global warming potential, followed closely by the ASP system. Within the low EOL emissions scenario, all EOL options demonstrate a net negative impact on global warming potential due to the carbon sequestration credit associated with all options. The high EOL emission scenario leads to notable contributions of this life cycle stage to net global warming potential impacts. The windrow composting system has the greatest potential contribution the GHG emissions, which indicates the importance of sound management if this system is to be employed without negative environmental effects. The biofilter emission control system of the ASP composting method leads to lower variability between the emission scenarios and the lowest net EOL global warming potential impacts under the high EOL emission scenario making it an attractive option for communities. The impact of the ASP system is dependent on the composition of the local electricity grid as it uses forced aeration to maintain aerobic conditions. The Bath regional electricity grid relies on a relatively clean set of generating technologies, and it is possible that the ASP system will demonstrate higher relative global warming potential impact in other regions of the country.

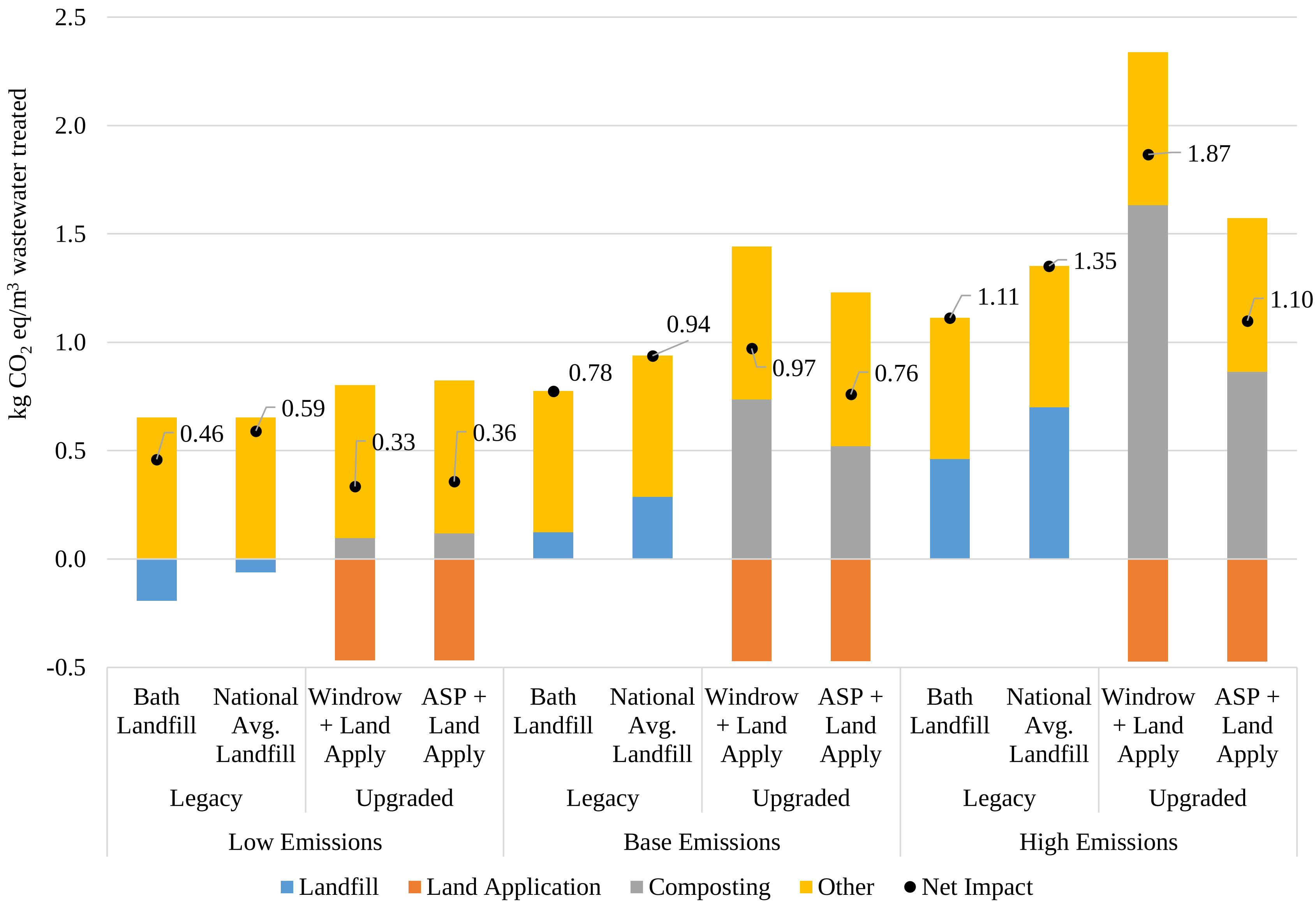

Figure 6-1. Life cycle global warming potential end-of-life emission scenario results.

6.2 Feedstock, AD, and End-of-Life Scenario Sensitivity

Three feedstock scenarios are analyzed in the sensitivity analysis, as outlined in Table 3-25. The base scenario assumes that the upgraded WWTP accepts 14,000 gallons of septic tank waste and 2,000 gallons of portable toilet waste on top of the approximately 93,000 gallons of combined primary and WAS that result from the daily treatment of 1 MGD of residential, commercial, and industrial sewage. The high feedstock scenario assumes that the facility accepts an additional 8,000 GPD of high strength organic waste, and while this is a relatively modest quantity of additional waste, it provides a significant boost to available VS for biogas production.

Each feedstock scenario is analyzed assuming low, base, and high AD operational performance parameters. In general, the high scenario corresponds to the greatest biogas and energy recovery as a result of more optimistic assumptions regarding biogas production rates, VS destruction, methane content of the resulting gas, and greater electrical efficiency of the CHP system.

The figures in this section list the combined feedstock and AD scenario names. The portion of the scenario name preceding the hyphen indicates the feedstock scenario listed in Table 3-25. The latter portion of the name, following the hyphen, refers to the AD operational assumptions listed in Table 3-26. Bar coloration is used to differentiate the landfill and compost emissions scenario results for each Feedstock-AD scenario. Results are presented for eutrophication potential, cumulative energy demand, global warming potential, particulate matter formation potential, and water use. Negative impact results represent a net environmental benefit attributable to the wastewater treatment system. The general trends exhibited by these five impact categories are representative of results for the other LCIA categories, and a description of these similarities is included in the discussion.

Figure 6-2 presents net eutrophication potential results for the legacy system, the 9 upgraded Feedstock-AD scenarios, and the landfill and compost emission scenarios. The feedstock and AD scenarios demonstrate a limited impact on eutrophication results. The visible effect is due largely to composting and land application. A portion of the ammonia that volatizes from the compost pile will eventually find its way into the freshwater system as a result of atmospheric deposition. Nitrogen and phosphorus emissions to both land and water result from land application. The magnitude of this effect for any given Feedstock-AD scenario yields an approximate 10 percent increase in the net impact result. From the figure, it appears that increased operational performance of the AD also exerts a slight positive influence on eutrophication potential impacts, however this is partially a consequence of modeling a static C:N ratio for the incoming digested biosolids across all feedstock scenarios. Variable carbon and nitrogen contents of high strength organic waste could lead to greater relative nitrogen content depending upon the feedstocks accepted for co-digestion. Taking this into account would affect eutrophication potential results.

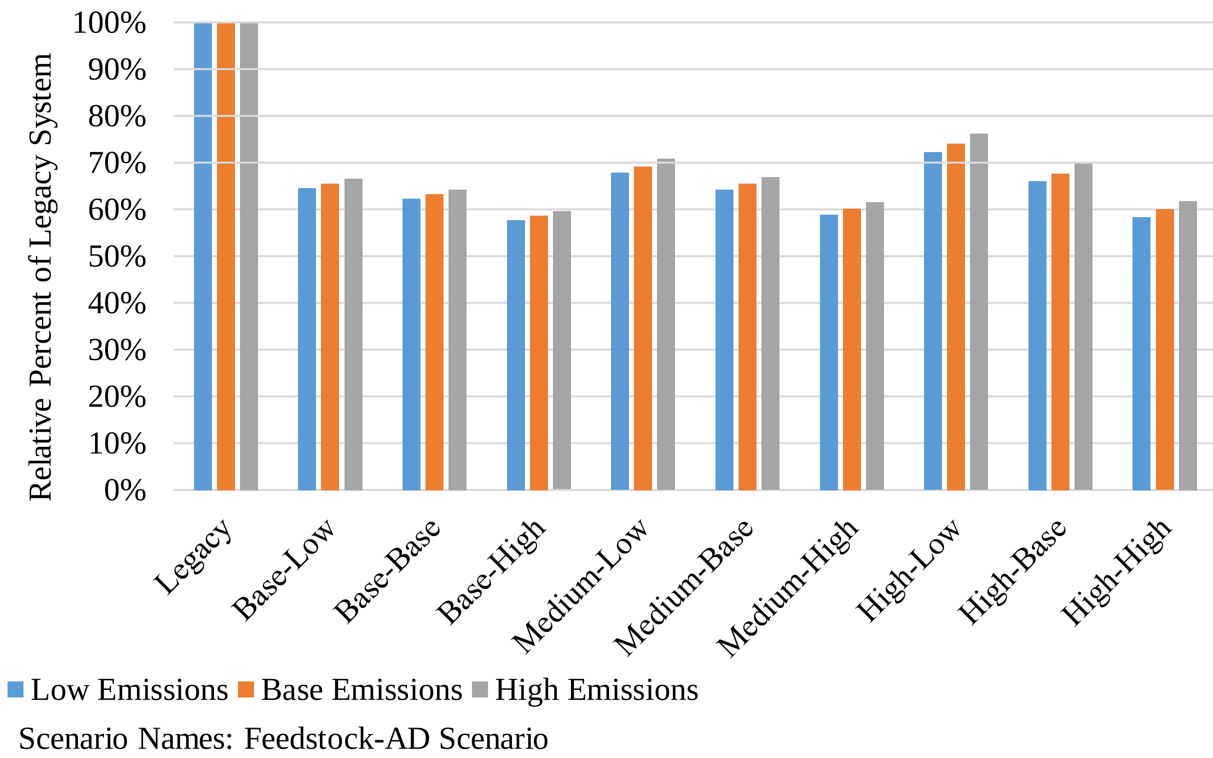

Figure 6-2. Effect of feedstock and anaerobic digestion sensitivity scenarios on eutrophication potential results.

Figure 6-3 presents net cumulative energy demand results for the legacy system, the 9 upgraded Feedstock-AD scenarios, and the landfill and compost emission scenarios. In the Base Feedstock-Base AD scenario, net cumulative energy demand impacts for the upgraded system exceed those of the legacy plant by between 3 and 7 percent depending upon the composting emissions scenario. Net cumulative energy demand decreases as the upgraded WWTP accepts more feedstock and generates greater quantities of avoided electricity and natural gas. The results are more sensitive to the assumed changes in AD operational performance than they are to the feedstock scenarios. The figure shows that through a combined approach of maximizing AD operational performance and accepting additional high strength organic wastes for biogas production it is possible to generate net negative impacts in the cumulative energy demand impact category. The general pattern shown in the figure below is representative of fossil depletion potential results. The reason for this is that impacts in both categories are strongly linked to energy production and consumption.

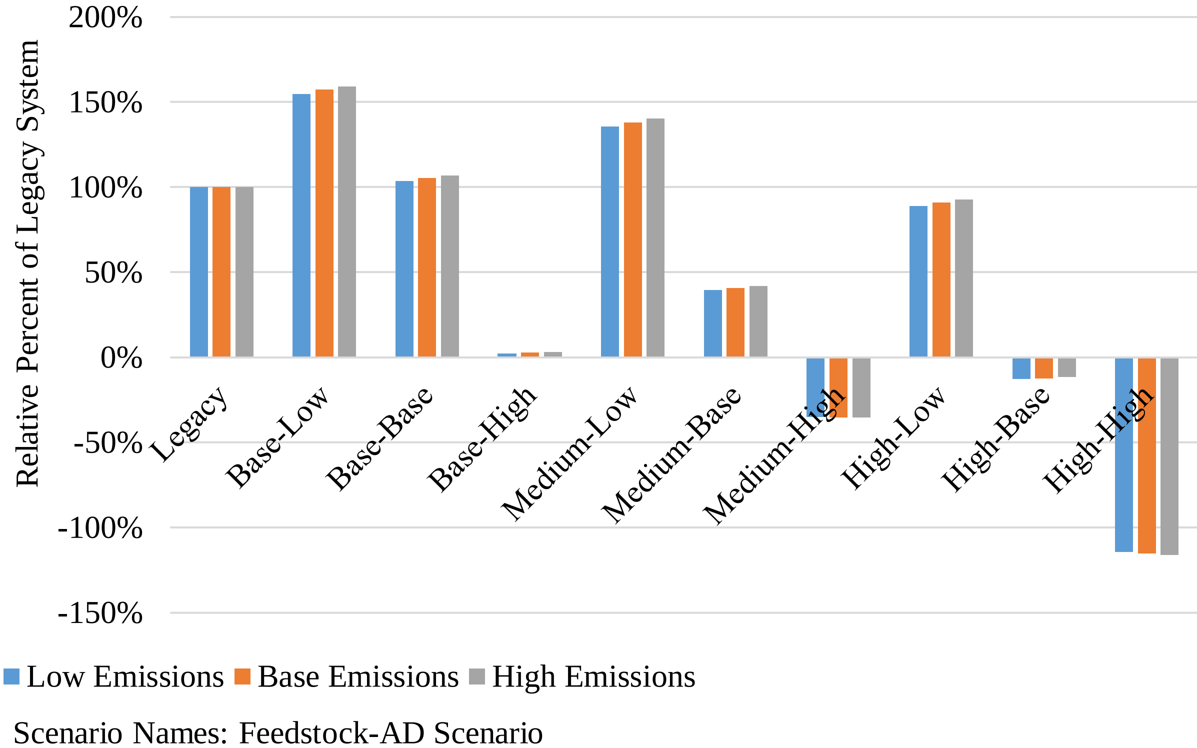

Figure 6-3. Effect of feedstock and anaerobic digestion sensitivity scenarios on cumulative energy demand results.

Figure 6-4 presents net global warming potential results for the legacy system, the 9 upgraded Feedstock-AD scenarios, and the landfill and compost emission scenarios. The compost GHG emissions scenario is the predominant determinant of the relationship of comparative impact results between the legacy and upgraded wastewater treatment systems. The gray bars demonstrate that that the upgraded system cannot generate competitive global warming potential impact results if composting emissions are at the high end of their potential range, regardless of assumptions related to feedstock acceptance or AD performance. The base scenario demonstrates a 25 percent greater net global warming potential than the legacy system. If high operational performance of the AD system is achieved this can be turned into a 28 percent reduction in impact, relative to the legacy system. This means that the presence of an anaerobic digester and the EOL processing steps have the potential to reduce the WWTPs cumulative global warming potential impacts while treating an additional 8,000 GPD of septage waste and achieving a higher effluent quantity. The base EOL and base AD scenario leads to nearly equivalent net global warming potential impacts between the legacy and upgraded system if the High feedstock quantity is accepted. If high AD performance is achieved, the system can reduce relative global warming potential impacts by 49 percent.

The low EOL emissions scenario allows the upgraded treatment plant to achieve competitive global warming potential impacts even assuming low AD operational performance, yielding a 14 percent increase relative to the legacy system when considering the Base Feedstock-Low AD performance scenario. All other scenarios demonstrate a reduction in global warming potential, with 6 of the 9 scenarios demonstrating net negative impacts. The gray bars illustrate the importance of avoiding high composting emissions if it is desired not to increase the global warming potential impacts attributable to the WWTP. All scenarios realize a relative increase in global warming potential impact, relative to the legacy system, under the high EOL emissions scenario. This relative increase is at a minimum of 25 percent for the Base Feedstock-High AD scenario and increases to a maximum of 178 percent for the High Feedstock-Low AD performance scenario. In general, the figure shows that increased operational performance of the AD leads to a reduction in net global warming potential impacts, but that the realization of true benefits is only possible when paired with a well-managed composting system.

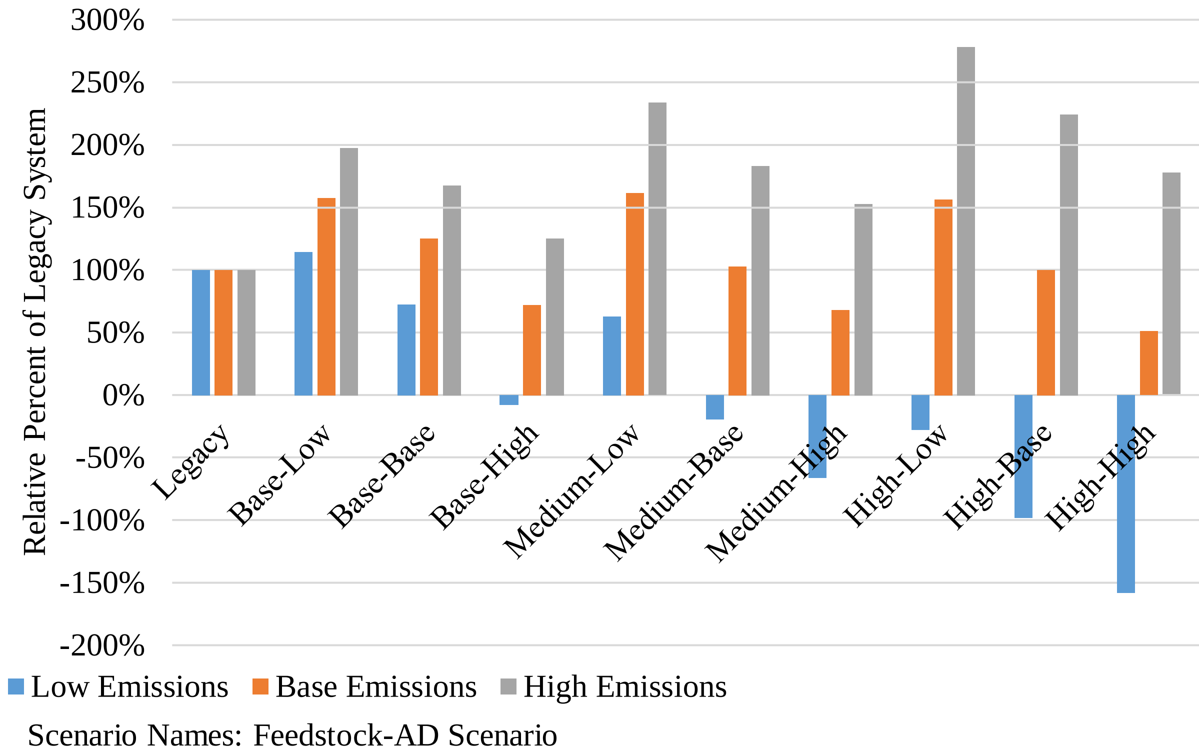

Figure 6-4. Effect of feedstock and anaerobic digestion sensitivity scenarios on global warming potential results.

Figure 6-5 presents net particulate matter formation potential results for the legacy system, the 9 upgraded Feedstock-AD scenarios, and the landfill and compost emission scenarios. Particulate matter impacts are dramatically affected by the Feedstock-AD scenarios. For the base scenario, particulate matter formation potential results of the upgraded system exceed the legacy plant's impact results by between 5 and 17 percent, depending upon the emissions scenario. High operational performance of the AD for the base feedstock scenario produces an almost net zero impact due to the benefits of avoided electricity and natural gas production. Low operational performance of the AD leads to a significant dampening of avoided energy production, and an associated increase in particulate matter formation potential as a result of lower avoided energy credits. Three of the Feedstock-AD scenarios generate net negative impact results, which indicates a reduction in environmental burdens as a result of wastewater treatment with AD. Similar patterns of relative results to those described are exhibited for smog formation potential and acidification potential, which like particulate matter formation potential, are strongly linked to electricity use and generation.

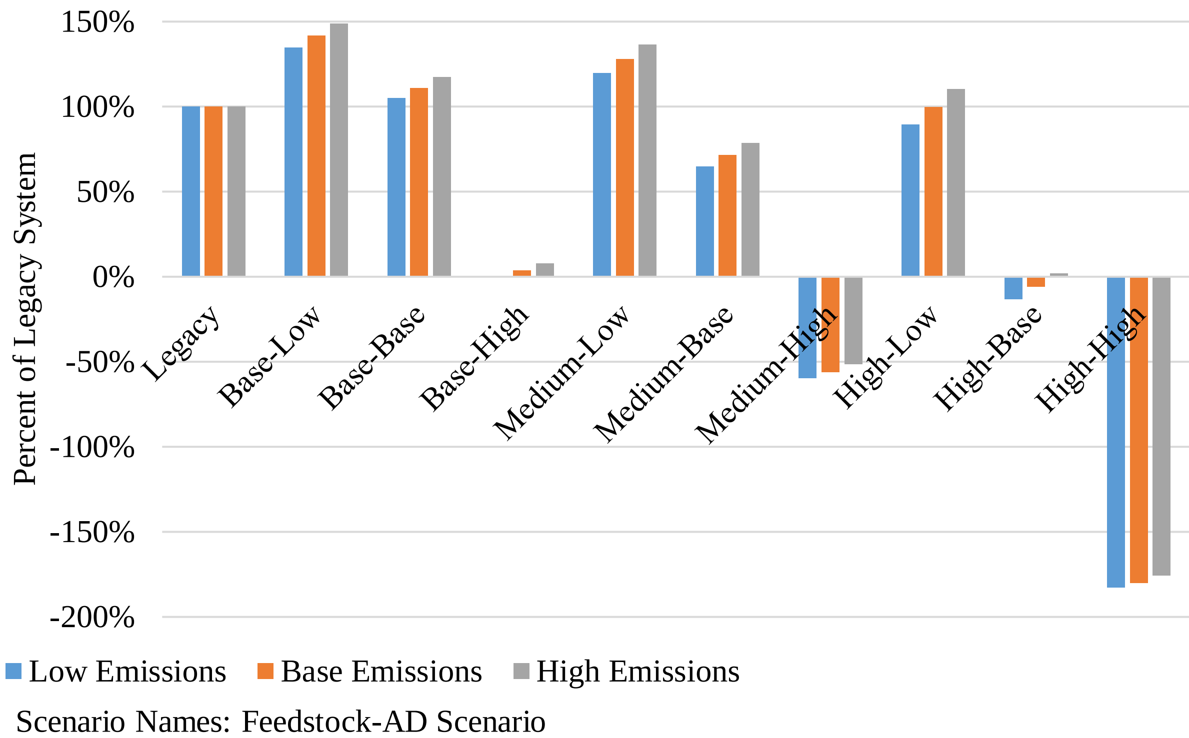

Figure 6-5. Effect of feedstock and anaerobic digestion sensitivity scenarios on particulate matter formation potential results.

Figure 6-6 presents net water use results for the legacy system, the 9 upgraded Feedstock-AD scenarios, and the landfill and compost emission scenarios. Most water use is in upstream manufacturing of chemicals. All Feedstock-AD scenarios for the upgraded treatment system lead to reduced water consumption as a result of avoided fertilizer production and effluent reuse, which yield the environmental benefit visible in the figure. Higher emissions of nitrous oxide and ammonia in the high EOL emission scenario leads to a slight reduction in avoided fertilizer production, which accounts for the observable pattern exhibited between the emission scenarios.

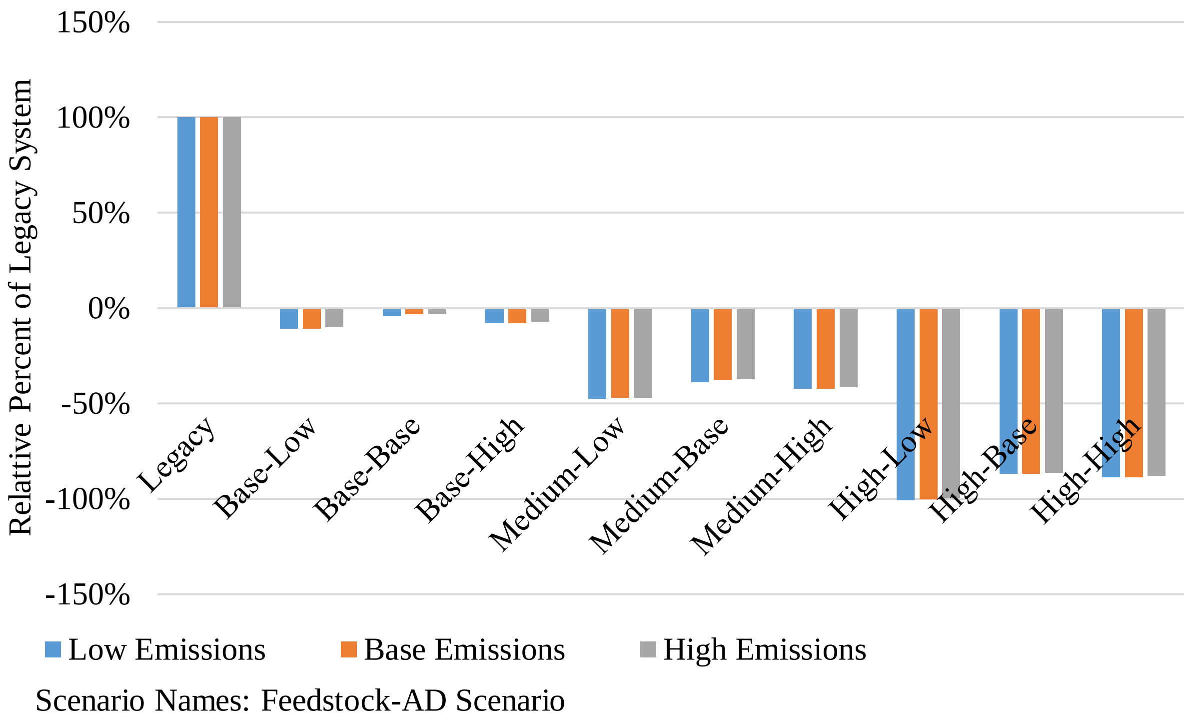

Figure 6-6. Effect of feedstock and anaerobic digestion sensitivity scenarios on water use results.

Table 6-1 shows impact results for the upgraded system relative to legacy impact results for all scenarios and impact categories. As an example of how to interpret the table, when referencing the Base Feedstock-Base AD scenario, the upgraded system generates a net global warming potential impact result that is 25 percent greater than that of the legacy system. Other values can be read in a similar manner.

Table 6-2 presents total annual LCIA results for the legacy system and all sensitivity scenarios analyzed for the upgraded treatment plant. Negative values in the table indicate a net environmental benefit for the treatment system and Feedstock-AD scenario to which they apply. For the legacy system, we can see that approximately 1 million kg of CO_2 equivalent emissions are released annually by the WWTP, which equates to approximately 191 kg of CO_2 equivalent emissions per resident in the Town of Bath. Potential GHG emissions for the upgraded treatment plant range between -1 and 4.3 million kg of CO_2 equivalents depending upon the specific assumptions of the sensitivity scenario. The breadth of this range highlights the importance of the decisions facing treatment plant personnel and community managers regarding technology selection and WWTP management. To put these numbers into context, net GHG emissions in 2015 were approximately 6,500 million metric tons of CO_2 equivalent emissions, which translates into 20.5 tons per U.S. citizen (U.S. EPA 2017). This indicates that wastewater treatment emissions can contribute between -1 and 4 percent of average per capita GHG emissions for a resident in Bath, NY.

Table 6-1. Percent Change in Impacts between the Upgraded and Legacy WWTPs[1]

Impact Category	**Global Warming Potential - kg CO_2 eq**			**Eutrophication Potential - kg N eq**			**Cumulative Energy Demand - MJ**			**Particulate Matter Formation Potential - kg PM2.5 eq**		
Emissions Scenario[2]	**Low**	**Base**	**High**	**Low**	**Base**	**High**	**Low**	**Base**	**High**	**Low**	**Base**	**High**
Legacy	-	-	-	-	-	-	-	-	-	-	-	-
Upgraded, Base-Low	14%	57%	97%	-36%	-34%	-33%	55%	57%	59%	35%	42%	49%
Upgraded, Base	-27%	25%	68%	-38%	-37%	-36%	3%	5%	7%	5%	11%	17%
Upgraded, Base-High	-108%	-28%	25%	-42%	-41%	-40%	-98%	-97%	-97%	-100%	-96%	-92%
Upgraded, Medium-Low	-37%	61%	134%	-32%	-31%	-29%	36%	38%	40%	20%	28%	37%
Upgraded, Medium-Base	-120%	2%	83%	-36%	-35%	-33%	-60%	-59%	-58%	-35%	-29%	-22%
Upgraded, Medium-High	-166%	-32%	53%	-41%	-40%	-39%	-135%	-135%	-135%	-160%	-156%	-151%
Upgraded, High-Low	-128%	57%	178%	-28%	-26%	-24%	-11%	-9%	-7%	-11%	0%	10%
Upgraded, High-Base	-199%	0%	124%	-34%	-32%	-30%	-113%	-112%	-112%	-113%	-106%	-98%
Upgraded, High-High	-258%	-49%	78%	-42%	-40%	-38%	-214%	-215%	-216%	-283%	-280%	-276%
Impact Category	**Smog Formation Potential - kg O_3 eq**			**Acidification Potential - kg SO_2 eq**			**Water Use - m^3 H2O**			**Fossil Depletion Potential - kg oil eq**		
Emissions Scenario[2]	**Low**	**Base**	**High**	**Low**	**Base**	**High**	**Low**	**Base**	**High**	**Low**	**Base**	**High**
Legacy	-	-	-	-	-	-	-	-	-	-	-	-
Upgraded, Base-Low	34%	37%	40%	44%	63%	82%	-111%	-111%	-110%	66%	68%	70%
Upgraded, Base	5%	7%	9%	14%	31%	48%	-104%	-103%	-103%	7%	9%	10%
Upgraded, Base-High	-101%	-101%	-101%	-90%	-77%	-61%	-108%	-108%	-107%	-99%	-98%	-98%
Upgraded, Medium-Low	19%	21%	24%	34%	58%	85%	-148%	-147%	-147%	46%	49%	51%
Upgraded, Medium-Base	-37%	-35%	-34%	-22%	-1%	23%	-139%	-138%	-137%	-64%	-63%	-62%
Upgraded, Medium-High	-161%	-163%	-164%	-144%	-127%	-107%	-142%	-142%	-142%	-132%	-132%	-132%
Upgraded, High-Low	-13%	-11%	-9%	11%	43%	79%	-201%	-200%	-200%	-5%	-3%	-1%
Upgraded, High-Base	-116%	-116%	-116%	-93%	-65%	-34%	-187%	-187%	-186%	-112%	-112%	-111%
Upgraded, High-High	-286%	-290%	-293%	-260%	-239%	-213%	-189%	-189%	-188%	-206%	-207%	-207%

[1] Percent change is calculated relative to the legacy system ($[Impact_{upgraded}/Impact_{legacy}]-1*100$)

[2] Upgraded treatment system names refer to the respective Feedstock-AD scenario.

Table 6-2. Annual LCIA Results by Feedstock, AD, and Emissions' Scenarios

Impact Category	Global Warming Potential - kg CO_2 eq			Eutrophication Potential - kg N eq			Cumulative Energy Demand - MJ			Particulate Matter Formation Potential - kg PM2.5 eq		
Emissions Scenario[1]	Low	Base	High	Low	Base	High	Low	Base	High	Low	Base	High
Legacy	635,695	1,071,006	1,537,446	33,764	33,736	33,715	12,726,175	12,537,715	12,398,843	5,777	5,653	5,556
Upgraded, Base-Low	726,775	1,683,282	3,032,516	21,772	22,103	22,462	19,668,863	19,714,209	19,760,647	7,777	8,009	8,271
Upgraded, Base	462,406	1,342,547	2,578,981	21,036	21,333	21,664	13,157,618	13,198,460	13,240,297	6,065	6,275	6,511
Upgraded, Base-High	-50,486	769,442	1,921,179	19,493	19,769	20,087	302,891	341,785	381,647	20	221	444
Upgraded, Medium-Low	400,341	1,728,670	3,595,535	22,919	23,364	23,875	17,264,359	17,327,336	17,391,833	6,906	7,233	7,587
Upgraded, Medium-Base	-125,470	1,097,189	2,812,692	21,678	22,092	22,547	5,061,231	5,117,590	5,175,302	3,737	4,032	4,360
Upgraded, Medium-High	-422,088	728,005	2,349,982	19,897	20,291	20,719	-4,452,492	-4,398,372	-4,342,939	-3,443	-3,156	-2,855
Upgraded, High-Low	-177,283	1,676,166	4,276,425	24,371	24,993	25,698	11,319,726	11,407,380	11,497,175	5,169	5,625	6,124
Upgraded, High-Base	-626,162	1,070,371	3,450,667	22,279	22,845	23,495	-1,605,024	-1,527,567	-1,448,245	-757	-345	115
Upgraded, High-High	-1,006,275	548,512	2,735,152	19,730	20,255	20,849	-14,544,060	-14,471,122	-14,396,387	-10,555	-10,175	-9,755
Impact Category	**Smog Formation Potential- kg O_3 eq**			**Acidification Potential - kg SO_2 eq**			**Water Use - m^3 H_2O**			**Fossil Depletion Potential - kg oil eq**		
Emissions Scenario[1]	Low	Base	High	Low	Base	High	Low	Base	High	Low	Base	High
Legacy	408,286	399,388	392,852	43,505	42,551	41,860	1,725	1,722	1,720	240,362	236,977	234,476
Upgraded, Base-Low	548,442	548,802	549,437	62,742	69,222	76,366	-186	-186	-172	397,881	398,779	399,691
Upgraded, Base	427,670	428,002	428,568	49,547	55,544	62,148	-72	-58	-58	257,240	258,056	258,885
Upgraded, Base-High	-3,288	-2,998	-2,459	4,436	9,990	16,152	-136	-136	-122	3,565	4,338	5,126
Upgraded, Medium-Low	484,554	485,037	485,908	58,404	67,426	77,374	-821	-807	-807	350,752	351,996	353,281
Upgraded, Medium-Base	258,484	258,926	259,727	33,976	42,307	51,509	-669	-655	-641	87,419	88,538	89,671
Upgraded, Medium-High	-250,940	-250,512	-249,752	-19,343	-11,564	-2,970	-728	-728	-714	-77,664	-76,600	-75,495
Upgraded, High-Low	354,787	355,478	356,693	48,207	60,794	74,722	-1,740	-1,726	-1,712	228,446	230,187	231,956
Upgraded, High-Base	-65,270	-64,662	-63,571	3,151	14,702	27,468	-1,497	-1,497	-1,483	-29,292	-27,758	-26,183
Upgraded, High-High	-759,051	-758,485	-757,462	-69,691	-59,135	-47,474	-1,528	-1,528	-1,514	-253,911	-252,460	-250,981

[1] Upgraded treatment system names refer to the respective Feedstock-AD scenario.

6.3 Bulking Material Amendment Sensitivity

The sensitivity of global warming potential impact results to EOL emissions warrants consideration of the effect of assumptions regarding compost bulking materials contribution to cumulative treatment impacts. Both windrow and ASP composting systems require bulking/amendment material to hit target ranges for moisture, carbon, and nitrogen content within the compost pile. Given this requirement, the bulking material can be considered a necessary input to biosolids composting, which provides a rationale for attributing the associated emissions to the wastewater treatment system. However, given that much of this bulking material is municipal yard waste, which may have been composted regardless of the chosen biosolids disposal method, there exists an alternate rationale for excluding emissions associated with the bulking material from the environmental burdens attributable to the WWTP. Figure 6-7 shows the effect of including and excluding compost bulking material on global warming potential impact results across the low, base, and high compost emission scenarios for both composting systems within the Base Feedstock-Base AD scenario.

The figure shows that for the windrow base EOL emissions scenario, the effect of including or excluding compost amendment from the system has only a minor effect on cumulative treatment impacts. Two separate forces are responsible for this. The additional carbon associated with compost amendment material yields both emissions during the composting process, and a carbon credit when the finished compost is land applied. These factors balance one another leading to minimal net effect on global warming potential impact results for the base EOL emission windrow and the high EOL emission ASP compost scenarios. Under the low emission scenario, where only a small fraction of C and N incoming to composting is assumed to be liberated as GHGs, the figure shows that global warming potential of the whole system experiences a net benefit when including compost amendment within the system boundaries because of the carbon credit that is associated with this material. The opposite is true under the high EOL emissions scenario where GHG emissions during the composting phase outweigh the benefit of the carbon credit accrued during land application. The ASP system is less sensitive to the choice to include or exclude compost amendment from the system boundary, as the potential range of emissions during the composting stage is narrower than that of the windrow system.

The fate of bulking material in the absence of a biosolids composting operation is the primary determinant of whether it is appropriate to attribute the environmental benefits and burdens of composting amendment to the WWTP. The exclusion of amendment materials from the system boundary only changes impact attributable to the WWTP, and not the larger environment, as these emissions will occur regardless of the methodological choice.

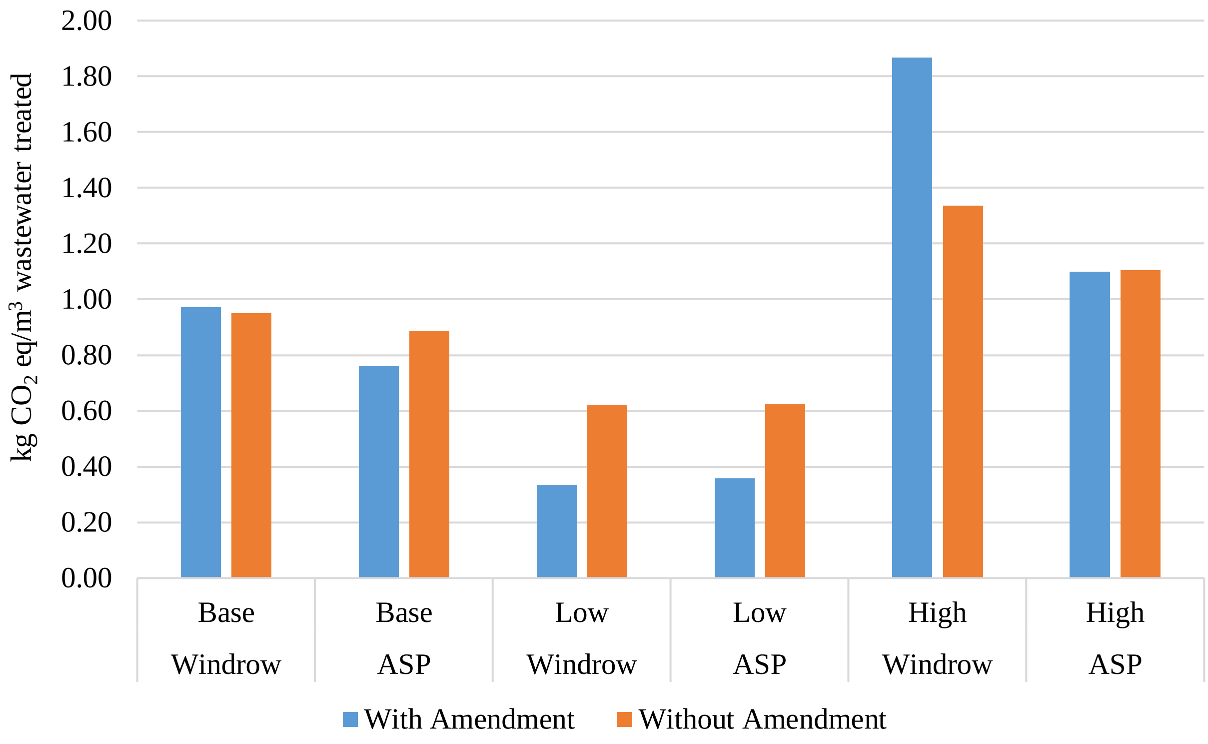

Figure 6-7. Effect of compost amendment on life cycle global warming potential results for Low, Base, and High end-of-life emissions scenarios.

6.4 Narrative Impact Scenario

The options presented in the sensitivity section above are intended to inform environmental managers, municipalities, and WWTP operators of the range of potential environmental impacts that are possible as upgrades are undertaken to increase effluent quality. The combination of options can be complex, and this section has been included to illustrate how a theoretical WWTP could use the results of this analysis to work towards management practices and system upgrades that realize environmental benefits. Figure 6-8 demonstrates a series of management steps and equipment upgrades that are undertaken, and the affect that these choices have on net eutrophication potential, global warming potential, and cumulative energy demand.

In Figure 6-8, legacy, or historical impacts prior to system upgrades, are set to 100 percent and are taken as the reference system. Legacy results in this figure assume national average landfill performance of the methane capture system. Following the initial upgrades, the plant realizes an immediate improvement in effluent quality and a corresponding reduction in eutrophication potential impact. One can imagine that during this time-period, operators are getting used to the management of both the AD and composting systems. Furthermore, the plant is not yet utilizing the full capacity of the digesters. Therefore, the plant sees an increase in global warming potential (High EOL emissions, Low AD scenario). The benefits of avoided energy production limit the increase in cumulative energy demand to just 3 percent over the impact of the legacy system. Over time, operators improve management of the composting system, better balancing pile C:N ratios, hitting target moisture content, and ensuring that pile temperatures remain elevated (base emissions scenario). After a time, the plant decides to invest in an ASP composting system to reduce GHG emissions, limit odors, and conserve space. With this step, the plant realizes an improvement in net global warming potential for the entire wastewater facility, relative to their historic baseline. Installation of ASP increases relative cumulative energy demand by 13 percent. Operators locate a steady source of high strength organic waste, yielding additional biogas production and a reduction in both cumulative energy demand and global warming potential. At this point the environmental impact of all three impact categories is reduced relative to the legacy system, despite treatment of a greater quantity of organic waste and achievement of improved effluent quality. Once operators become comfortable with the management of co-digestion, they maximize the available capacity of their digesters and realize a consistent improvement in digester performance (High Feedstock-High AD). With this final step, the plant begins to produce more energy than they consume, and the facility approaches climate neutrality.

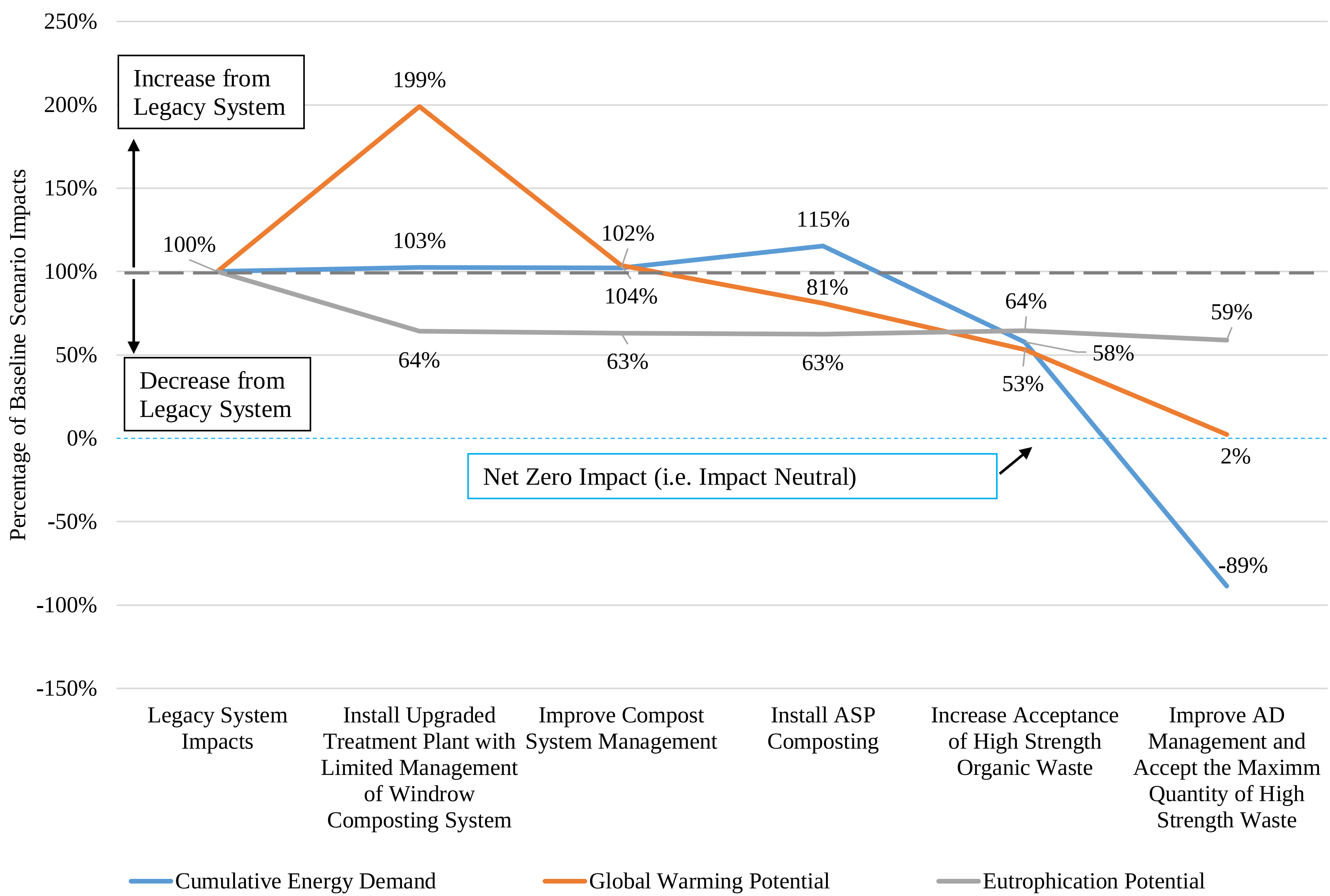

Figure 6-8. Narrative environmental impacts of an upgraded wastewater treatment plant.

6.5 LCCA Cost Scenarios

Figure 6-9 presents total NPV value for each Feedstock-AD-cost scenario broken down by cost category. Parameter values that correspond to each cost scenario are defined in Section 4.3.7. Generally, the low cost scenario corresponds to parameter values that will yield a lower system NPV than the base cost scenario, while the high cost scenario corresponds to parameter values that define a high estimate of system NPV. The base case scenario (Base Feedstock-Base AD-Base Cost) yields an NPV of just over 37 million dollars over a 30-year time horizon. Low cost assumptions drop the NPV by approximately 12 percent to 32.6 million dollars. A payback period is calculated separately for the AD and the composting facility, each of which produces a revenue stream. The payback period calculation for the AD unit includes costs to install and maintain the CHP system. No payback period is calculated for other elements of the upgraded facility such as the chemically enhanced primary clarifier or the MLE biological treatment unit.

Neither the AD, nor the composting facility, can payback their initial capital cost under base case assumptions, as shown in Table 6-3. Given the low value of finished compost there are no scenarios for which the composting facility can pay for itself over 30 years. With base cost assumptions, the Medium Feedstock-Base AD, Medium Feedstock-High AD, and all the High feedstock scenarios can generate a positive payback period which ranges from 850 years for the Medium Feedstock-Base AD scenario to 45 years for the High Feedstock-High AD scenario. Assuming the high cost scenario, the Medium Feedstock-Base AD scenario no longer generates a payback period, and the payback period for the High Feedstock-High AD increases to 70 years. The high cost scenario raises the calculated NPV of the Base Feedstock-Base AD scenario to 48.7 million dollars. The minimum potential payback period for the AD unit is 16 years. Under the low cost scenario assumptions, the three High Feedstock scenarios yield an AD payback period of less than the assumed system lifespan of 30 years.

Table 6-3. Summary Table of Calculated Payback Period for Anaerobic Digester and Composting Facilities (in years)

Scenario (Feedstock Scenario-Anaerobic Digester Scenario)	Low Cost Scenario		Base Cost Scenario		High Cost Scenario	
	Anaerobic Digester	Compost Facility	Anaerobic Digester	Compost Facility	Anaerobic Digester	Compost Facility
Base Feed-Low AD	No Payback	No Payback	No Payback	No Payback	No Payback	No Payback
Base Feed-Base AD	No Payback	No Payback	No Payback	No Payback	No Payback	No Payback
Base Feed-High AD	378	No Payback	No Payback	No Payback	No Payback	No Payback
Medium Feed-Low AD	79	No Payback	No Payback	No Payback	No Payback	No Payback
Medium Feed-Base AD	56	No Payback	847	No Payback	No Payback	No Payback
Medium Feed-High AD	34	No Payback	162	No Payback	No Payback	No Payback
High Feed-Low AD	27	No Payback	98	No Payback	No Payback	No Payback
High Feed-Base AD	21	No Payback	65	No Payback	243	No Payback
High Feed-High AD	16	No Payback	45	No Payback	70	No Payback

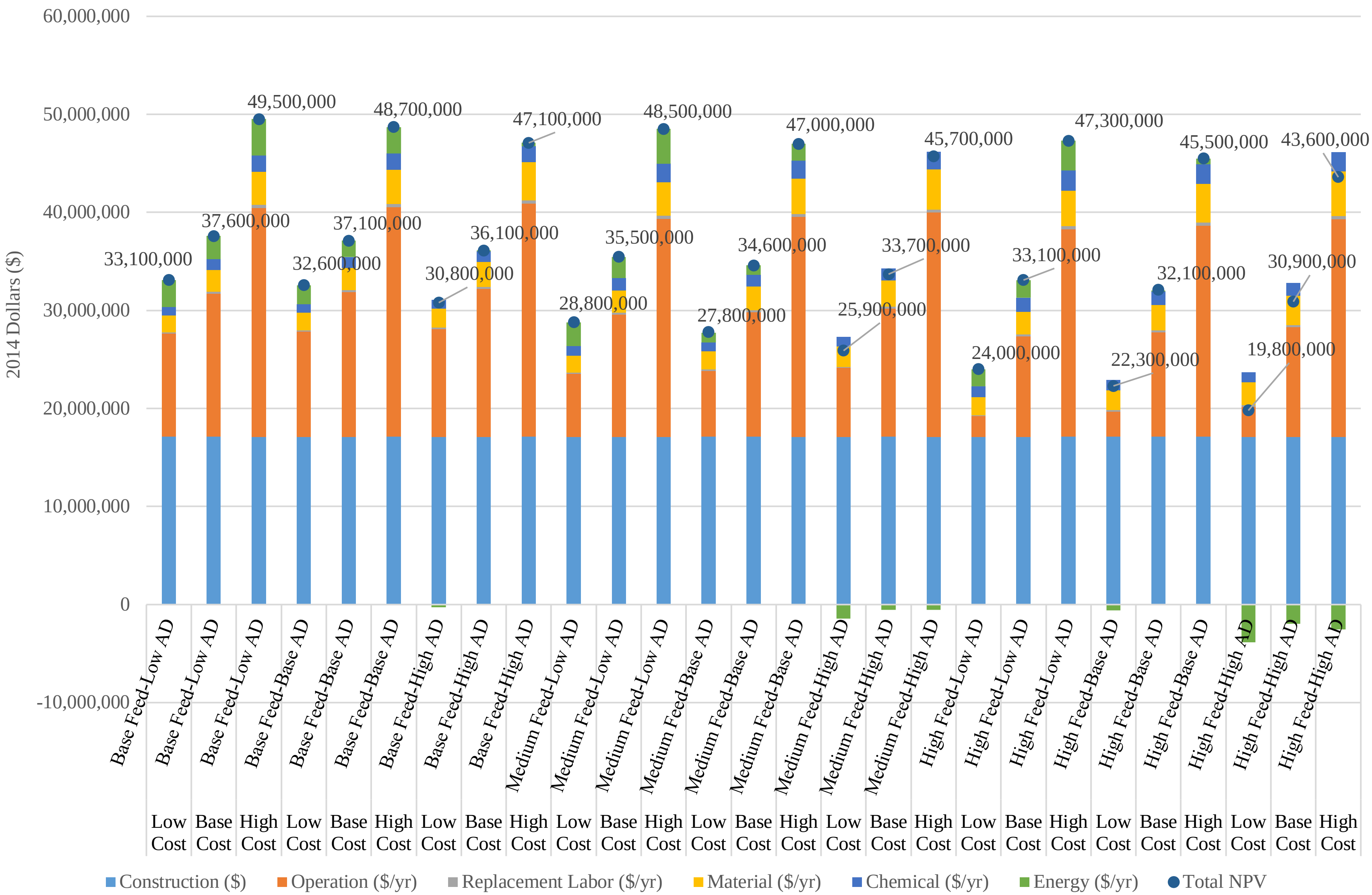

Figure 6-9. Life cycle cost assessment summary showing results for each Feedstock-AD Scenario by cost scenario.

7. Conclusions

LCA results presented in this study serve to highlight the trade-offs in environmental performance that can accompany efforts to reduce nutrient loading to receiving waters and identify several key treatment options and management practices that can be used to effectively reduce or eliminate trade-offs. As would be expected, the upgraded treatment system realizes a consequential 25-40 percent reduction in net eutrophication impact dependent on the Feedstock-AD scenario being considered. Eutrophication impacts are generally less sensitive to scenario assumptions than are other impact categories more strongly linked to electricity use and process air emissions. The eutrophication benefit comes at the expense of an approximate 25-30 percent increase in global warming potential and acidification potential within the base case scenario. Net smog formation potential, cumulative energy demand, fossil depletion potential, and particulate matter formation potential results for the upgraded treatment system are between 5 and 11 percent greater than the legacy system in the base scenario, while water use in the base scenario is reduced dramatically due to avoided fertilizer production and wastewater reuse.

The relative gap in global warming potential impact between the two systems narrows considerably if low composting emissions are achieved, and widens if composting emissions at the higher end of the spectrum are assumed. In general, the results demonstrate a strong sensitivity to the use of composting and associated assumptions regarding EOL emission factors. The results indicate that considerable effort is warranted to ensure that compost management practices minimize GHG emissions. Further research determining best management practices that can be used to ensure low composting emissions and/or alternative strategies for pest and vector reduction warrant consideration. The ASP composting system demonstrated the potential to avoid the highest GHG emission rates associated with the windrow system and provides a good option for communities, particularly when paired with AD as a source of clean electrical energy. Section 6.1 also demonstrates the environmental benefit of improved landfill methane gas capture systems, such as the system installed at the Bath regional landfill, as compared to national average gas capture performance.

The sensitivity analysis clearly demonstrates the benefit of avoided natural gas and electricity production attributable to the addition of AD as part of the upgraded plant. Marked reductions in environmental impact are demonstrated in scenarios exploring increased acceptance of high strength organic waste and the pursuit of exceptional digester operational performance, even as the plant accepts additional high strength waste relative to quantities treated in the legacy scenario. Both strategies boost biogas production, and subsequently yield environmental credits from avoided energy production. Net environmental benefits are demonstrated to be possible for some of the Feedstock-AD scenarios in seven of eight environmental impact categories included in this study, with eutrophication potential being the sole exception where impact results remain positive although reduced in respect to the legacy system.

The absolute magnitude of LCCA results show a strong dependence on basic parameters employed within the analysis, specifically the discount rate, escalation rates, and revenue rates for trucked organic waste and electricity sales. Setting this aside, the analysis demonstrates the economic benefit on project NPV when high strength organic waste is processed in the AD unit, particularly if high AD operational performance is achieved. Biogas yields for the high AD scenario are specifically related to the expected pairing of chemically enhanced primary treatment with AD, and indicate a potential cost benefit of this combination if pilot scale results concerning biogas yield can be achieved at full-scale. LCCA results show that achieving an AD payback period which is shorter than the system lifetime is challenging at this scale. The results suggest that future work should focus on determining the minimum quantity of high strength organic waste processing that begins to demonstrate appreciable cost benefits for 1 MGD facilities and the communities that they serve.

The environmental benefits of installing AD and biosolids reuse programs accrue more quickly than do financial benefits to the utility and municipality. However, the analysis shows that even modest quantities of high strength organic waste begin to show a potential cost justification for the installation of AD, providing a quantitative justification for the concept of the resource recovery hub, its environmental benefits, and the possibility of an economic rationale if the capacity of infrastructure is maximized and markets are found for recovered energy and material resources.

The following next steps are suggested by the results of this analysis:

- Exploration of the effect that increased acceptance of high strength organic waste for a larger capacity AD would have on cumulative environmental impacts of the Bath facility, the potential to generate revenue, and the WWTP's position as a resource recovery hub within the community.
- Investigation of the additional system-wide benefits due to diversion of high strength organic waste from current disposal methods to treatment at the Bath facility. For example, industrial waste sources may currently be treated at the industrial facility. The need for smaller industrial WWTPs and the associated environmental burdens would be eliminated if the Bath WWTP were to treat this waste.
- Further research into composting emissions, particularly whether there exists sufficient evidence to tie specific management practices to emission rates in the lower end of the potential range.
- Analysis of alternative pathogen reduction and vector control strategies that can be used to produce Class A biosolids.

8. REFERENCES

ALS (ALS Group USA). 2015. Analytical Report on Incoming Septage Waste. Performed for Bath Wastewater Treatment Facility.

Appleton, A.R., and T. Rauch-Williams. 2017. Co-Digestion of Organic Waste Addressing Operational Side-Effects. Prepared for Water Environment & Reuse Foundation (WE&RF).

Bare, J., G.A. Norris, D.W. Pennington, and T. McKone. 2003. TRACI: The Tool for the Reduction and Assessment of Chemical and other Environmental Impacts. *Journal of Industrial Ecology*. 6(3-4): p. 49-78.

Bare, J. 2011. TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and other Environmental Impacts 2.0. *Clean Technology and Environmental Policy*. 13(5): 687-696.

Barton, P.K., and J.W. Atwater. 2002. Nitrous Oxide Emissions and the Anthropogenic Nitrogen in Wastewater and Solid Waste. *Journal of Environmental Engineering*. 128(2): 137-150.

BEGWS (Bath Electric, Gas & Water Systems). 2016. Bath Influent and Effluent Water Quality Data: October 2011 to November 2015. Bath, NY.

Belhadj, S., F. Karouach, H. El Bari, Y. Joute. 2013. The Biogas Production from Mesophilic Anaerobic Digestion of Vinasse. *Journal of Environmental Science, Toxicology and Food Technology*. 5(6): 72-77.

Bond, T., and M.R. Templeton. 2011. History and Future of Domestic Biogas Plants in the Developing World. *Energy for Sustainable Development*. 15: 347-354.

Borjesson, G., and B.H. Svensson. 1997. Nitrous Oxide Emissions from Landfill Cover Soils in Sweden. Tellus. 49B: 357–363.

Bothi, K.L. 2007. Characterization of Biogas from Anaerobically Digested Dairy Waste for Energy Use. Master's Thesis, Cornell University, Ithaca, New York.

Brake, P. 2007. A Bug's-Eye-View of the BOD Test. http://www.perrybrake.com/BODBook.html Accessed 30 August, 2016.

Braun, R., and A. Wellinger. 2003. Potential of Co-Digestion. International Energy Agency. http://www.iea-biogas.net/files/daten-redaktion/download/publi-task37/Potential%20of%20Codigestion%20short%20Brosch221203.pdf. Accessed 30 June, 2016.

Brown, S., M. Cotton, S. Messner, F. Berry, and D. Norem. 2009. Issue Paper: Methane Avoidance from Composting. http://faculty.washington.edu/slb/docs/CCAR_Composting_issue_paper.pdf Accessed 9 September 2016.

Brown, S., C. Kruger, and S. Subler. 2008. Greenhouse Gas Balance for Composting Operations. *Journal of Environmental Quality*. 37: 1396-1410.

Bustamente, M.A., Paredes, C., Moral, R., Moreno-Caselles, J., Perez-Espinosa, A., and Perez-Murcia, M.D. 2005. Uses of Winery and Distillery Effluents in Agriculture: Characterization of Nutrient and Hazardous Components. *Water Science and Technology*. 51(1):145-151.

Chandran, K. 2012. Greenhouse Nitrogen Emissions from Wastewater Treatment Operation: Phase I, Final Report. Water Environment Research Foundation. U4R07.

CBF (Chesapeake Bay Foundation). 2016a. About the Bay: The Issues. http://www.cbf.org/about-the-bay/issues. Accessed 22 June, 2016.

CBF (Chesapeake Bay Foundation). 2016b. Creatures of the Chesapeake. http://www.cbf.org/about-the-bay/more-than-just-the-bay/creatures-of-the-chesapeake. Accessed 22 June, 2016.

CCME (Canadian Council of Ministers of the Environment). 2009. Biosolids Emissions Assessment Model (BEAM): User Guide. http://www.ccme.ca/files/Resources /waste/biosolids/beam_user_guide_1430.pdf Accessed 10 April, 2017.

CDM Smith. 2012. Guidelines for Water Reuse. Prepared for U.S. Environmental Protection Agency. EPA/600/R-12/618. https://watereuse.org/wp-content/uploads/2015/04/epa-2012-guidelines-for-water-reuse.pdf Accessed 9 May, 2017.

Chardoul, N. K. O'Brien, B. Clawson, and M. Flechter, ed. 2011. Compost Operator Guidebook: Best Management Practices for Commercial Scale Composting Operations. Michigan Department of Environmental Quality. https://www.michigan.gov/documents/deq/deq-oea-compostoperatorguidebook_488399_7.pdf Accessed 10 April, 2017.

Cunningham, E. 2016. Personal communication with Erin Cunningham. GHD Engineering. 14 June, 2016.

CRA (Conestoga-Rovers and Associates). 2015. Village of Bath WWTP Upgrades Final Engineering Report. Report No.2, Revision 2. Prepared for Bath Electric, Gas & Water Systems. Syracuse, NY.

CWMI (Cornell Waste Management Institute). 1990. Yard Waste Composting. http://compost.css.cornell.edu/yardwastecomposting2.pdf Accessed 9 September, 2016.

Czepiel, P.M., P.M. Crill, and R.C. Harriss. 1993. Methane Emissions from Municipal Wastewater Treatment Processes. *Environmental Science and Technology*. 27: 2472-2477.

Czepiel, P., P. Crill, and R. Harriss. 1995. Nitrous Oxide Emissions from Municipal Wastewater Treatment. *Environmental Science and Technology*. 29: 2352-2356.

Daelman, M.R.J., E.M. Voorthuizen, L.G.J.M. van Dongen, E.I.P. Volcke, and M.C.M van Loosdrecht. 2013. Methane and Nitrous Oxide Emissions from Municipal Wastewater Treatment–Results from a Long-Term Study. *Water Science and Technology.* 67(10): 2350-2355.

De Guardia, A., P. Mallard, C. Teglia, A. Marin, C. Le Pape, M. Launay, J.C. Benoist, and C. Petiot. 2009. Comparison of Five Organic Wastes Regarding their Behaviour During Composting: Part 1, Biodegradability, Stabilization Kinetics and Temperature Rise. *Waste Management.* https://hal.archives-ouvertes.fr/hal-00455647/document Accessed 9 May, 2017.

Ecoinvent Centre. 2010. Cumulative Energy Demand (CED) Method Implemented in Ecoinvent Data v2.2. Swiss Centre for Life Cycle Inventories.

Emmerson, R.H.C., G.K. Morse, J.N. Lester, and D.R. Edge. 1995. The Life Cycle Analysis of Small-Scale Sewage-Treatment Processes. *Water and Environment Journal.* 9(3): 317-325.

Engineering Toolbox. 2016. Rebar Weight. http://www.engineeringtoolbox.com/rebar-rods-weight-d_1709.html Accessed 6 September, 2016.

Frischknecht R., N. Jungbluth, H.J. Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, and M. Spielmann. 2005. The Ecoinvent Database: Overview and Methodological Framework. *International Journal of Life Cycle Assessment*. 10: 3–9.

Fukumoto, Y. T. Osada. D. Hanajima, and K. Haga. 2003. Patterns and Quantities of NH3, N2O, and CH4 Emissions during Swine Manure Composting without Forced Aeration – Effect of Compost Pile Scale. *Bioresource Technology.* 89: 109-114.

Gelegenis, J., D. Georgakakis, I. Angelidaki, and V. Mavris. 2007. Optimization of Biogas Production by Co-Digesting Whey with Diluted Poultry Manure. *Renewable Energy*. 32: 2147-2160.

GHD Engineering. 2015. Preliminary Solids Handling Basis of Design at Maximum Month Conditions. Provided by BEGWS.

GHD. 2016. Life Cycle Cost Analysis Evaluation: Preliminary and Primary Treatment Processes Village of Bath WWTP Upgrades. Prepared for Bath Electric, Gas, and Water Systems. Bath, NY.

Goedkoop, M., R. Heijungs, M. Huijbregts, A.D. Schryver, J. Struijs, and R. van Zelm. 2009. ReCiPe 2008: A Life Cycle Impact Assessment Method which comprises Harmonised Category Indicators at the Midpoint and Endpoint Level; First Edition Report I: Characterization. http://www.leidenuniv.nl/cml/ssp/publications /recipe_characterisation.pdf Accessed 20 September, 2016.

Hao, X., C. Chang, F. Larney, and G.R. Travis. 2001. Greenhouse Gas Emissions during Cattle Feedlot Manure Composting. *Journal of Environmental Quality*. 30: 376–386.

Harris, R.A., and D.R. Phillips. 1986. Density of Selected Wood Fuels. http://www.gfc.state.ga.us/resources/publications/research-papers/GFRP61.pdf. Accessed 18 August 2016.

Hellebrand, H.J. 1998. Emission of N_2O and other Trace Gases during Composting of Grass and Green Waste. *Journal of Agricultural Engineering Research*. 96: 365-375

Hellmann, B. L. Zelles, A. Palojarvi, and Q. Bai. 1997. Emission of Climate-Relevant Trace Gases and Succession of Microbial Communities during Open-Windrow Composting. *Applied and Environmental Microbiology*. 63(3): 1011-1018.

Hydromantis. 2014. CAPDETWorks™ Version 3.0 Software: Rapid Design and Costing Solution for Wastewater Treatment Plants.

IEA (International Energy Agency). 2009. Biogas from Slaughterhouse Waste: Towards an Energy Self-Sufficient Industry. http://www.iea-biogas.net/success-stories.html?file=files/daten-redaktion/download/Success%20Stories/st_martin.pdf. Accessed 30 June, 2016.

ISO (International Organization for Standardization). 2006. Environmental Management -- Life Cycle Assessment -- Requirements and Guidelines; ISO No. 14044; ISO: Switzerland, Jan 07.

IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan

ISO-NE (Independent System Operators New England). 2016. 2014 ISO New England Electric Generator Air Emissions Report. http://www.iso-ne.com/static-assets/documents/2016/01/2014_emissions_report.pdf Accessed 30 August, 2016.

Jasko, J., E. Skripsts, V. Dubrovskis, E. Zabarovskis, and V. Kotelenecs. 2011. Biogas production from Cheese Whey in Two Phase Anaerobic Digestion. Presented at Engineering for Rural Development Conference, Jelgava, Latvia.

Luste, S., and Luostarinen, S. 2010. Anaerobic Co-Digestion of Meat-Processing By-Products and Sewage Sludge - Effect of Hygienization and OLR. *Bioresource Technology*. 101: 2657-2664.

Malinska, K., M. Zabochnicka-Swiatek. 2013. Selection of Bulking Agents for Composting of Sewage Sludge. *Environment Protection Engineering*. 39(2): 91-103.

Maulini-Duran, C. A. Artola, X. Font, and A. Sanchez. 2013. A Systematic Study of the Gaseous Emissions from Biosolids Composting: Raw Sludge versus Anaerobically Digested Sludge. *Bioresource Technology*. 147: 43-51.

Miller, Kim. 2016. Personal communication with Kim Miller, from Bath Electric, Gas, and Water. Bath, NY. Spring 2016.

Myhre, G., D. Shindell, F.M. Breon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.F. Lamarque, et al. 2013. Anthropogenic and Natural Radiative Forcing, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T. Stocker, et al., Editors. Cambridge University Press: Cambridge, UK and New York, NY, USA.

Norris, G.A. 2003. Impact Characterization in the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts: Methods for Acidification, Eutrophication, and Ozone Formation. *Journal of Industrial Ecology*. 6 (3-4): 79-101.

Palatsi, J., M. Vinas, B. Fernandez, and X. Flotats. 2011. Anaerobic Digestion of Slaughterhouse Waste: Main Process Limitations and Microbial Community Interactions. *Bioresource Technology*. 102(3). 2219-2227.

Pawlowski, A., M.R. Dudzinska, L. Pawlowski., ed. 2013. Environmental Engineering IV. London: Taylor and Francis Group, LLC.

Richard, T. 2014. Moisture and Carbon/Nitrogen Ratio Calculations Spreadsheet. http://compost.css.cornell.edu/download.html Accessed 9 September 2016.

Rico, C., R. Diego, A. Valcarce, and J.L. Rico. 2014. Biogas Production from Various Typical Organic Wastes Generated in the Region of Cantabria (Spain): Methane Yields and Co-Digestion Tests. *Smart Grid and Renewable Energy*. 5: 128-136.

Rinne, J., M. Pihlatie, A. Lohila, T. Thum, M. Aurela, J. P. Tuovinen, T. Laurila, and T. Vesala. 2005. Nitrous Oxide Emissions from a Municipal Landfill. *Environmental Science and Technology*. 39(20): 7790-7793.

ROU (Recycled Organics Unit). 2006. Life Cycle Inventory and Life Cycle Assessment for Windrow Composting Systems. Prepared for Department of Environment and Conservation, Sydney, Australia.

RSMeans. 2016. Building Construction Cost Data. https://www.rsmeansonline.com/ Accessed 20 September, 2016.

RTI (Research Triangle Institute). 2010. Greenhouse Gas Emissions Estimation Methodologies for Biogenic Emissions from Selected Source Categories: Solid Waste Disposal, Wastewater Treatment, Ethanol Fermentation. Prepared for U.S. EPA. https://www3.epa.gov/ttnchie1/efpac/ghg/GHG_Biogenic_Report_draft_Dec1410.pdf Accessed 27 April, 2017.

Saginaw Pipe. 2016. Welded and Seamless Steel Pipe Chart. http://www.saginawpipe.com/steel_pipe_chart-2.htm Accessed 6 September, 2016.

Sindt, L.G. 2006. Environmental Issues in the Rendering Industry, in: D. Meeker (Ed.), Essential Rendering, National Renderers Association, Washington DC. pp. 245–258.

Smith, K. J. Grylls, and P. Metcalfe. 2007. Nutrient Value of Digestate from Farm-Based Biogas Plants in Scotland. Report for Scottish Executive Environmental and Rural Affairs Department. http://www.gov.scot/resource/doc/1057/0053041.pdf Accessed 20 September, 2016.

SPDES (State Pollution Discharge Elimination System). 2014. SPDES Permit Documentation for Bath NY Wastewater Treatment Facility: 9/1/2014 to 8/31/2019.

Stamatelatou, K. N. Giantsiou, V. Diamantis, C. Alexandridis, A. Alexandridis, and A. Aivasidis. 2012. Anaerobic Digestion of Cheese Whey Wastewater through a Two Stage System. Third International Conference on Industrial and Hazardous Waste Management. Crete, 2012.

SYLVIS Environmental. 2011. The Bioslids Emissions Assessment Model (BEAM). Version 1.1. Prepared for the Canadian Council of Ministers of the Environment.

Tchobanoglous, G., H.D. Stensel, R. Tsuchihashi, F. Burton, M. Abu-Orf, G. Bowden, and W. Pfrang. 2014. Wastewater Engineering: Treatment and Resource Recovery. Fifth Edition. McGraw-Hill Education, New York, NY.

Turner Company. 2011. Reinforced Concrete Piping. http://www.theturnerco.com/products /reinforced-concrete-pipe Accessed 6 September, 2016.

U.S. EPA (U.S. Environmental Protection Agency). 2017. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015. EPA 430-P-17-001. https://www.epa.gov/ghgem issions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2015 Accessed 3 May, 2017.

U.S. EPA (U.S. Environmental Protection Agency). 1994. A Plain English Guide to the EPA Part 503 Biosolids Rule. Office of Wastewater Management. EPA/832/R-93-003.

U.S. EPA (U.S. Environmental Protection Agency). 2013. Table 1- U.S. Consumption of Nitrogen, Phosphate, and Potash 1960-2011. http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx. Accessed 26 July, 2016.

U.S. EPA (U.S. Environmental Protection Agency). 2015a. ORD LCA Database. LCA Research Center, National Risk Management Research Laboratory.

U.S. EPA (U.S. Environmental Protection Agency). 2015b. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013. EPA 430-R-15-004. https://www3.epa.gov/ climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf Accessed 18 September, 2016.

U.S. EPA (U.S. Environmental Protection Agency). 2016. Power Profiler Tool. https://www.epa.gov/energy/power-profiler Accessed 30 August, 2016.

U.S. LCI (U.S. Life Cycle Inventory Database). 2012. National Renewable Energy Laboratory. https://www.lcacommons.gov/nrel/search Accessed 20 September, 2016.

USPC (United States Plastic Corporation). 2016. Schedule 40 & 80 Dimensions. http://www.usplastic.com/catalog/files/drawings/pipespecs.pdf Accessed 6 September, 2016.

Varnier, D. 2004. Life Cycle Cost Analysis as a Decision Support Tool for Managing Municipal Infrastructure. in Proceedings of the CIB 2004 Triennial Congress. 2014. Toronto, Ontario, May 2-9, 2004: International Council for Research and Innovation Building and Construction, Rotterdam, Netherlands.

Williams, T.O. 2009. The Next Generation of Aerated Static Pile Biosolids Composting Facilities. US Composting Council 17th Annual Conference and Tradeshow, Houston, TX. http://compostingcouncil.org/wp/wp-content/uploads/2013/02/Williams1.pdf Accessed 14 April, 2017.

Wiser, J.R., J.W. Schettler, and J.L. Willis. 2010. Evaluation of Combined Heat and Power Technologies for Wastewater Treatment Facilities. Prepared for Columbus Water Works, Columbus, GA. EPA 832-R-10-006.

APPENDIX A: DETAILED LCI CALCULATIONS AND BACKGROUND INFORMATION

Appendix A
Detailed LCI Calculations and Background Information

GHG Calculations

Process based GHG emissions are 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 are assumed to be biogenic in origin, and therefore do not contribute to global warming potential impacts. Calculation of CO_2 process emissions are therefore not included in this study. The following sections describe detailed calculation procedures used to estimate process based GHG emissions in this analysis.

Nitrous Oxide Emissions from Biological Treatment

The methodology for calculating N_2O emissions associated with wastewater treatment is based on estimates of emissions reported in the literature. The guidance provided in the IPCC Guidelines for national inventories does not provide a sufficient basis to distinguish N_2O emissions from varying types of wastewater treatment configurations, particularly related to biological nutrient reduction. 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 (Chandran 2012).

Data collected from 12 WWTPs were reviewed to identify which wastewater treatment configuration they may best represent (Chandran 2012). Using the emissions measured from these systems, an average emission factor (EF) was calculated and applied to the modeled data. The methodological equation is:

$$N_2O\ PROCESS = TKN\ (mg/L) \times Flow\ (MGD) \times 3.785\ L/gal \times 365.25\ days/yr \times 1x10\text{-}6\ kg/mg \times EF_{\%} \times 44/14$$

where:

N_2O PROCESS = N_2O emissions from wastewater treatment process (kg N_2O /yr)

TKN = Concentration of TKN entering biological treatment process (mg/L)

Flow = Wastewater treatment flow entering biological treatment process (MGD)

$EF_{\%}$ = average measured % of TKN emitted as N_2O, %

44/14 = molecular weight conversion of N to N_2O

Annual emissions per system were translated to emissions per m^3 of wastewater treated, using the following calculation.

$$N_2O\ Process\ Emissions\ (kg\ N_2O\ /m^3\ wastewater) = N_2O\ PROCESS \div [1\ MGD \times 365\ days/yr \times 0.00378541\ m3/gal]$$

Methane Emissions from Biological Treatment

The methodology for calculating CH_4 emissions associated with the wastewater treatment configurations evaluated as part of this study is generally based on the guidance provided in the IPCC Guidelines for national inventories. CH_4 emissions are 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 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.

For this analysis, some of the wastewater treatment configurations include anaerobic zones within the treatment system. For these configurations, a methane correction factor (MCF) was used. The methodological equation is:

$$CH_4\ \text{PROCESS} = \text{BOD (mg/L)} \times \text{Flow (MGD)} \times 3.785\ \text{L/gal} \times 365.25\ \text{days/yr} \times 1\text{x}10\text{-}6\ \text{kg/mg} \times \text{Bo} \times \text{MCF}$$

where:

CH_4 PROCESS = CH_4 emissions from wastewater treatment process (kg CH_4 /yr)

BOD = Concentration of BOD entering biological treatment process (mg/L)

Flow = Wastewater treatment flow entering biological treatment process (MGD)

Bo = maximum CH_4 producing capacity, kg CH_4/kg BOD

MCF = methane correction factor (fraction)

For this analysis, there was no relevant MCF provided in the IPCC guidance for centralized aerobic treatment with the wastewater treatment configurations included in this study. Instead, MCFs were developed based on GHG emission studies that were conducted at two U.S. WWTPs. The first study (Czepiel, 1993) evaluated emissions associated with a conventional activated sludge treatment plant, resulting in an MCF of 0.005, which was used for the legacy system. The second study (Daelman et al., 2013) evaluated emissions associated with a municipal treatment plant with biological nutrient removal (specifically nitrification and denitrification), resulting in an MCF of 0.05, which was used for the upgraded WWTP.

Annual emissions per system were than translated to emissions per m^3 of wastewater treated, using the following calculation.

$$CH_4\ \text{Process Emissions (kg } CH_4\text{ /m3 wastewater)} = CH_4\ \text{PROCESS} \div [10\ \text{MGD x } 365\ \text{days/yr x } 0.00378541\ m^3\text{/gal}]$$

Nitrous Oxide Emissions from Effluent Release

The methodology for calculating nitrous oxide emissions associated with effluent discharge is based on the guidance provided in the IPCC Guidelines for national inventories. N_2O emissions from domestic wastewater (wastewater treatment) were estimated based on the amount of nitrogen discharged to aquatic environments from each of the system configurations, which accounts for nitrogen removed with sewage sludge.

$$N_2O_{EFFLUENT} = N_{EFFLUENT} \times Flow \times 3.785\ L/gal \times 365.25\ days/yr \times 1x10\text{-}6\ kg/mg \times EF_3 \times 44/28$$

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, MGD

EF_3 = Emission factor (0.005 kg N_2O -N/kg sewage-N produced)

44/28 = Molecular weight ratio of N_2O to N_2

Annual emissions per system were translated to emissions per m^3 of wastewater treated, using the following calculation.

$$N_2O\ Effluent\ Emissions\ (kg\ N_2O/m^3\ wastewater) = N_2OEFFLUENT \div [1\ MGD\ x\ 365\ days/yr\ x\ 0.00378541\ m^3/gal]$$

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 the U.S. EPA (RTI 2010). The quantity of degradable carbon that breaks down over 100 years is calculated, using the following equation. 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 Table 3-10 of the main report.

$$Degradable\ Carbon\ Remaining\ (metric\ tons) = C_t = C_0 * e^{(-k*t)}$$

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 is assumed to degrade to CH_4 with the remainder degrading to CO_2. Under base case 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 warming 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 are 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.

GHG Emissions from Composting

The composting emissions scenario employs a range of emission factors for methane, nitrous oxide, ammonia, and carbon monoxide as presented in Table A-1. The table also calculates the fraction of incoming nitrogen or carbon that these emissions represent and demonstrates that they conform to the range of expected composting emissions as stated by the IPCC (2006).

Table A-1. Composting Emission Factors by Feedstock-AD Scenario

Emission Scenario	Feedstock-AD Scenario	Emission Species	Element	LCI Emission Factor	LCI Units	Loss of Incoming Element to GHGs	Units
Low	Base-Low	CH_4	C	1.6E-03	kg CH_4/m^3 wastewater	0.11%	% of incoming C lost as CH_4
Low	Medium-Low	CH_4	C	2.1E-03	kg CH_4/m^3 wastewater	0.11%	% of incoming C lost as CH_4
Low	High-Low	CH_4	C	3.0E-03	kg CH_4/m^3 wastewater	0.11%	% of incoming C lost as CH_4
Low	Base-Base	CH_4	C	1.4E-03	kg CH_4/m^3 wastewater	0.11%	% of incoming C lost as CH_4
Low	Medium-Base	CH_4	C	2.0E-03	kg CH_4/m^3 wastewater	0.11%	% of incoming C lost as CH_4
Low	High-Base	CH_4	C	2.7E-03	kg CH_4/m^3 wastewater	0.11%	% of incoming C lost as CH_4
Low	Base-High	CH_4	C	1.3E-03	kg CH_4/m^3 wastewater	0.11%	% of incoming C lost as CH_4
Low	Medium-High	CH_4	C	1.9E-03	kg CH_4/m^3 wastewater	0.11%	% of incoming C lost as CH_4
Low	High-High	CH_4	C	2.5E-03	kg CH_4/m^3 wastewater	0.11%	% of incoming C lost as CH_4
Low	Base-Low	N_2O	N	2.2E-04	kg N_2O/m^3 wastewater	0.35%	% of incoming N lost as N_2O
Low	Medium-Low	N_2O	N	3.0E-04	kg N_2O/m^3 wastewater	0.34%	% of incoming N lost as N_2O
Low	High-Low	N_2O	N	4.2E-04	kg N_2O/m^3 wastewater	0.34%	% of incoming N lost as N_2O
Low	Base-Base	N_2O	N	2.0E-04	kg N_2O/m^3 wastewater	0.34%	% of incoming N lost as N_2O
Low	Medium-Base	N_2O	N	2.8E-04	kg N_2O/m^3 wastewater	0.34%	% of incoming N lost as N_2O
Low	High-Base	N_2O	N	3.8E-04	kg N_2O/m^3 wastewater	0.34%	% of incoming N lost as N_2O
Low	Base-High	N_2O	N	1.9E-04	kg N_2O/m^3 wastewater	0.34%	% of incoming N lost as N_2O
Low	Medium-High	N_2O	N	2.6E-04	kg N_2O/m^3 wastewater	0.35%	% of incoming N lost as N_2O
Low	High-High	N_2O	N	3.5E-04	kg N_2O/m^3 wastewater	0.34%	% of incoming N lost as N_2O
Low	Base-Low	NH_3	N	5.8E-04	kg NH_3/m^3 wastewater	1.20%	% of incoming N lost as NH_3
Low	Medium-Low	NH_3	N	8.1E-04	kg NH_3/m^3 wastewater	1.20%	% of incoming N lost as NH_3
Low	High-Low	NH_3	N	1.1E-03	kg NH_3/m^3 wastewater	1.20%	% of incoming N lost as NH_3
Low	Base-Base	NH_3	N	5.4E-04	kg NH_3/m^3 wastewater	1.20%	% of incoming N lost as NH_3
Low	Medium-Base	NH_3	N	7.5E-04	kg NH_3/m^3 wastewater	1.20%	% of incoming N lost as NH_3
Low	High-Base	NH_3	N	1.0E-03	kg NH_3/m^3 wastewater	1.20%	% of incoming N lost as NH_3
Low	Base-High	NH_3	N	5.0E-04	kg NH_3/m^3 wastewater	1.20%	% of incoming N lost as NH_3

Table A-1. Composting Emission Factors by Feedstock-AD Scenario

Emission Scenario	Feedstock-AD Scenario	Emission Species	Element	LCI Emission Factor	LCI Units	Loss of Incoming Element to GHGs	Units
Low	Medium-High	NH_3	N	7.0E-04	kg NH_3/m^3 wastewater	1.20%	% of incoming N lost as NH_3
Low	High-High	NH_3	N	9.5E-04	kg NH_3/m^3 wastewater	1.20%	% of incoming N lost as NH_3
Base	Base-Low	CH_4	C	1.2E-02	kg CH_4/m^3 wastewater	0.82%	% of incoming C lost as CH_4
Base	Medium-Low	CH_4	C	1.6E-02	kg CH_4/m^3 wastewater	0.82%	% of incoming C lost as CH_4
Base	High-Low	CH_4	C	2.3E-02	kg CH_4/m^3 wastewater	0.82%	% of incoming C lost as CH_4
Base	Base-Base	CH_4	C	1.1E-02	kg CH_4/m^3 wastewater	0.82%	% of incoming C lost as CH_4
Base	Medium-Base	CH_4	C	1.5E-02	kg CH_4/m^3 wastewater	0.82%	% of incoming C lost as CH_4
Base	High-Base	CH_4	C	2.1E-02	kg CH_4/m^3 wastewater	0.82%	% of incoming C lost as CH_4
Base	Base-High	CH_4	C	1.0E-02	kg CH_4/m^3 wastewater	0.82%	% of incoming C lost as CH_4
Base	Medium-High	CH_4	C	1.4E-02	kg CH_4/m^3 wastewater	0.82%	% of incoming C lost as CH_4
Base	High-High	CH_4	C	1.9E-02	kg CH_4/m^3 wastewater	0.82%	% of incoming C lost as CH_4
Base	Base-Low	N_2O	N	1.7E-03	kg N_2O/m^3 wastewater	2.68%	% of incoming N lost as N_2O
Base	Medium-Low	N_2O	N	2.3E-03	kg N_2O/m^3 wastewater	2.67%	% of incoming N lost as N_2O
Base	High-Low	N_2O	N	3.3E-03	kg N_2O/m^3 wastewater	2.67%	% of incoming N lost as N_2O
Base	Base-Base	N_2O	N	1.6E-03	kg N_2O/m^3 wastewater	2.67%	% of incoming N lost as N_2O
Base	Medium-Base	N_2O	N	2.2E-03	kg N_2O/m^3 wastewater	2.67%	% of incoming N lost as N_2O
Base	High-Base	N_2O	N	3.0E-03	kg N_2O/m^3 wastewater	2.67%	% of incoming N lost as N_2O
Base	Base-High	N_2O	N	1.4E-03	kg N_2O/m^3 wastewater	2.67%	% of incoming N lost as N_2O
Base	Medium-High	N_2O	N	2.0E-03	kg N_2O/m^3 wastewater	2.68%	% of incoming N lost as N_2O
Base	High-High	N_2O	N	2.7E-03	kg N_2O/m^3 wastewater	2.67%	% of incoming N lost as N_2O
Base	Base-Low	NH_3	N	3.3E-03	kg NH_3/m^3 wastewater	6.70%	% of incoming N lost as NH_3
Base	Medium-Low	NH_3	N	4.5E-03	kg NH_3/m^3 wastewater	6.70%	% of incoming N lost as NH_3
Base	High-Low	NH_3	N	6.3E-03	kg NH_3/m^3 wastewater	6.70%	% of incoming N lost as NH_3
Base	Base-Base	NH_3	N	3.0E-03	kg NH_3/m^3 wastewater	6.70%	% of incoming N lost as NH_3
Base	Medium-Base	NH_3	N	4.2E-03	kg NH_3/m^3 wastewater	6.70%	% of incoming N lost as NH_3

Table A-1. Composting Emission Factors by Feedstock-AD Scenario

Emission Scenario	Feedstock-AD Scenario	Emission Species	Element	LCI Emission Factor	LCI Units	Loss of Incoming Element to GHGs	Units
Base	High-Base	NH_3	N	5.8E-03	kg NH_3/m^3 wastewater	6.70%	% of incoming N lost as NH_3
Base	Base-High	NH_3	N	2.8E-03	kg NH_3/m^3 wastewater	6.70%	% of incoming N lost as NH_3
Base	Medium-High	NH_3	N	3.9E-03	kg NH_3/m^3 wastewater	6.70%	% of incoming N lost as NH_3
Base	High-High	NH_3	N	5.3E-03	kg NH_3/m^3 wastewater	6.70%	% of incoming N lost as NH_3
High	Base-Low	CH_4	C	3.6E-02	kg CH_4/m^3 wastewater	2.50%	% of incoming C lost as CH_4
High	Medium-Low	CH_4	C	5.0E-02	kg CH_4/m^3 wastewater	2.50%	% of incoming C lost as CH_4
High	High-Low	CH_4	C	6.9E-02	kg CH_4/m^3 wastewater	2.50%	% of incoming C lost as CH_4
High	Base-Base	CH_4	C	3.3E-02	kg CH_4/m^3 wastewater	2.50%	% of incoming C lost as CH_4
High	Medium-Base	CH_4	C	4.6E-02	kg CH4/m^3 wastewater	2.50%	% of incoming C lost as CH_4
High	High-Base	CH_4	C	6.3E-02	kg CH_4/m^3 wastewater	2.50%	% of incoming C lost as CH_4
High	Base-High	CH_4	C	3.1E-02	kg CH_4/m^3 wastewater	2.50%	% of incoming C lost as CH_4
High	Medium-High	CH4	C	4.4E-02	kg CH_4/m^3 wastewater	2.50%	% of incoming C lost as CH_4
High	High-High	CH_4	C	5.8E-02	kg CH_4/m^3 wastewater	2.50%	% of incoming C lost as CH_4
High	Base-Low	N_2O	N	2.9E-03	kg N_2O/m^3 wastewater	4.65%	% of incoming N lost as N_2O
High	Medium-Low	N_2O	N	4.1E-03	kg N_2O/m^3 wastewater	4.65%	% of incoming N lost as N_2O
High	High-Low	N_2O	N	5.7E-03	kg N_2O/m^3 wastewater	4.65%	% of incoming N lost as N_2O
High	Base-Base	N_2O	N	2.7E-03	kg N_2O/m^3 wastewater	4.65%	% of incoming N lost as N_2O
High	Medium-Base	N_2O	N	3.8E-03	kg N_2O/m^3 wastewater	4.65%	% of incoming N lost as N_2O
High	High-Base	N_2O	N	5.2E-03	kg N_2O/m^3 wastewater	4.65%	% of incoming N lost as N_2O
High	Base-High	N_2O	N	2.5E-03	kg N_2O/m^3 wastewater	4.65%	% of incoming N lost as N_2O
High	Medium-High	N_2O	N	3.5E-03	kg N_2O/m^3 wastewater	4.65%	% of incoming N lost as N_2O
High	High-High	N_2O	N	4.8E-03	kg N_2O/m^3 wastewater	4.65%	% of incoming N lost as N_2O
High	Base-Low	NH_3	N	6.2E-03	kg NH_3/m^3 wastewater	12.74%	% of incoming N lost as NH_3
High	Medium-Low	NH_3	N	8.6E-03	kg NH_3/m^3 wastewater	12.74%	% of incoming N lost as NH_3
High	High-Low	NH_3	N	1.2E-02	kg NH_3/m^3 wastewater	12.74%	% of incoming N lost as NH_3

Table A-1. Composting Emission Factors by Feedstock-AD Scenario

Emission Scenario	Feedstock-AD Scenario	Emission Species	Element	LCI Emission Factor	LCI Units	Loss of Incoming Element to GHGs	Units
High	Base-Base	NH_3	N	5.7E-03	kg NH_3/m^3 wastewater	12.74%	% of incoming N lost as NH_3
High	Medium-Base	NH_3	N	8.0E-03	kg NH_3/m^3 wastewater	12.74%	% of incoming N lost as NH_3
High	High-Base	NH_3	N	1.1E-02	kg NH_3/m^3 wastewater	12.74%	% of incoming N lost as NH_3
High	Base-High	NH_3	N	5.3E-03	kg NH_3/m^3 wastewater	12.74%	% of incoming N lost as NH_3
High	Medium-High	NH_3	N	7.4E-03	kg NH_3/m^3 wastewater	12.74%	% of incoming N lost as NH_3
High	High-High	NH_3	N	1.0E-02	kg NH_3/m^3 wastewater	12.74%	% of incoming N lost as NH_3
All	Base-Low	CO	C	1.0E-03	kg CO/m^3 wastewater	0.04%	% of incoming C lost as CO
All	Medium-Low	CO	C	1.4E-03	kg CO/m^3 wastewater	0.04%	% of incoming C lost as CO
All	High-Low	CO	C	1.9E-03	kg CO/m^3 wastewater	0.04%	% of incoming C lost as CO
All	Base-Base	CO	C	9.2E-04	kg CO/m^3 wastewater	0.04%	% of incoming C lost as CO
All	Medium-Base	CO	C	1.3E-03	kg CO/m^3 wastewater	0.04%	% of incoming C lost as CO
All	High-Base	CO	C	1.8E-03	kg CO/m^3 wastewater	0.04%	% of incoming C lost as CO
All	Base-High	CO	C	8.6E-04	kg CO/m^3 wastewater	0.04%	% of incoming C lost as CO
All	Medium-High	CO	C	1.2E-03	kg CO/m^3 wastewater	0.04%	% of incoming C lost as CO
All	High-High	CO	C	1.6E-03	kg CO/m^3 wastewater	0.04%	% of incoming C lost as CO
All	Base-Low	NMVOCs	n.a.	1.9E-04	kg $NMVOCs/m^3$ wastewater	n.a.	n.a.
All	Medium-Low	NMVOCs	n.a.	2.7E-04	kg $NMVOCs/m^3$ wastewater	n.a.	n.a.
All	High-Low	NMVOCs	n.a.	3.7E-04	kg $NMVOCs/m^3$ wastewater	n.a.	n.a.
All	Base-Base	NMVOCs	n.a.	1.8E-04	kg $NMVOCs/m^3$ wastewater	n.a.	n.a.
All	Medium-Base	NMVOCs	n.a.	2.4E-04	kg $NMVOCs/m^3$ wastewater	n.a.	n.a.
All	High-Base	NMVOCs	n.a.	3.4E-04	kg $NMVOCs/m^3$ wastewater	n.a.	n.a.
All	Base-High	NMVOCs	n.a.	1.6E-04	kg $NMVOCs/m^3$ wastewater	n.a.	n.a.
All	Medium-High	NMVOCs	n.a.	2.3E-04	kg $NMVOCs/m^3$ wastewater	n.a.	n.a.
All	High-High	NMVOCs	n.a.	3.1E-04	kg $NMVOCs/m^3$ wastewater	n.a.	n.a.

Electricity Scaling Factors for Feedstock-AD Scenarios

Baseline electricity consumption is scaled for the following units based on the following factors, which are calculated based on the relative increase in the appropriate flow or loading rate attributable to the Feedstock-AD scenario for each piece of equipment. For example, the Medium Feedstock-Low AD scenario yields a 56 percent increase in solids treated at the BFP. Electricity use is scaled up by a factor of 1.56.

Table A-2. Electricity Scaling Factors for Units Affected by Feedstock-AD Scenarios

Equipment	Base Feedstock -Low AD	Base Feedstock -Base AD	Base Feedstock -High AD	Medium Feedstock -Low AD	Medium Feedstock -Base AD	Medium Feedstock -High AD	High Feedstock -Low AD	High Feedstock - Base AD	High Feedstock -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
CHEM FEED - Polymer BFP	1.11	1.00	0.96	1.56	1.38	1.32	2.18	1.89	1.79
CHEM 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	0.96	1.56	1.38	1.32	2.18	1.89	1.79
Drum Drive	1.11	1.00	0.96	1.56	1.38	1.32	2.18	1.89	1.79
Belt Drive	1.11	1.00	0.96	1.56	1.38	1.32	2.18	1.89	1.79
Spray Pump	1.11	1.00	0.96	1.56	1.38	1.32	2.18	1.89	1.79
Screw Conveyor Drive	1.11	1.00	0.96	1.56	1.38	1.32	2.18	1.89	1.79
Belt Conveyor Drive	1.11	1.00	0.96	1.56	1.38	1.32	2.18	1.89	1.79
Digested Sludge Transfer Pump	1.00	1.38	1.89	1.11	1.56	2.18	0.96	1.32	1.79

Infrastructure Calculations

All infrastructure calculations are based on a unit lifespan of 40 years, which is assumed to be a conservative estimate of unit lifespan. Some of these units have already been in existence beyond 40 years, while others have yet to be built. The actual value varies by unit, and as unit lifespan increases the results will show a proportional decrease in impacts associated with infrastructure. If infrastructure impacts were expected to be more prominent in the results, a greater attention to the details of infrastructure assumptions would be required. In this analysis, the impacts from infrastructure are intended to highlight the general magnitude of infrastructures contribution to wastewater treatment impacts, keeping in mind the previous caveats and the necessity to omit the materials associated with mechanical systems such as pumps and blowers.

Concrete estimates are based on unit dimensions as read from engineering design documents associated with each of the units in question. Concrete values are based on the volume of unit walls and floor slabs, and are calculated in cubic meters of concrete per cubic meter of wastewater treated over the assumed 40-year infrastructure lifespan. The following is an example of such a calculation for the parshall flume:

Total wall length = L = 108.9 feet (varies by unit)
Wall height = H = 5.5 feet (varies by unit)
Wall thickness = W = 10in/12in = 0.8 feet (varies by unit)
Volume = LxWxH = 499.1 ft^3 ÷ 35.3 ft^3/m^3 = 14.1 m^3
Concrete (m^3 concrete/m^3 wastewater) = 14.1 m^3/(40 x 1,381,676 m^3/yr) = 2.56E-07 m^3/m^3

Gravel estimates are based on unit area and the depth of crushed stone required for the foundation. The following is an example of such a calculation for the parshall flume included the assumed values used for all units:

Porosity = ŋ = 0.6 (same for all units)
Specific Gravity = 2.7 (same for all units)
Unit Area = A = 435 ft^2
Gravel Depth = d = 2 feet
Gravel (kg/m3) = [(A x d) x (1- ŋ) ÷ 35.3 ft^3/m^3 x (s.g. x 1000 kg/m3)]/(40 yrs x 1,381,676 m^3/yr)
= 4.72E-4 kg/m^3

Earthwork estimates are calculated using the unit area, assumed depth of excavation, and a safety factor. The following is an example of such a calculation for the parshall flume:

Unit Area = A = 435 ft^2
Excavation Depth = d = 2 feet
Safety Factor = SF = 0.3
Earthwork (m^3/m^3 wastewater) = A x d x SF = 435ft^2 x 2ft x 0.3 = 6.96E-7 m^3/m^3

Rebar quantities are based on rebar spacing values as specified in the engineering design documentation. Engineering drawings specified horizontal spacing, vertical spacing, rebar size, and the number of layers per wall. Total length of each rebar size for each unit was measured from the documents and a standard weight for each rebar size was used to determine the quantity of rebar steel as reported in Table A-3.

Table A-3. Rebar Weight per Linear Foot[1]

Rod Number	Rebar size (in)	(lb per linear foot)	kg/linear ft
2	0.250 = 1/4"	0.17	0.08
3	0.375 = 3/8"	0.38	0.17
4	0.500 = 1/2"	0.67	0.30
5	0.625 = 5/8"	1.04	0.47
6	0.750 = 3/4"	1.5	0.68
7	0.875 = 7/8"	2.04	0.93
8	1.000 = 1"	2.67	1.21
9	1.128 = 1 1/8"	3.4	1.54
10	1.270 = 1 1/4"	4.3	1.95
11	1.410 = 1 3/8"	5.31	2.41
14	1.693 = 1 3/4"	7.65	3.47
18	2.257 = 2 1/4"	13.6	6.17

References:
[1] Engineering Toolbox 2016

Piping quantities are also taken from the engineering design documents are assigned to units within the plant. Pipe sizing is provided in the planning documents. In a few cases, the pipes are labeled to be made of PVC, in all other cases the piping is assumed to be made of low-alloy steel. Total length of each pipe size for each unit was measured from the documents and a standard weight for each pipe size, Table A-4, was used to determine the quantity of piping required.

Table A-4. Pipe Weight per Linear Foot

Pipe Material	Size, diameter (in)	kg/linear foot
Concrete[1]	27	146
Metal[2]	18	42
Metal[2]	8	13
Metal[2]	12	23
Metal[2]	4	5
Metal[2]	10	19
Metal[2]	3	4
Concrete[1]	24	120
Metal[2]	6	10
PVC[3]	6	2
PVC[3]	4	1

References:
[1] Turner Co. 2011
[2] Saginaw Pipe 2016
[3] USPC 2016

Historic Influent and Effluent Characteristics

Figure A-1 through Figure A-4 show historic influent and effluent water quality records for the legacy WWTP from October 2011 to August 2014 (BEGWS 2016).

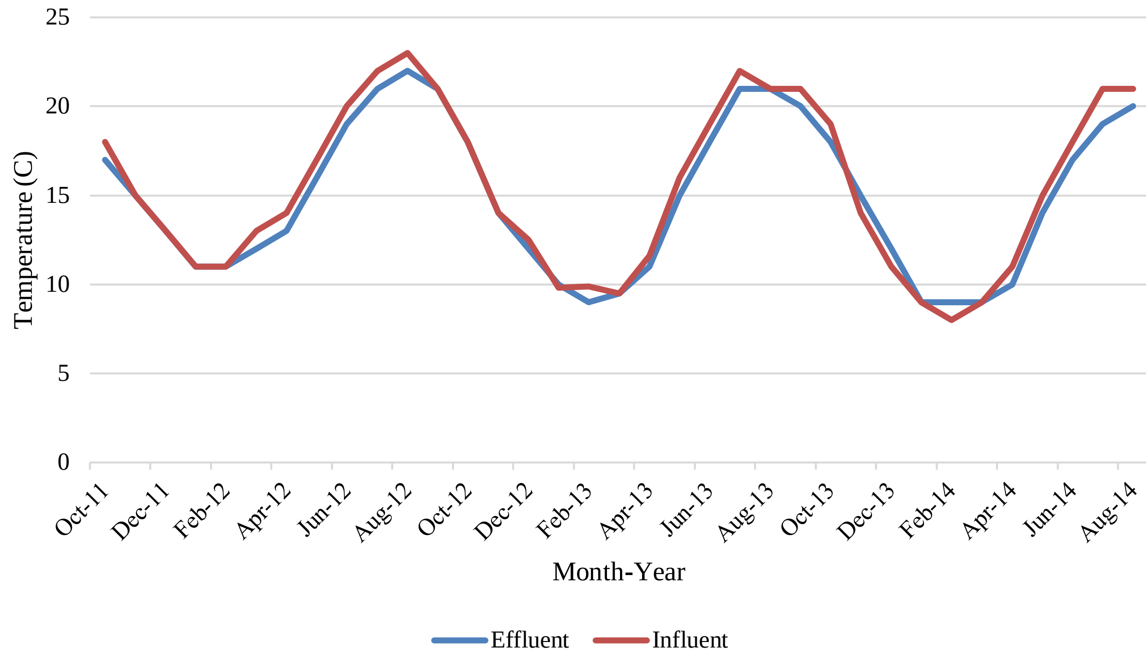

Figure A-1. Bath influent and effluent wastewater temperatures between October 2011 and August 2014 (monitored).

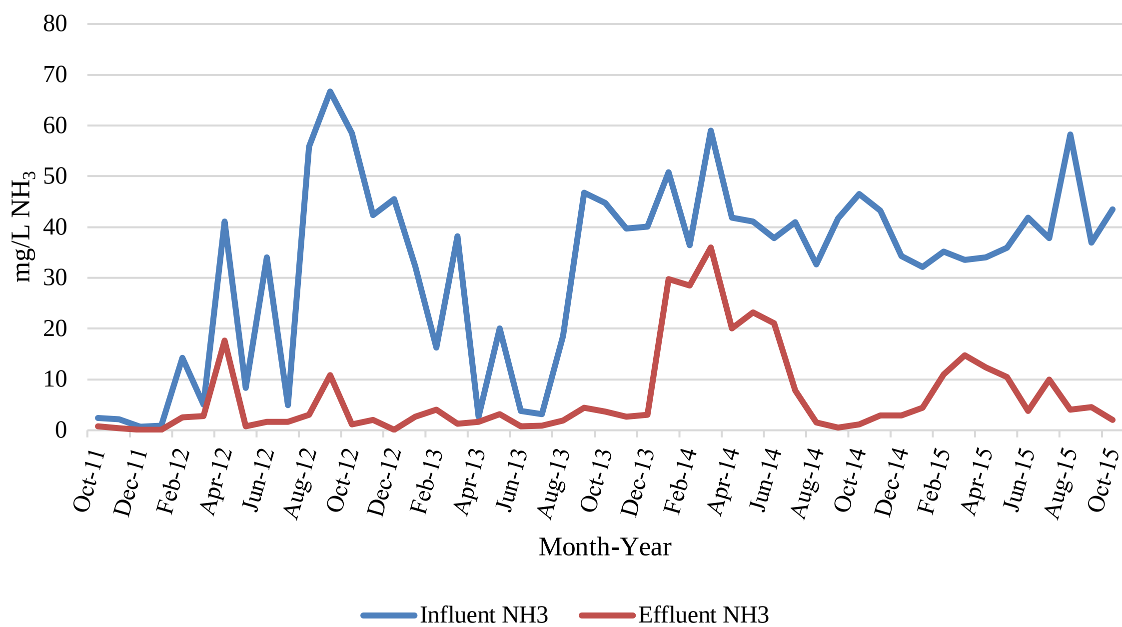

Figure A-2. Bath influent and effluent ammonia concentrations (as NH_3) October 2011 to October 2015 (monitored).

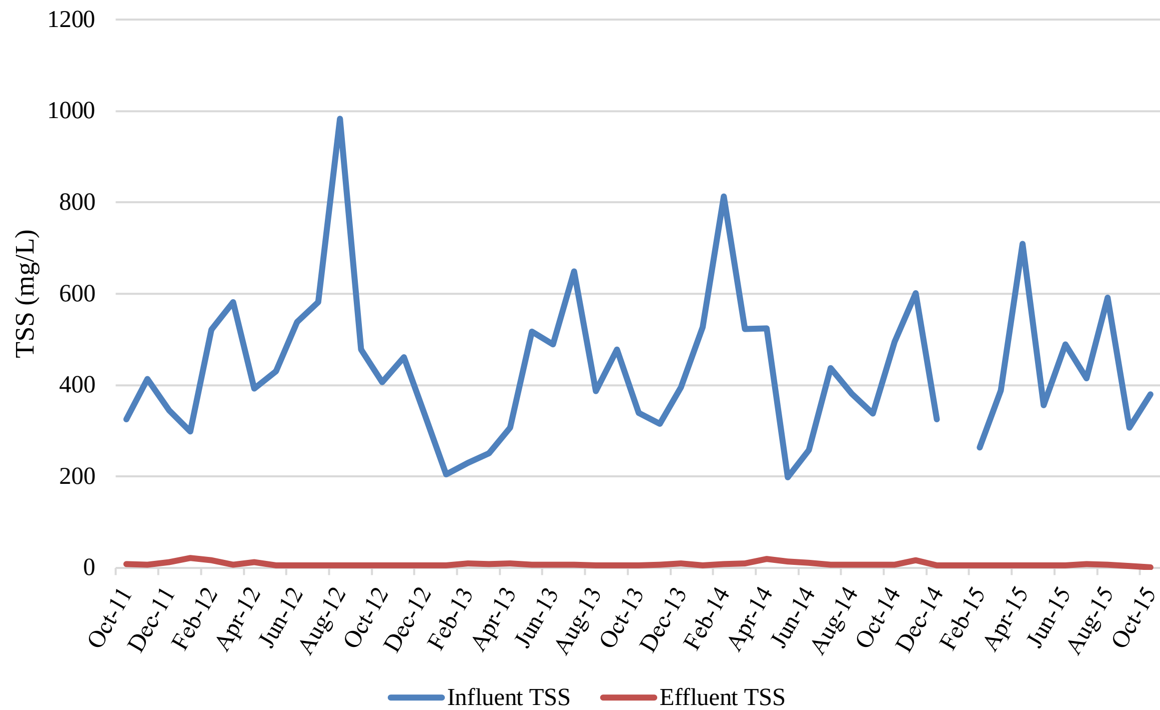

Figure A-3. Bath influent and effluent total suspended solids (TSS) concentrations (mg/L) October 2011 to October 2015 (monitored).

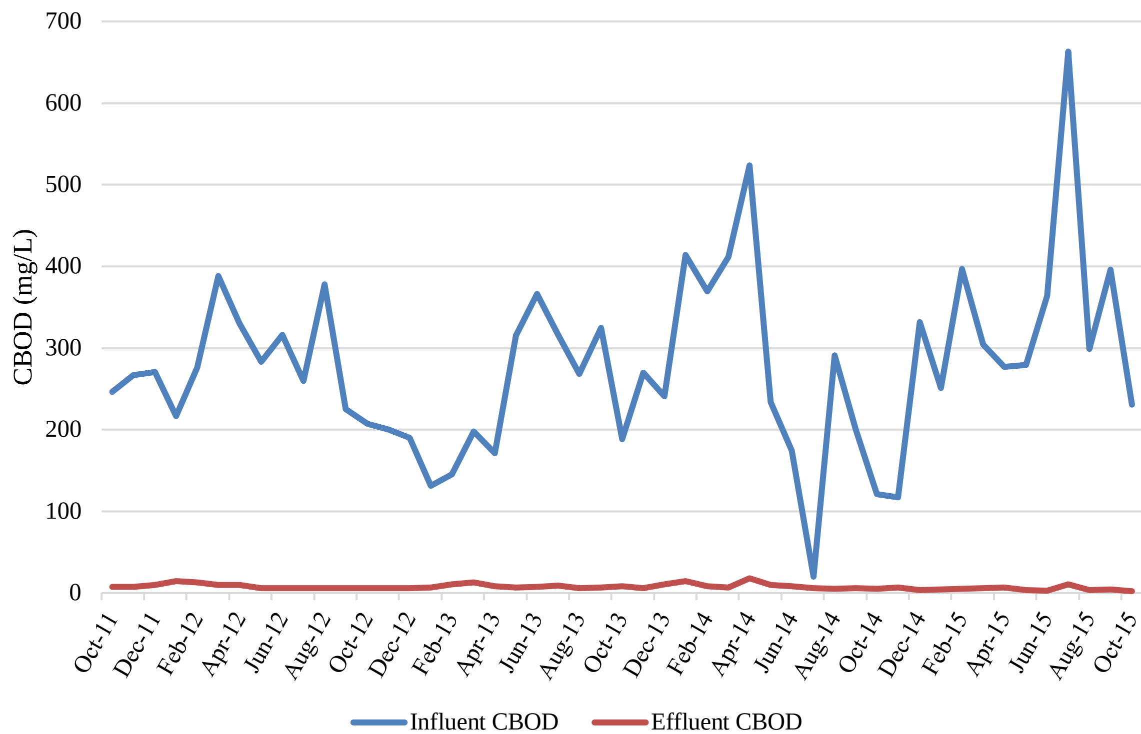

Figure A-4. Bath influent and effluent CBOD concentrations (mg/L) October 2011 to October 2015 (monitored).

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