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Life Cycle Assessment and Cost Analysis of Municipal Wastewater Treatment Expansion Options for Food Waste Anaerobic Co-Digestion

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ABSTRACT

This study presents results of a life cycle assessment (LCA) and life cycle cost assessment (LCCA) of a case-study wastewater treatment facility (WWTF) in Massachusetts, the Greater Lawrence Sanitary District (GLSD). The GLSD WWTF is a medium-sized facility that treats an average municipal sewage flowrate of 23.5 million gallons per day (MGD). The WWTF is currently (2017-2018) in the process of installing additional anaerobic digestion (AD) capacity and a combined heat and power (CHP) system to expand energy recovery. The AD and CHP expansion project will allow GLSD to accept up to 92,000 gallons per day of source separated organic (SSO) waste, avoiding landfill and waste-to-energy disposal of food waste, while considerably boosting biogas production.

A scenario and sensitivity analysis were included to understand the effect of SSO acceptance rate, AD performance, avoided disposal processes and LCCA parameters on environmental impact and life cycle cost results. Results associated with two co-digestion feedstock scenarios were compared to results for baseline (2016) WWTF operation, prior to co-digestion and the AD and CHP expansion. Results are presented for both a low and base AD performance scenario. Base results consider avoided food waste disposal processes that correspond to 2016 end-of-life disposal pathways in Massachusetts, where approximately 68 and 32 percent of food waste were incinerated and landfilled, respectively. The cost analysis compares the above LCA scenarios across two cost scenarios to establish a low and base estimate of system operating costs over a 30-year period.

The study develops life cycle inventory data for the GLSD WWTF based on plant records, engineering design documents and process models of the WWTF. The report presents results for eight environmental impact categories.

Results demonstrate that adoption of SSO co-digestion in combination with the AD and CHP expansion project reduce plant-wide environmental impacts and system operating cost in six of eight environmental impact categories when base AD performance is maintained. Water use is negative, indicating an environmental benefit in all scenarios due to on-site and industrial effluent reuse programs. Eutrophication potential is the only impact category that increases because of anaerobic co-digestion in the base AD performance scenario. Eutrophication impact was found to increase by between 10 and 24 percent, depending upon the scenario.

Results in all other impact categories respond positively (i.e. yielding reductions in net environmental impact) to anaerobic co-digestion. Reductions in fossil fuel depletion, cumulative energy demand and global warming potential can be particularly dramatic due to their strong link with avoided energy products and disposal processes that yield environmental credits within the analysis. Biogas is a source of non-fossil and low-carbon energy that displaces fossil fuel consumption in the Northeast Regional grid mix as well as on-site natural gas combustion. Net present value (NPV) results decrease moderately with AD expansion under the base scenario. These reductions in system NPV correspond to payback periods for the AD expansion and CHP installation project of ten to 27 years in the base AD performance scenario, depending on the cost and SSO acceptance scenario. Payback periods of less than the 30 year analysis period were not identified within the low AD performance scenario.

LIST OF ACRONYMS

AD	Anaerobic digester/digestion
AEC	Alternative energy credit
AP	Acidification potential
ASP	Aerated static pile
BOD_5	Biological oxygen demand, 5-day
CAS	Conventional activated sludge
cBOD	Carbonaceous biological oxygen demand
CED	Cumulative energy demand
CHP	Combined heat and power
COD	Chemical oxygen demand
DMR	Discharge monitoring report
DO	Dissolved oxygen
DTH	Dekatherms
EOL	End-of-life
EP	Eutrophication potential
EPA	Environmental Protection Agency (U.S.)
ERG	Eastern Research Group, Inc.
FDP	Fossil fuel depletion potential
GBT	Gravity belt thickener
GHG	Greenhouse gas
GLSD	Greater Lawrence Sanitary District
gpd	Gallons per day
GWP	Global warming potential
HP	Horsepower
HRT	Hydraulic retention time
ICE	Internal combustion engine
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standardization Organization
km	Kilometer
kW	Kilowatt
kWh	Kilowatt-hour
LCA	Life cycle assessment
LCCA	Life cycle cost assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LMOP	Landfill methane outreach program
MA	Massachusetts
MassDEP	Massachusetts Department of Environmental Protection
MCF	Methane correction factor
Mg	Megagram
MGD	Million gallons per day
MLSS	Mixed liquor suspended solids
MSW	Municipal solid waste
MSW DST	Municipal solid waste decision support tool
NIST	National Institute of Standards and Technology

NMVOC	Non-methane volatile organic compounds
NPDES	National Pollutant Discharge Elimination System
NPV	Net present value
PM	Particulate matter
PMFP	Particulate matter formation potential
QAPP	Quality assurance project plan
RAS	Return activated sludge
REC	Renewable energy credit
SCADA	Supervisory control and data acquisition
SFP	Smog formation potential
SOTE	Standard oxygen transfer efficiency
SRT	Solids retention time
SSO	Source separated organics
TKN	Total kjeldahl nitrogen
TN	Total nitrogen
TP	Total phosphorus
TPY	Tons per year
TRACI	Tool for the Reduction and Assessment of Chemical and Environmental Impacts
TSS	Total suspended solids
U.S.	United States
U.S. LCI	United States Life Cycle Inventory Database
VOC	Volatile organic compound
VS	Volatile solids
VSR	Volatile solids reduction
VSS	Volatile suspended solids
WAS	Waste activated sludge
WTE	Waste-to-Energy
WU	Water use
WWTF	Wastewater treatment facility

LIST OF CHEMICAL SYMBOLS

C	Carbon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
H_2	Hydrogen, gas
H_2O	Water
H_2S	Hydrogen sulfide
NO_3	Nitrate
NO_2	Nitrite
N	Nitrogen
N_2	Nitrogen, gas
N_2O	Nitrous oxide/dinitrogen monoxide
NH_3	Ammonia
NOx	Nitrogen oxides

O_3	Ozone
P	Phosphorus
P_2O_5	Phosphorus pentoxide
SOx	Sulfur oxides

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ES. EXECUTIVE SUMMARY

ES.1 INTRODUCTION

Communities and states throughout the United States (U.S.) are leveraging diverse strategies to manage and transform waste streams to avoid landfilling or incineration by increasing recycling and alternative beneficial uses (U.S. EPA 2017a). The waste ban on organic materials disposed of by large commercial and industrial waste generators in Massachusetts is a specific example of the strategies available (Commonwealth of Massachusetts 2017a). The waste ban motivates institutions to compete and cooperate to identify and enact beneficial alternative disposal methods for diverted organic materials. The U.S. Environmental Protection Agency (U.S. EPA) is working with states to develop best practices based on local experience, providing guidance and objective information that other communities can use to make important management decisions.

This study investigates the potential benefits and burdens of anaerobically digesting diverted organic materials in the context of a case-study wastewater treatment facility (WWTF) in Massachusetts, the Greater Lawrence Sanitary District (GLSD). Life cycle assessment (LCA) and life cycle cost assessment (LCCA) tools were used to examine how the environmental impacts and cost of wastewater treatment are affected when large-scale co-digestion of organic waste is introduced to an existing WWTF. The organic waste is expected to be primarily fruit and vegetable waste, referred to as source separated organics (SSO), from regional commercial and institutional sources.

The GLSD WWTF treats municipal sewage and septic waste for several communities in Massachusetts. The plant treats an average flowrate of approximately 23 million gallons per day (MGD), with a permitted capacity of 52 MGD. The treatment process uses primary sedimentation, conventional activated sludge (CAS) preceded by an anoxic zone and secondary clarification to meet biochemical oxygen demand (BOD_5) and total suspended solids (TSS) permit requirements. The facility was not designed for nutrient removal and has no permit requirements for nitrogen or phosphorus. Sludge processing at the facility consists of dewatering, anaerobic digestion (AD) and biosolids drying and pelletization. Pelletized biosolids are used locally as an agricultural amendment. In response to the Massachusetts organic waste ban, the GLSD WWTF is undergoing a series of renovations to increase AD capacity and expand on-site energy recovery with the installation of a combined heat and power (CHP) system.

This study’s objectives are to:

- Calculate the baseline environmental benefits and burdens of wastewater treatment with AD for a typical mid-sized WWTF;
- Quantify the comparative environment benefits and burdens associated with expanding AD capacity for the co-digestion of SSO;
- Determine the energy recovery potential of AD, and evaluate the environmental and cost benefits of offsetting external electricity and heat generation and alternative organic waste disposal methods such as landfilling or incineration for waste-to-energy (WTE); and

- Determine the life cycle costs associated with the upgraded treatment plant over a 30-year timespan, compare to the baseline scenario prior to co-digestion and calculate a discounted payback period for the AD expansion and CHP project.

ES.2 Methodology

The study employs standard LCA and LCCA methods to simultaneously understand the environmental and economic impacts of expanding AD capacity and energy recovery for the co-digestion of SSO. The analysis complies with the guidelines established for conducting an LCA study in ISOs 14040 and 14044 (ISO 2006a; ISO 2006b). The LCCA results were generated using methods developed by the National Institute of Standards and Technology (NIST) (Fuller and Petersen 1996).

A scenario analysis was used to characterize the energy recovery potential for two co-digestion scenarios at two levels of AD performance. Impact results for the co-digestion and AD performance scenarios were compared against a historical (2016), baseline scenario that is representative of typical plant operations prior to co-digestion. The studies functional unit is the treatment of one cubic meter (m^3) of municipal wastewater. The acceptance of SSO material has a negligible effect on the volume of waste treated by the facility and was therefore excluded from the definition of the functional unit.

Table ES-1 summarizes the impact category metrics calculated for each scenario. Most of the life cycle impact assessment (LCIA) metrics were estimated using the Tool for the Reduction and Assessment of Chemical and environmental Impacts (TRACI), version 2.1 (Bare et al. 2003; Bare 2011). Global warming potential was estimated using the 100-year characterization factors provided by the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (Pachauri and Reisinger 2007). The ReCiPe LCIA method was used to characterize water use and fossil fuel depletion potential (Goedkoop et al. 2009). To provide another perspective on energy, cumulative energy demand was estimated using a method adapted from the Ecoinvent Centre (Hischier et al. 2010).

Table ES-1. Environmental Impact and Cost Metrics

Metric	Method	Unit
Cost – Net present value (NPV)	LCCA	U.S. Dollars (2016)
Global warming potential (GWP)	TRACI 2.1	kg CO_2 equivalent (eq.)
Eutrophication potential (EP)	TRACI 2.1	kg N eq.
Particulate matter formation potential (PMFP)	TRACI 2.1	kg $PM_{2.5}$ eq.
Smog formation potential (SFP)	TRACI 2.1	kg O_3 eq.
Acidification potential (AP)	TRACI 2.1	kg SO_2 eq.
Water use (WU)	ReCiPe	m^3
Fossil fuel depletion potential (FDP)	ReCiPe	kg oil eq.
Cumulative energy demand (CED)	Ecoinvent	MJ

ES.2.1 SCENARIO AND SENSITIVITY ANALYSIS

A scenario analysis was used to generate and compare impact results for two co-digestion and AD performance scenarios against a historical (2016), baseline scenario that is representative of typical plant operations prior to co-digestion. Table ES-2 lists the volume, in gallons per day (gpd), of solid streams destined for digestion in each of the three feedstock scenarios. Source separated organics are received by the facility and pumped directly into the digesters from a temporary holding tank. The partial and full capacity scenarios were designed to represent 50 percent and 100 percent capacity utilization of the AD capacity available for SSO co-digestion.

Table ES-2. Feedstock Scenario Waste Treatment Volumes (gpd)

Waste Source	Baseline	Partial Capacity Scenario	Full Capacity Scenario
Thickened primary and WAS	1.7E+5	1.8E+5	1.9E+5
Septage	8.0E+4	8.0E+4	8.0E+4
Trucked-in municipal solids	8.0E+3	8.0E+3	8.0E+3
SSO	-	4.6E+4	9.2E+4

Each of the co-digestion feedstock scenarios were evaluated for two AD performance scenarios that determine biogas production and availability for energy recovery. Table ES-3 lists the main parameters that were varied between the low and base (expected) AD performance scenarios.

Table ES-3. Anaerobic Digestion Performance Scenario Parameters

Parameter Name	Feedstock Scenario	Low AD	Base AD
Percent volatile solids reduction[1] (% of influent VS)	Baseline	n.a.	55%
	Partial capacity	61%	69%
	Full capacity	63%	72%
Biogas yield[2] (standard ft^3/lb of VS destroyed)	Baseline	n.a.	17.4
	Partial capacity	15.0	18.4
	Full capacity	15.0	18.5
Flaring rate	All	20%	10%

1 The low AD performance scenario assumes a 50% volatile solids reduction for municipal solids and a 70% reduction for SSO.

2 Biogas yield values for the base AD scenario were based on GPS-X™ model output (Hydromantis 2017). The low AD performance scenario biogas yield estimate was based on CAPDETWorks™ defaults (Harris, et al. 1982).

The study includes a sensitivity analysis that examines the impact of assumptions related to avoided food waste end-of-life (EOL) disposal options on environmental impact results. The main LCA results presented in Section 5 include the effects of avoided landfill disposal and WTE combustion for the SSO material according to recent (2016) estimates of EOL disposal for municipal solid waste (MSW) in the state of Massachusetts. It was estimated that 32 percent of food waste is diverted from landfill disposal, while the remaining 68 percent of food waste avoids combustion in WTE facilities. The sensitivity analysis also presents results based on national average avoided disposal processes and hypothetical scenarios where 100 percent of food waste is diverted from landfills or WTE facilities.

To evaluate sensitivity to cost parameters, a low cost scenario was evaluated in addition to the base cost scenario. The cost scenarios vary discount rate and revenue unit costs such as electricity and SSO tipping fees. Low and base cost parameter values were specified to yield a reasonable range of estimated life cycle costs. Further detail on specific LCCA parameters is provided in Section 4.2.6.

Appendix A presents the results of a secondary analysis that directly compares five alternative food waste treatment and disposal options including, AD, windrow composting, aerated static pile composting, landfill disposal and WTE combustion.

ES.2.2 LIFE CYCLE INVENTORY DEVELOPMENT

The analysis is a case-study of an existing WWTF, and life cycle inventory (LCI) data were based primarily on plant records, engineering documents, budget information and conversations with the plant manager and operations supervisor. Results for the partial and full capacity scenarios were additionally based on modeling performed in the wastewater treatment simulation software GPS-X™ (Hydromantis 2017). The main sources of data include:

- Air permit application for the AD and CHP expansion (2016) (Cousens 2016);
- CAPDETWorks™ design and costing software (Hydromantis 2014);
- Discharge Monitoring Report information (2016) (U.S. EPA 2016);
- Engineering report assessing the feasibility of several AD expansion, CHP and SSO acceptance scenarios (2013) (CDM Smith 2013);
- Engineering energy evaluation (2009) (PES and UTS 2009);
- GPS-X™ model results (Hydromantis 2017).
- Plant purchasing records for: electricity, natural gas, chemicals, potable water and grit disposal (2016);
- Plant influent and effluent quality and quantity records (2016);
- National Pollutant Discharge Elimination System (NPDES) permit (valid 2010-publication) (U.S. EPA and MADEP 2005);
- The Municipal Solid Waste Decision Support Tool (MSW DST) (RTI International 2012);

The primary LCI data for wastewater treatment processes include electricity, natural gas and chemical use. Purchasing records were used to quantify chemical consumption in the baseline scenario and standard dosage rates were applied to estimate values for the partial and full capacity scenarios. Biogas production was estimated in the base AD performance scenario using the GPS-X™ model and was allocated among the potential uses based on a hierarchy established by GLSD that prioritizes biogas use in the pelletization facility. The quantity of biogas not required for biosolids drying is combusted in the CHP facility, producing net-metered electricity and thermal energy available for on-site use. Emissions data from air permit applications was used to develop LCI data for on-site combustion equipment including the CHP engines, boiler, pellet drier and flares. The MSW DST model was used to develop LCI data for avoided EOL disposal options. The U.S. LCI and Ecoinvent 2.2 inventory databases were used to model background production processes such as electricity generation, chemical and infrastructure materials, and transportation (Frischknecht et al. 2005; NREL 2012). Data quality estimates for the developed inventory and background processes are documented in Appendix E.

LCI data compiled from these sources, using the methods described in this report, was modeled in the openLCA software program version 1.6.3 (GreenDelta 2016).

ES.3 RESULTS SUMMARY

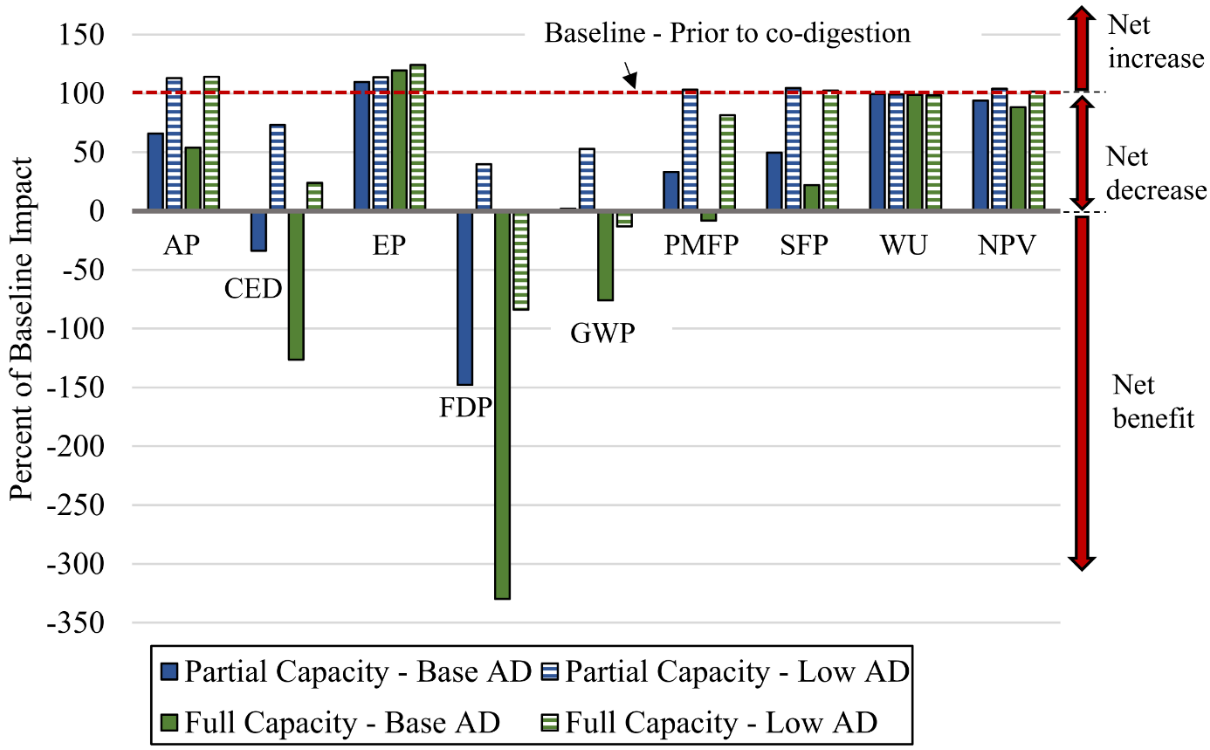
Figure ES-1 presents LCIA results for both co-digestion feedstock and AD performance scenarios relative to baseline LCIA results. Baseline LCIA results have been standardized to equal 100 for all impact categories and are depicted in the figure as a dashed red line. Each bar represents an individual feedstock-AD performance scenario impact result. Bars that extend above the baseline represent an increase in environmental impact for that category due to the AD expansion and associated SSO co-digestion. Bars that fall between the baseline and x-axis represent a net decrease in impact potential because of SSO co-digestion. Bars with a negative net value, falling below the x-axis, indicate scenario results that yield a net environmental benefit.

Eutrophication potential (EP) impacts increase in all co-digestion scenarios. Increases of less than 15 percent also occur for acidification potential (AP) in the partial capacity-low AD performance scenario, when increased facility material and energy demands are not fully compensated for by avoided product benefits. Particulate matter formation potential (PMFP) and smog formation potential (SFP) and fossil depletion potential (FDP) yield slight increases in environmental impact for the partial capacity-low AD performance scenario for the same reason.

Water use potential varies negligibly between scenarios, due to the results being driven by effluent reuse which remains constant across scenarios. The WWTF reuses approximately 10 percent of treated effluent to satisfy their own non-potable water demands, avoiding potable water purchases and impacts. The plant also sells a fraction of treated effluent, approximately 3 percent, to an industrial partner for reuse.

Cumulative energy demand (CED), FDP and global warming potential (GWP) impact results drop rapidly as more SSO is accepted and as AD performance increases due to increased energy recovery. Net benefits are possible for all three impact categories when base AD performance is achieved.

Figure ES-1 also presents relative system net present value (NPV) for the base cost scenario introduced in Section 4.2.6. Using base cost assumptions, both low AD performance scenarios yield modest increases in system cost over a 30-year time horizon of between one and five percent. Base AD performance scenarios yield four and 10 percent reductions in system NPV for the partial and full capacity feedstock scenarios, respectively. These reductions in system NPV correspond to payback periods for the AD expansion and CHP installation project of 27 and 14 years for the partial and full capacity scenarios. Low cost LCCA scenario assumptions improve system economic performance, reducing system payback periods to 19 and 10 years for the partial and full capacity scenarios, respectively.



Acronyms: AP – acidification potential, CED – cumulative energy demand, EP – eutrophication potential, FDP – fossil fuel depletion potential, GWP – global warming potential, PMFP – particulate matter formation potential, SFP – smog formation potential, WU – water use

Figure ES-1. Presentation of co-digestion scenario LCIA results relative to baseline (2016) LCIA impacts.

Table ES-4 presents midpoint LCA impact results that corresponded to the relative result values presented in Figure ES-1. Acidification potential impact is reduced by 35 and 50 percent by accepting SSO material according to the partial and full capacity-base AD performance scenario assumptions, respectively. A review of detailed process results, in Appendix D, reveals that over 80 percent of this impact reduction is due to avoided energy products.

Cumulative energy demand decreases from a maximum of 5.0 MJ per m^3 of wastewater treated in the baseline scenario to a minimum of -6.4 MJ per m^3 for the full capacity-base AD performance scenario. In this scenario the WWTF avoids more energy use than is required for its own operation, and becomes a net exporter of electricity, producing an annual surplus of over six million kWh. Eutrophication potential results increase by between 10 and 25 percent across the analyzed scenarios. The low AD performance scenario was based on the conservative assumption that 80 percent of nitrogen influent to the digesters is solubilized, thereby returning to primary and secondary treatment processes. Fossil depletion potential results reveal that the use of biogas as an energy source leads to a net reduction in fossil fuel consumption. Increased biogas production attributable to co-digestion and the installation of CHP eliminates the need for on-site natural gas combustion in both the partial and full capacity scenarios. Avoided energy products associated with digestion more than offset increased facility energy demand, substituting natural gas and grid electricity with a non-fossil energy alternative.

Table ES-4. Midpoint Impacts for the Baseline and Feedstock-AD Performance Scenario (per m^3 wastewater treated)

			Feedstock - AD Performance Scenario			
Impact Category	**Units**	**Baseline**	**Partial Capacity - Base AD**	**Partial Capacity - Low AD**	**Full Capacity - Base AD**	**Full Capacity - Low AD**
AP	kg SO_2 eq	1.0E-3	6.6E-4	1.1E-3	5.4E-2	1.1E-3
CED	MJ	5.0	-1.7	3.7	-6.4	1.2
EP	kg N eq	0.02	0.03	0.03	0.03	0.03
FDP	kg oil eq	0.05	-0.07	0.02	-0.15	-0.04
GWP	kg CO_2 eq	0.36	0.01	0.19	-0.28	-0.05
PFMP	kg $PM_{2.5}$ eq	5.4E-5	1.8E-5	5.6E-5	-4.5E-6	4.4E-5
SFP	kg O_3 eq	0.02	8.3E-3	0.02	3.7E-3	0.02
WU	m^3 H_2O	-0.13	-0.12	-0.12	-0.12	-0.12
NPV	Million $ (2016)	314	301	329	282	317

Global warming potential decreases from a maximum of 0.36 kg CO_2-eq. per m^3 of wastewater in the baseline scenario to a minimum of -0.28 kg CO_2-eq. per m^3 in the full capacity scenario. Avoided energy production credits are the largest contributor to reductions in net GWP, yielding an environmental credit of -0.80 kg CO_2 eq. per m^3 wastewater treated in the full capacity scenario. The GWP benefits of avoiding landfill disposal are also considerable, -0.33 kg CO_2 eq. per m^3 wastewater treated, and are primarily attributable to avoided methane emissions.

The partial and full capacity-base AD performance scenarios yield 50 and 75 percent reductions in SFP relative to the baseline scenario. Avoided electricity production is responsible for the greatest reduction in SFP. The partial and full capacity scenarios yield 65 and 110 percent reductions in PMFP relative to the base feedstock scenario. Review of detailed process results reveals that avoided natural gas combustion yields the greatest reduction in PMFP.

ES.3.1 KEY FINDINGS

- Reductions in environmental impact or the generation of environmental benefits are possible in seven of eight impact categories, except for eutrophication potential, which increases by between 10 and 25 percent depending upon the scenario.
- While the magnitude of impact reductions and benefits was found to be sensitive to feedstock scenarios, AD performance scenarios and avoided EOL disposal processes, the general trend of realizing reduced impact following the introduction of co-digestion was consistent over the full range of sensitivity scenarios.
- For medium-scale WWTFs with a ready source of SSO, or similar high strength organic waste, investment in AD capacity and CHP systems provides an opportunity to reduce net environmental impact, while reducing energy expenditures over time.
- The AD expansion and energy recovery project can yield a reliable economic payback period for both feedstock scenarios assuming base AD performance. Economic benefits were not identified under conditions of low AD performance and capacity utilization.

1. INTRODUCTION AND STUDY GOAL

Communities and states throughout the United States (U.S.) are leveraging diverse strategies to manage and transform waste streams to avoid landfilling or incineration by increasing recycling and alternative beneficial uses (U.S. EPA 2017a). The waste ban on organic materials disposed of by large commercial and industrial waste generators in Massachusetts is a specific example of the strategies available (Commonwealth of Massachusetts 2017a). The waste ban motivates institutions to compete and cooperate to identify and enact beneficial alternative disposal methods for diverted organic materials. The U.S. Environmental Protection Agency (U.S. EPA) is working with states to develop best practices based on local experience, providing guidance and objective information that other communities can use to make important management decisions. These decision-making processes must broadly consider local perspectives and available financing in addition to environmental objectives.

This report is intended to support that decision-making process. This report will provide valuable information to wastewater treatment personnel, municipalities and local or state officials as they look to reduce the environmental impact of the wastewater treatment sector, identify good opportunities for resource and energy recovery, and seek organic waste disposal practices that either minimize impact or generate environmental benefits. The report is also intended to directly benefit the case-study wastewater treatment facility, the Greater Lawrence Sanitary District (GLSD), as they complete their AD expansion project and transition to its long-term management.

Several alternative disposal methods for organic waste are common, including food donation, use as animal feed, composting and anaerobic digestion (AD). This study investigates the potential benefits and burdens of digesting diverted organic materials in the context of a case-study wastewater treatment facility in Massachusetts. Life cycle assessment (LCA) and life cycle cost assessment (LCCA) tools are used to examine how the environmental impacts and cost of wastewater treatment are affected when large-scale co-digestion of organic waste is introduced to an existing wastewater treatment plant (WWTF). The organic waste is expected to be primarily fruit and vegetable waste, referred to as source separated organics (SSO), from commercial and institutional sources. Side-by-side use of LCA and LCCA techniques allows a broad range of environmental and economic indicators to be considered, with the aim of facilitating a reasoned and informed decision-making process that does not unknowingly shift burdens from one sustainability indicator to another.

LCA 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 inform decision-making.

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 and Saidur 2004). It is used to evaluate differences in cost and the timing of costs between alternative projects.

The GLSD WWTF treats municipal sewage and septic waste for several communities in Massachusetts. The plant treats an average flowrate of approximately 23 million gallons per day (MGD), with a permitted capacity of 52 MGD. The treatment process uses primary sedimentation, conventional activated sludge (CAS) preceded by an anoxic zone and secondary clarification meet biochemical oxygen demand (BOD_5) and total suspended solids (TSS) permit requirements. The facility is not designed for nutrient removal and has no permit requirements for nitrogen or phosphorus. Sludge processing at the facility consists of dewatering, AD and biosolids drying and pelletization. Pelletized biosolids are used locally as an agricultural amendment. In response to the Massachusetts organic waste ban, the GLSD WWTF is undergoing a series of renovations to increase AD capacity and expand on-site energy recovery.

This study's objectives are to:

- Calculate the baseline environmental benefits and burdens of wastewater treatment with AD for a typical mid-sized WWTF;
- Quantify the comparative environment benefits and burdens associated with expanding AD capacity for the co-digestion of SSO;
- Determine the energy recovery potential of AD, and evaluate the environmental and cost benefits of offsetting external electricity and heat generation and alternative organic waste disposal methods such as landfilling or incineration for waste-to-energy (WTE); and
- Determine the life cycle costs associated with the upgraded treatment plant over a 30-year timespan, compare to the baseline scenario prior to co-digestion and calculate a discounted payback period for the AD expansion and combined heat and power (CHP) project.

The metrics planned for use in this assessment are cost and a suite of LCA-related impact categories in addition to traditional wastewater quality parameters. The life cycle impact assessment (LCIA) categories include global warming potential, eutrophication potential, particulate matter formation potential, smog formation potential, acidification potential and fossil depletion potential. Water use and cumulative energy demand inventory indicators are also included. The specific impact categories and associated methods considered are introduced in more detail in Section 2.4.

2. STUDY SCOPE

This study design follows the guidelines for LCA provided by ISO 14040 and 14044 (ISO 2006b; ISO 2006a) and LCCA practices outlined in the National Institute of Standards and Technology (NIST) guidelines (Fuller and Petersen 1996). 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.

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 2-1. Impact results are standardized per cubic meter of the 23.5 MGD average flowrate (approximately 32.4 million cubic meters per year). The quantity of waste treated by the facility varies depending upon the investigated waste scenario. However, the minor increase in waste volume treated, attributable to accepted SSO, is not considered in the definition of the functional unit given that its contribution to facility level volumetric flow is less than 0.5 percent of total waste treated. Waste scenarios are described in detail in Section 3.2. The main results section presents results per cubic meter of wastewater treated.

Table 2-1. Average Influent Composition of GLSD WWTF

Characteristic	Value	Unit
Total Suspended Solids (TSS)	251	mg/L
Volatile Solids (VS)	75%	-
Carbonaceous Biological Oxygen Demand (cBOD)	184	mg/L
Total Kjeldahl Nitrogen (TKN)	35	mg/L N
Ammonia (NH_3)	20	mg/L N
Total Phosphorus (TP)	4.85	mg/L P
Nitrite (NO_2)	0	mg/L N
Nitrate (NO_3)	0	mg/L N
Organic Nitrogen	15	mg/L N
Temperature	15.6	ºC

2.2 System Definition and Boundaries

System boundaries include all on-site wastewater and sludge treatment processes necessary to treat the average flowrate of 23.5 MGD of municipal wastewater. The beginning of the wastewater treatment system is the influent pump station, which contributes significantly to the facilities overall energy demand. Also included within the system boundary is final discharge of the treated effluent and disposal of pelletized biosolids via land application. A general system diagram that depicts system boundaries for all scenarios is presented in Figure 2-1.

The main inventory elements considered in this study include electricity consumption and generation, on-site fuel combustion, water use and consumable materials. Only select infrastructure elements associated with the AD and combined heat and power (CHP) expansion are modeled to understand the relative impacts from the new infrastructure components. Infrastructure materials include unit concrete, rebar, excavation and sub-grade coarse aggregate. All included infrastructure components are expected to have a useful lifespan that extends beyond the 40-year study timeframe (Harris, et al. 1982), which eliminates the need to consider material replacement of infrastructure in the environmental analysis. Pumps, electronics, other in-unit mechanical equipment 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. Process greenhouse gas emissions (GHG) resulting from biological treatment and effluent release, fugitive methane releases from AD and emissions from pellet land application are estimated and included in the calculation of impacts. The electrical grid mix for the New England region is used in the analysis and is depicted in Table 2-2 (van Welie 2017).

Table 2-2. New England Electrical Grid Mix

Energy Source	Percent of Grid Generation
Biomass	6.2
Coal	2.4
Natural Gas	50
Hydroelectric	7.1
Nuclear	31
Solar	0.62
Wind	2.4

Reference: (van Welie 2017)

The analysis includes consideration of avoided electricity and heat production associated with biogas utilization and avoided fertilizer production associated with biosolids pellet land application. The study also investigates the impact of avoided EOL disposal processes for SSO such as disposal in a landfill or WTE incineration. The plant reuses approximately 10 percent of treated effluent for cleaning, chemical delivery and other non-potable uses, avoiding the use of treated drinking water. A small fraction of treated effluent (approximately 165 million gallons per year) is purchased for reuse by a local industrial partner. Avoided products and waste processes lead to the generation of environmental credits, decreasing the environmental impact of the treatment system. 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.

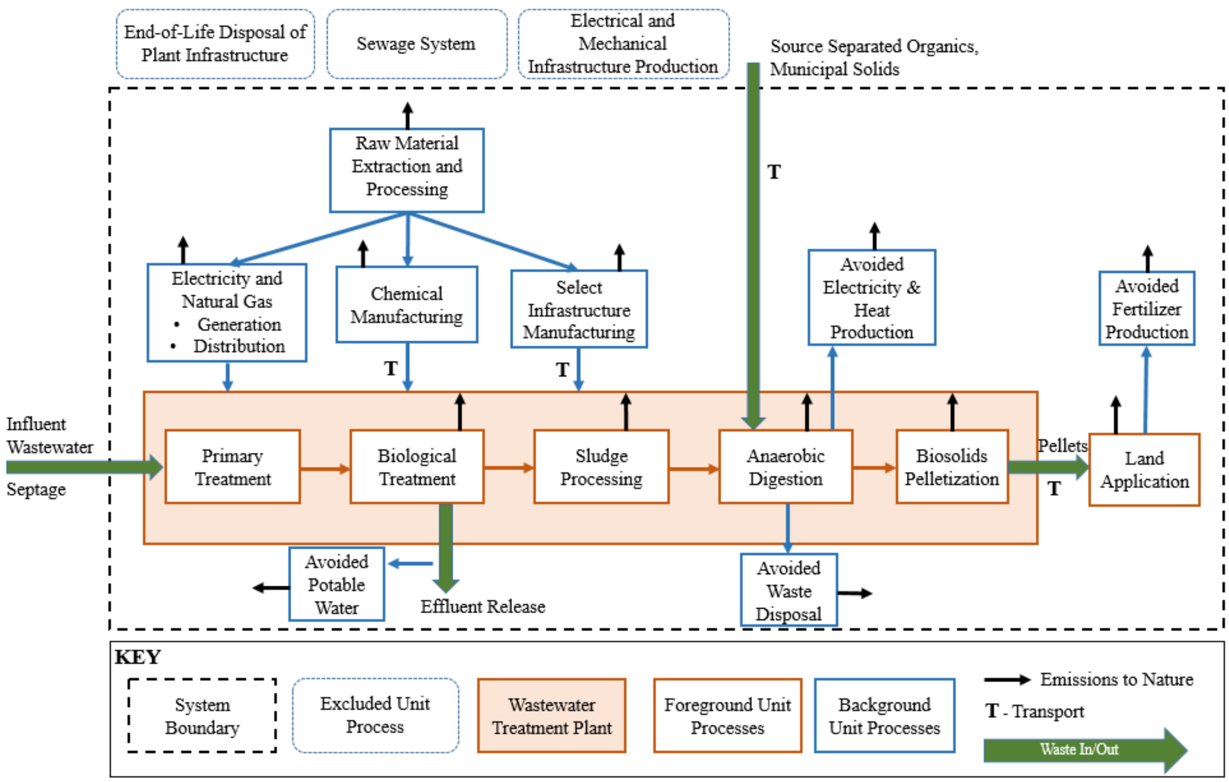


Figure 2-1. General system boundaries for case-study wastewater treatment plant.

2.3 Study Site Description

The Greater Lawrence Sanitary District (GLSD) WWTF provides wastewater treatment services for five communities with a combined population of over 200,000 people. The facility has a design flowrate of 52 MGD and a peak flow capacity of 135 MGD and treats an average flowrate of 23.5 MGD. The plant also accepts around 90,000 gallons per day (gpd) of trucked in septage and thickened biosolids from small WWTFs in the region. Thickened septage, primary sludge and waste activated sludge (WAS) are collectively referred to as municipal solids throughout this report. The plant has been in operation since 1971 having undergone a series of updates since initial construction. The existing AD facility began operation in 2002 and is paired with a thermal drying facility that produces pelletized biosolids for use as an agricultural or horticultural amendment. The WWTF is required to meet effluent BOD_5, TSS, pH, chlorine residual, fecal coliform and dissolved oxygen (DO) permit requirements (U.S. EPA and MADEP 2005).

In 2017, the facility pursued upgrades to expand AD capacity to allow for co-digestion of SSO. The term SSO refers to organic material that is separated from conventional landfill or recycling waste streams at the point of generation. The SSO for the GLSD WWTF is an engineered feedstock composed primarily of fruit and vegetable waste that undergoes additional processing steps to reduce contamination, ensuring consistent composition that will support stable digester performance. The move to expand co-digestion capacity was driven by a commercial organics disposal ban implemented in 2014 in Massachusetts (Commonwealth of

Massachusetts 2017a). The facility also began installation of a CHP system in 2017 allowing the facility to produce both heat and electricity from biogas.

2.3.1 New England Case-Study Wastewater Treatment Plant

2.3.1.1 Primary and Secondary Treatment System

Figure 2-2 is a process flow diagram of the GLSD WWTF. Preliminary treatment consists of aerated grit chambers, bar screens and two parallel 175’ diameter primary clarifiers. Primary sludge is dewatered in one of four gravity thickeners. Effluent of the preliminary treatment processes flows via gravity into a completely mixed, plug-flow anoxic reactor before entering a series of four parallel, plug-flow activated sludge basins. The anoxic reactor is not intended for denitrification, having no internal recycle, and is operated to minimize nitrification and associated energy demand. The activated sludge system is operated with a low solids retention time and mixed liquor suspended solids (MLSS) concentration. Effluent from the activated sludge tank flows into one of four 175’ diameter secondary clarifiers. Waste activated sludge is sent to two gravity belt thickeners for dewatering before being combined with thickened primary sludge, trucked in municipal solids and SSO for pumping to the ADs (depending on scenario). Return activated sludge (RAS) is pumped back to the anoxic unit at a recycle rate that is approximately 78 percent of the average influent flow rate, or 18 MGD.

2.3.1.2 Anaerobic Digestion

Anaerobic digestion is the main sludge processing step, which uses a methanogenic process to break down volatile suspended solids (VSS) contained within the sludge. Biogas is produced from this degradation process. Table 2-3 illustrates a typical composition for biogas generated at a municipal WWTF. Feedstocks for AD include primary solids, WAS, trucked-in septage, trucked-in municipal solids and SSO.

The baseline scenario WWTF (2016) is equipped with three 1.5-million gallon mesophilic AD units. A fourth identical unit is being constructed (2017-2018) to allow for the co-digestion of regionally supplied SSO waste. Each vessel has a diameter of 85 feet and a sidewall depth of 38.5 feet. The vessels run at a constant temperature of 95°F. Sludge influent to the ADs is heated to match the reactor temperature prior to introduction into the vessel. Biogas is the primary source of thermal energy used to provide process heat for AD and the on-site control buildings, thereby off-setting natural gas usage. Natural gas use is required to provide a small portion of facility heat demand in some scenarios. It was assumed that CHP thermal energy production exceeding facility demand is wasted as there are no current plans to utilize this energy. Each digester is equipped with a floating cover that allows for a maximum storage capacity of 146,000 cubic feet (ft^3) of biogas. Two bowl-style centrifuges are used to dewater digested biosolids to reach a target solids concentration of greater than 25 percent (mass fraction), before entering the thermal drying and pelletization facility.

Table 2-3. Typical Biogas Composition

Biogas Component	Expected Range[1]
Methane (CH_4)	60-70%
Carbon Dioxide (CO_2)	30-40%
Water Vapor (H_2O)	<7%
Nitrogen (N_2)	
Hydrogen (H_2)	
Hydrogen Sulfide (H_2S)	

[1] dry basis, by volume (Wiser et al. 2010)

2.3.1.3 Biosolid Thermal Drying and Pelletization

The drying facility is contracted to accept thickened biosolids to produce a pelletized agricultural amendment. The maximum facility capacity allows for the daily processing of 38 dry short tons of thickened biosolids. The facility requires a significant input of thermal and electrical energy requiring 8,500 MJ and 350 kWh per dry short ton of biosolids processed. Biogas or natural gas is combusted in a rotary drum dryer, which is used to reduce the moisture content of biosolids to between two and three percent. Pellets are screened to ensure a consistent product size and conveyed to a hopper to await shipment. A trucking distance of 121 km was assumed based on the distance between the GLSD facility and Massachusetts's main agricultural region. Pellets are spread on agricultural fields, where they replace chemical fertilizers. Pelletized biosolids contain on average four and two percent nitrogen (N) and phosphorus (P) as N and P_2O_5, respectively.

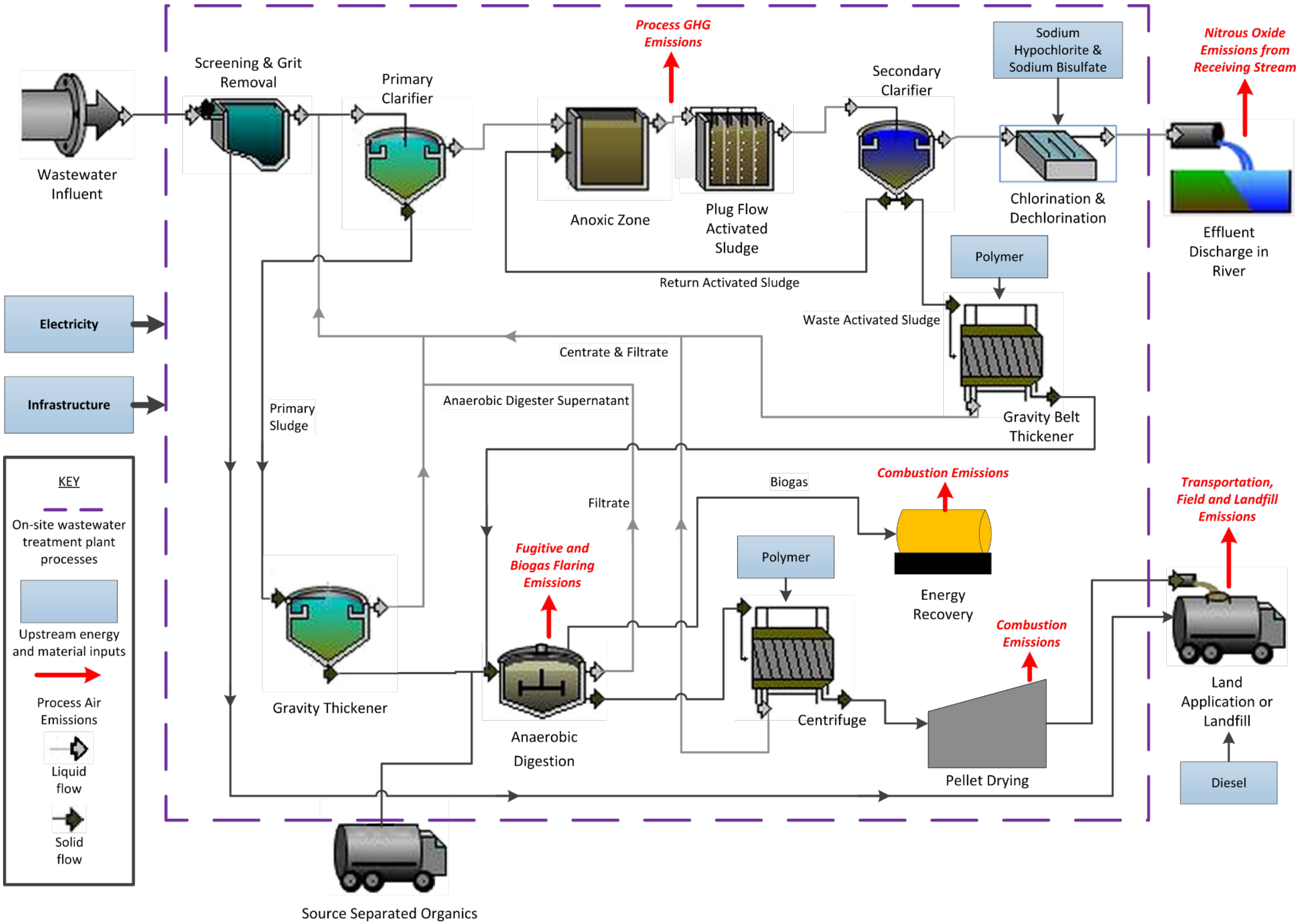


Figure 2-2. Process flow diagram of Greater Lawrence Sanitary District wastewater treatment facility.

2.3.2 Introduction to Waste Scenarios and Sensitivity Analysis

The analysis modeled three waste acceptance scenarios. The baseline scenario represents 2016 conditions prior to commencing acceptance of SSO material for co-digestion and enhanced energy recovery. The partial and full capacity scenarios are differentiated to isolate the effect of AD infrastructure capacity utilization on environmental impact and life cycle cost. The sensitivity analysis examines the effect of AD performance, avoided SSO disposal and cost parameters on environmental and economic indicators. Appendix A includes the results of an additional analysis where AD of food waste is compared to composting as an alternative EOL disposal strategy.

2.3.2.1 Waste Acceptance (Feedstock) Scenarios

Within the baseline feedstock scenario, energy recovery was limited to heat generation for AD and facility heating and biosolids pelletization. The partial and full capacity feedstock scenarios, referred to also as the partial and full capacity scenarios, assume that 50 and 100 percent of available SSO capacity are utilized, respectively. The 50 percent utilization scenario was included to reflect the concern that SSO availability may reduce over time as demand for organic wastes increase. Table 2-4 illustrates all sources and quantities of organic waste processed by the facility according to feedstock scenario.

Table 2-4. Feedstock Scenario Waste Treatment Volumes (gpd)

Waste Source	Baseline	Partial Capacity	Full Capacity
Thickened primary and WAS	1.7E+5	1.8E+5	1.9E+5
Septage	8.0E+4	8.0E+4	8.0E+4
Trucked-in municipal solids[1]	8.0E+3	8.0E+3	8.0E+3
SSO	-	4.6E+4	9.2E+4

[1] Trucked-in municipal solids refers to thickened primary and WAS from small, regional WWTFs.

2.3.2.2 Anaerobic Digester Performance Sensitivity

Two AD performance scenarios were modeled. The parameters used to represent digester performance are the expected volatile solids reduction (VSR) and biogas yield per unit of digested volatile solids (VS). The values presented in Table 2-5 refer to the composite waste stream that is fed to the digesters and considers the variable digestibility of SSO as compared to average characteristics of the municipal solids stream. The low AD performance scenario additionally incorporates a low estimate of biogas utilization, assuming that 80 percent of biogas was used for biosolids pelletization and CHP. The remaining 20 percent of biogas is flared. Low AD performance parameters were only applied to the partial and full capacity feedstock scenarios, as the baseline scenario represents historical performance. The base AD performance scenario assumes 90 percent utilization of produced biogas. Both scenarios consider potential losses of methane from the floating lid, estimating that five percent of biogas methane is lost to the atmosphere, untreated (UNFCCC 2012).

Table 2-5. Anaerobic Digestion Performance Scenario Parameters

Parameter Name	Feedstock Scenario	Low AD	Base AD
Percent VSR[1] (% of influent VS)	Baseline	n.a.	55%
	Partial Capacity	61%	69%
	Full Capacity	63%	72%
Biogas Yield[2] (standard ft^3/lb of VS destroyed)	Baseline	n.a.	17.4
	Partial Capacity	15.0	18.4
	Full Capacity	15.0	18.5

[1] The low AD performance VSR assumes a 50% reduction for municipal solids and 70% for SSO.

[2] Biogas yields for the base AD performance scenario were based on GPS-X™ model output (Hydromantis 2017). Low AD performance biogas yield was based on CAPDETWorks™ defaults (Harris, et al. 1982).

Table Acronyms: VS – volatile solids, VSR – volatile solids reduction

2.3.2.3 Avoided Source Separated Organic Disposal Sensitivity

The avoided SSO disposal analysis expands the system boundaries to calculate the net benefits and burdens of displacing alternative disposal routes for the SSO material used as a digester feedstock. Baseline results, presented in Section 5, utilize typical SSO disposal routes for organic material in Massachusetts prior to the landfill ban (MA disposal mix scenario). In the MA disposal mix scenario, 68 percent of SSO was assumed to be diverted from WTE facilities, while the remaining 32 percent is diverted from landfills (Fischer 2017). In the national disposal mix scenario, 18 percent of MSW is combusted in WTE facilities and the remaining 82 percent is disposed of in landfills (U.S. EPA 2014). Additionally, the sensitivity analysis generates comparative results excluding the effect of avoided SSO disposal and considering 100 percent displacement of landfill and WTE disposal pathways. Appendix A includes the results of an additional analysis where anaerobic digestion of food waste is compared to composting as an alternative EOL management strategy.

2.3.2.4 Life Cycle Cost Assessment Parameter Sensitivity

To evaluate sensitivity to cost parameters, A low cost scenario was evaluated in addition to a base (expected) cost scenario. The cost scenarios vary discount rate and revenue unit costs such as electricity and SSO tipping fees. Low and base cost parameter values are specified to yield a reasonable range of estimated life cycle costs. Further detail on specific LCCA parameters is provided in Section 4.2.6.

2.4 Metrics and Life Cycle Impact Assessment Scope

Table 2-6 summarizes the metrics calculated for each scenario. The life cycle cost of operating the baseline and upgraded system configurations was estimated using standard approaches for LCCA, with more detail on the costing methodology provided in Section 4. Most of the environmental metrics were 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 to assess local, regional and global impacts. It incorporates 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 data. Global warming potential was estimated using the 100-year characterization factors provided by the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (Pachauri and Reisinger 2007). In addition to TRACI, the ReCiPe LCIA method was used to characterize water use and fossil fuel depletion potential (Goedkoop et al. 2009), impacts which are not included in the current version of TRACI. ReCiPe's water depletion potential impact assessment method was altered to exclude cooling water and turbine water for hydroelectricity production. To provide another perspective on energy use and generation, cumulative energy demand (CED) was estimated using a method adapted from the Ecoinvent Centre (Hischier et al. 2010). CED includes the energy content of all non-renewable and renewable energy resources utilized at the WWTF and throughout upstream supply-chains. As specified in the Ecoinvent CED method, the energy content of biogas was not inventoried, as it enters the facility as a waste product. Table 2-7 provides a description of each impact category.

Table 2-6. Environmental Impact and Cost Metrics

Metric	Method	Unit
Cost	LCCA	U.S. Dollars (2016)
Global warming potential (GWP)	TRACI 2.1	kg CO_2 equivalent (eq.)
Eutrophication potential (EP)	TRACI 2.1	kg N eq.
Particulate matter formation potential (PMFP)	TRACI 2.1	kg $PM_{2.5}$ eq.
Smog formation potential (SFP)	TRACI 2.1	kg O_3 eq.
Acidification potential (AP)	TRACI 2.1	kg SO_2 eq.
Water use (WU)	ReCiPe (adapted)	m^3
Fossil fuel depletion potential (FDP)	ReCiPe	kg oil eq.
Cumulative energy demand (CED)	Ecoinvent	MJ

Table 2-7. Description of LCA Impact Categories

Impact/Inventory Category	Description	Unit
Eutrophication potential (EP)	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.

Table 2-7. Description of LCA Impact Categories

Impact/Inventory Category	Description	Unit
Global warming potential (GWP)	The GWP impact category represents the heat trapping capacity of GHGs over a 100-year period. All GHGs are characterized as kg CO_2 eq. using the TRACI 2.1 method. TRACI GHG characterization factors align with the IPCC 4th Assessment Report for a 100-year time horizon (Pachauri and Reisinger 2007).	kg CO_2 eq.
Cumulative energy demand (CED)	The CED inventory indicator accounts for the total use of non-renewable fuels (natural gas, petroleum, coal and nuclear) and renewable fuels (such as biomass and hydroelectricity). Energy is tracked based on the higher 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 (WU)	Water use results are based on the volume of fresh water inputs to the life cycle of products within the WWTF 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 potential category in the ReCiPe impact assessment method.	m^3
Particulate matter formation potential (PMFP)	Particulate matter formation potential results in human health impacts such as effects on breathing and respiratory systems, damage to lung tissue, cancer and premature death. Primary pollutants (including $PM_{2.5}$) and secondary pollutants (e.g. NOx) leading to particulate matter formation are characterized as kg $PM_{2.5}$ eq. based on the TRACI 2.1 impact assessment method.	kg $PM_{2.5}$ eq.
Acidification potential (AP)	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 sulfur dioxide (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 (SFP)	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 in units of kg of ozone (O_3) eq. according to the TRACI 2.1 impact assessment method. Some key emissions leading to SFP include carbon monoxide (CO), CH_4 and NOx.	kg O_3 eq.
Fossil fuel depletion potential (FDP)	Fossil fuel depletion potential quantifies the consumption of fossil fuels, primarily coal, natural gas and crude oil. All fuels are characterized in units of kg oil eq. based on the heating value of the fossil fuel, according to the ReCiPe impact assessment method.	kg oil eq.

LCIA results are grouped according to treatment group for results presentation in all LCIA impact categories (Table 2-8).

Table 2-8. Assignment of Unit Processes to Treatment Group for Results Presentation

Treatment Group	Unit Process Name
Influent pump station	Influent pump station
Preliminary/primary	Screening and grit removal
	Primary clarification
Biological treatment	Pre-anoxic tank
	Aeration basins
	Secondary clarification
Plant water and disinfection[1]	Plant water and disinfection
Sludge dewatering	Gravity belt thickener
	Gravity thickener
	Centrifuge
Anaerobic digestion and CHP[2]	SSO transport and processing
	Anaerobic digestion
	Combined heat and power
Pellet drying	Biosolids drying and pelletization
Land application[3]	Land application of biosolids pellets
Effluent release	Effluent release; to surface water
Building operation	Administration building utilities

1 Includes avoided drinking water treatment
2 Includes avoided electricity and natural gas and avoided SSO EOL disposal
3 Includes avoided fertilizer production

Results are also presented according to process categories for global warming potential (GWP) and CED. All unit processes in the LCA model were assigned to the process categories listed below:

- Avoided electricity, CHP.
- Avoided fertilizer.
- Avoided natural gas, CHP.
- Avoided SSO disposal.
- Avoided water.
- Chemicals.
- Effluent release.
- Electricity.
- Grit disposal.
- Infrastructure.
- Land application.
- Natural gas.
- On-site combustion.
- Potable water use.
- Transport.
- Unit process emissions.

3. LCI METHODOLOGY

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

3.1 Data Sources and Modeling Approach

The analysis is a case-study of an existing WWTF that was based primarily on plant records, engineering documents, budget information, conversations with the plant manager and operations supervisor and the wastewater treatment simulation software GPS-X™ (Hydromantis 2017). GPS-X™ was used to estimate changes in plant operating conditions when the facility expands AD capacity to accept SSO feedstock. The main sources of data include:

- Air permit application for the AD and CHP expansion (2016) (Cousens 2016);
- CAPDETWorks™ design and costing software (Hydromantis 2014);
- Discharge Monitoring Report (DMR) information (2016) (U.S. EPA 2016);
- Engineering report assessing the feasibility of several AD expansion, CHP and SSO acceptance scenarios (2013) (CDM Smith 2013);
- Engineering energy evaluation (2009) (PES and UTS 2009);
- GPS-X™ model results (Hydromantis 2017).
- Plant purchasing records for: electricity, natural gas, chemicals, potable water and grit disposal (2016);
- Plant influent and effluent quality and quantity records (2016);
- National Pollutant Discharge Elimination System (NPDES) permit (valid 2010-publication) (U.S. EPA and MADEP 2005);
- The Municipal Solid Waste Decision Support Tool (MSW DST) (RTI International 2012);

The above information, in addition to literature cited throughout this document, was used to define the system boundaries for the analysis and to parameterize the GPS-X™ model. Model results were compared against known plant data. For the partial and full capacity scenarios, the GPS-X™ model was adjusted to account for added AD capacity and the quantity of accepted SSO waste. Model output was used to calculate the effect of additional nutrient and BOD loading that results from returning centrifuge supernatant to the primary and secondary treatment units. Details of the modeling process and adjustments made to GPS-X™ model results are presented in Section 3.3.

LCI data compiled from these sources, using the methods described in this report, was modeled in the OpenLCA software program for results generation (GreenDelta 2016).

3.2 Influent Water Quality, Septage and SSO Characteristics

The characteristics associated with the influent municipal wastewater are the same for all scenarios (Table). Influent flowrate, BOD and TSS represent the average daily value recorded at the GLSD WWTF during 2016. Other influent parameters are representative of medium strength, residential wastewater (Tchobanoglous et al. 2014). The temperature of influent and effluent wastewater varies throughout the year but was set at 60°F (15.6 °C) in the GPS-X™ model as a representative annual average.

In addition to influent wastewater from the municipal sewer system, the treatment plant also processes trucked-in septage waste, municipal solids from small WWTFs and an engineered SSO waste stream. The characteristics and accepted quantities of each waste stream are listed in Table 3-1 and Table 3-4, respectively. Septage is treated with municipal sewage waste and is subject to primary and secondary treatment. Trucked-in municipal solids are transported to the facility and are pumped directly from temporary holding tanks into the digesters, as is SSO. The SSO scenarios analyzed in the sensitivity analysis were previously presented in Section 2.3.2.1.

Table 3-1. Septage, Municipal Solids and SSO Characteristics

Characteristic	Feedstock			Unit
	Septage[1]	Trucked Municipal Solids[2]	SSO[3]	
TSS	15,000	22,500	137,000	mg/L
VSS	10,000	16,500	124,000	mg/L
VSS/TSS	67	73	90	%
Total Nitrogen[4]	750	600	3,750	mg N/L
Total P[5]	375	210	620	mg P/L
Chemical Oxygen Demand (COD)[5]	17,000	29,000	216,000	mg COD/L
Density	1,020	1,030	1,050	kg/m^3

[1] (U.S. EPA 1984)
[2] (Tchobanoglous et al. 2014), assumes 67 percent primary solids and 37 percent WAS by mass.
[3] Personal communication with Lauren Fillmore (Fillmore 2017)
[4] Fraction of TKN in TSS is 0.05
[5] Based on GPS-X™ default TP and COD fractions of influent TSS

Baseline effluent characteristics, listed in Table 3-2, were calculated using 2016 DMR data. Effluent constituent concentrations for the partial and full capacity scenarios were estimated using percent removal values corresponding to baseline plant operations and scenario specific loading estimates drawn from the GPS-X™ model. Table 3-2 also lists GLSD's state pollutant discharge elimination system permit requirements.

Table 3-2. Scenario Effluent Composition and Permit Requirements

Characteristic	Baseline	Partial Capacity	Full Capacity	Unit	Effluent Limits	Unit
TSS	6.05	6.28	6.55	mg/L	30	mg/L, average monthly
BOD	17.7	18.0	18.5	mg O_2/L	30	mg/L, average monthly
TN	20.6	22.4	23.8	mg/L N	no permit requirements	
TKN	19.9	21.7	23.1	mg/L N		
NH_3	22.5	24.5	26.0	mg/L NH_3		
NO_3	2.85	3.10	3.30	mg/L NO_3		
Organic nitrogen	1.44	1.57	1.67	mg/L N		

Table 3-2. Scenario Effluent Composition and Permit Requirements

Characteristic	Baseline	Partial Capacity	Full Capacity	Unit	Effluent Limits	Unit
TP	0.367	0.378	0.389	mg/L P		

3.3 GLSD WWTF Life Cycle Inventory Development

Process configuration and key operational parameters used to establish the GPS-X™ model were provided by facility staff. Facility records of electricity use were provided for the year 2016 and were allocated to units based on supervisory control and data acquisition (SCADA) system data for the years 2007/2008 according to the breakout established in Figure 3-1. This is the most recent period for which detailed electricity consumption data was available by unit process.

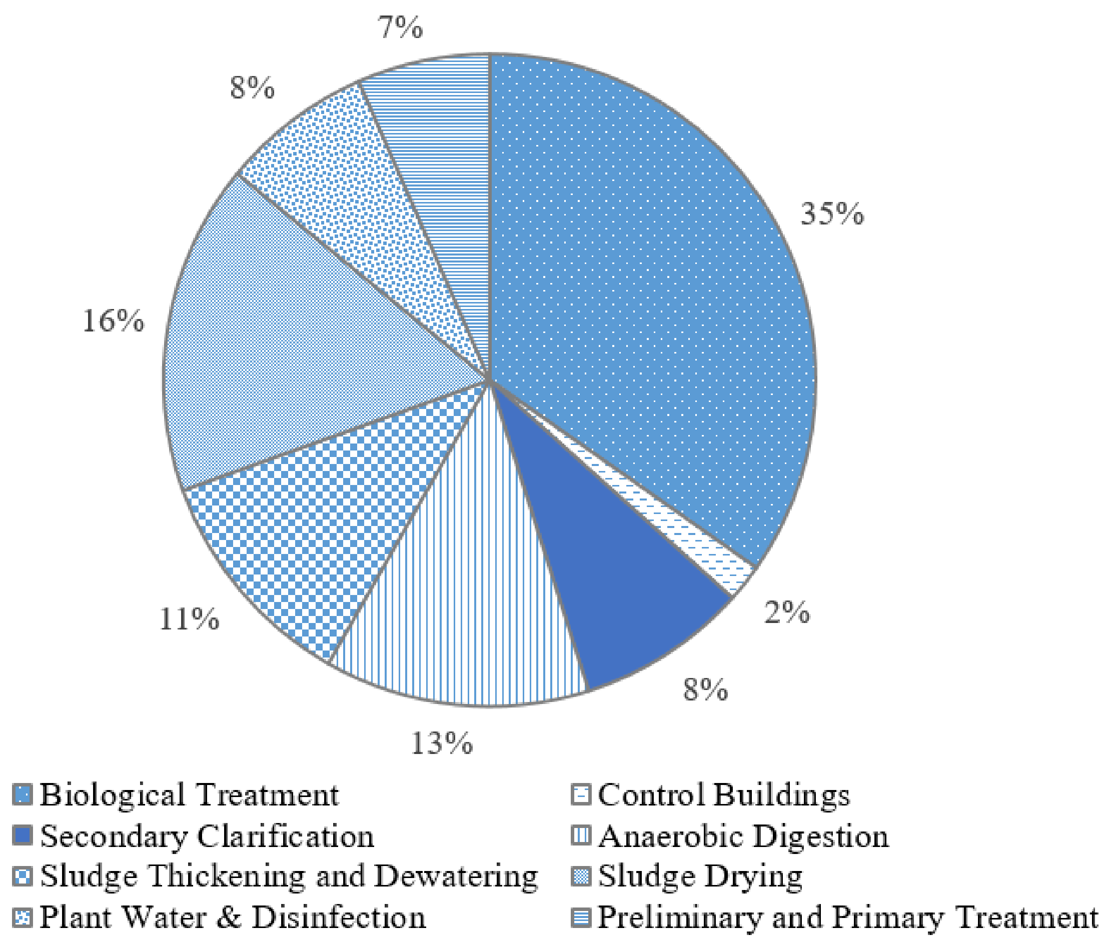


Figure 3-1. Allocation of electricity to process units.

Table 3-3 reports plant-level electricity consumption for 2016. Changes in electricity consumption associated with the partial and full capacity waste scenarios are described throughout Section 3.3.

Table 3-3. 2016 Plant Electricity Use Allocated to Unit Processes

Electricity User	**% of Total Electricity Use**	**Usage (kwh)**
Influent pump station	31%	5,716,065
Electricity User	**% of Plant Electricity Use (excluding pump station)**	**Usage (kwh)**
Control buildings	2%	234,702
Preliminary and primary treatment	7%	821,458
Biological treatment	35%	4,341,991
Secondary clarification and RAS pumping	8%	1,056,160
Anaerobic digestion	13%	1,642,915
Sludge thickening/dewatering	11%	1,408,213
Sludge drying	16%	2,047,752
Plant water & disinfection	8%	938,809
	Plant Electricity Use (excluding influent pump station)	**12,492,000**
	Total Electricity Use (including influent pump station)	**18,208,065**

Equipment power consumption associated with existing unit processes was input into GPS-X™ to generate estimates of electricity consumption for components common to all three feedstock scenarios. We then use the relationship between actual and modeled electricity consumption in the baseline feedstock scenario to adjust model estimates of energy consumption for the partial and full-capacity scenarios using Equation 1. This approach allows GPS-X™ to be used to estimate increased electricity consumption within the SSO feedstock scenarios, while linking these estimates directly to recorded plant electricity use.

$$\boldsymbol{Electricity_{LCA,x,y} = Electricity_{GPS-X,x,y} \times \frac{Baseline_{actual,x}}{Baseline_{GPS-X,x}}}$$

Equation 1

where:

$Electricity_{LCA,x,y}$ = LCA model electricity consumption of unit *x* for the *y* feedstock scenario

$Electricity_{GPS\text{-}X,x,y}$ = GPS-X™ estimated electricity consumption of unit *x* in the *y* feedstock scenario

$Baseline_{actual,x}$ = Actual electricity consumption of unit *x* (2016) in the baseline feedstock scenario

$Baseline_{GPS\text{-}X,x}$ = GPS-X™ estimated electricity consumption of unit *x* in the baseline feedstock scenario

The following subsections describe the detailed operational LCI developed for the WWTF by unit process on an annual basis. Annual inputs and outputs were 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 SSO waste, were standardized to the average flowrate of 23.5 MGD.

3.3.1 External Waste Processing and Transport

Septage and municipal solids are trucked to the WWTF primarily from communities served by the facility, assuming a 25-kilometer (km) transport distance. SSO material is trucked 48 km from a processing facility located within the Boston metropolitan area. Raw food waste is collected from commercial and institutional facilities. A 25-km transport distance was assumed for movement of raw food waste to the SSO processing facility. Table 3-4 summarizes truck transport requirements for incoming organic waste. A food waste bulk density of 1.8 kg/gallon (475 kg/m^3) was used to calculate the transport weight to the SSO processing facility (RTI International 2012). A water addition of 2.3 kg per gallon of SSO was estimated based on an assumed 31 percent solids content of raw food waste (RTI International 2012) and a 13 percent solids content of the engineered SSO product. Energy required to grind and pump the SSO slurry was estimated based on specifications for a small scale commercial food grinder and an assumed pumping head of 20 meters, which yields an estimated electricity requirement of 762,000 kWh per year for the full capacity scenario (approximately 3% of WWTF electricity use).

Table 3-4. Transport Calculations for Incoming External Waste and SSO

Scenario	Waste Type[1]	Quantity (gpd)	Mass (metric tons/day)	transport distance (km)	Transport (tkm/yr)[2]
All scenarios	Septage	80,000	308	25	2.81E+6
	Municipal solids	8,000	31.2	25	2.85E+5
Baseline scenario	Food waste	-	-	-	-
	SSO	-	-	-	-
Partial capacity scenario	Food waste	42,900	77.0	25	7.03E+5
	SSO	46,000	183	48	3.23E+6
Full capacity scenario	Food waste	85,700	154	25	1.41E+6
	SSO	92,000	367	48	6.46E+6

[1] Food waste is an input to SSO. It is SSO that is an input to the WWTF.

[2] tkm = ton-kilometers

3.3.2 Influent Pump Station

The influent pump station used 5.7 million kWh in 2016, corresponding to an electricity consumption of 0.176 kWh/m^3. An activated carbon tower is used for odor control at the influent pump station. The tower contains 1,200 ft^3 (35 m^3) of activated carbon. To develop the LCI quantity, it was assumed that the activated carbon was replaced every three years and has a density of 480 kg/m^3. Influent pump station LCI quantities remain constant across scenarios.

3.3.3 Preliminary and Primary Treatment

Preliminary treatment consists of aerated grit removal and bar screening. The case-study facility provided records of grit disposal for 2016. A total annual grit production of 404 metric tons was allocated evenly to annually treated wastewater leading to a grit disposal requirement of 0.012 kg grit/m^3 of treated wastewater. Preliminary and primary treatment were allocated seven percent of plant electricity consumption as reported in Table 3-3, which equates to 821,000 kWh or 0.025 kWh/m^3 of treated wastewater. Electricity use for grit removal and primary clarification remains constant across the three feedstock scenarios, due to the minor change in influent flowrate across scenarios (less than 0.5 percent). The WWTF spends approximately $11,000 per year on potassium permanganate, which is used for odor control. Potassium permanganate is purchased as 97.5% $KMnO_4$ for a unit cost of $3.25 per pound ($7.16 per kg), leading to an annual $KMnO_4$ consumption of approximately 1500 kg.

Table 3-5. Primary Clarifier Operational Parameters (GPS-X™ output)

Parameter	Baseline	Partial Capacity	Full Capacity	Units
Influent flowrate	9.6E+4	9.6E+4	9.7E+4	m^3/d
Influent TSS	3.2E+2	3.3E+2	3.4E+2	mg/L
Influent cBOD	2.0E+2	2.0E+2	2.1E+2	mg O_2/L
Influent TN	44	48	51	mg N/L
Influent phosphorus	12	13	13	mg P/L
TSS removal efficiency	55	56	57	%
$cBOD_5$ removal efficiency	42	43	45	%
TN removal efficiency	20	20	20	%
TP removal efficiency	15	15	17	%

3.3.4 Biological Treatment

Biological treatment consists of a plug-flow anoxic tank, followed by a series of four plug-flow aeration basins. The biological treatment unit was allocated 35 percent of plant electricity consumption as reported in Table 3-3, which equates to 4.3 million kWh or 0.134 kWh/m^3 of treated wastewater for the baseline scenario. Electricity consumption for the partial and full capacity scenarios was estimated based on GPS-X™ estimated increases in BOD loading to aeration tank of three and six percent, respectively. The model was set to maintain a DO concentration of two mg O_2/L. All modeling assumes a standard oxygen transfer efficiency (SOTE) of 0.23, which is based on the annual average plant SOTE as reported in a plant energy evaluation and documented in Table 3-6.

Table 3-6 and Table 3-7 document design and operational parameters for the aeration basins. The anoxic and aerobic reactors have a combined hydraulic retention time (HRT) of 4.6 hours. A solids retention time (SRT) of two days was used in the GPS-X™ model (Table 3-7). SRT controls the MLSS concentration via the RAS flow rate from the secondary clarifiers. A low SRT is maintained to minimize nitrification, avoiding the associated oxygen demand and aeration energy costs.

Table 3-6. Aeration Tank Standard Oxygen Transfer Efficiency

Month	Standard Oxygen Transfer Efficiency (SOTE)
January	0.38
February	0.38
March	0.38
April	0.30
May	0.20
June	0.15
July	0.10
August	0.13
September	0.13
October	0.18
November	0.23
December	0.23
Average	**0.23**

Table 3-7. Biological Treatment Operational Parameters (GPS-X™ output)

Parameter	Baseline	Partial Capacity	Full Capacity	Units
Influent flowrate[1]	9.26E+4	9.27E+4	9.29E+4	m^3/day
Influent TKN	36.3	39.8	42.4	mg N/L
Influent TP	7.27	7.42	7.53	mg P/L
Influent cBOD	115	115	115	mg O_2/L
Influent COD	246	246	246	mg COD/L
MLSS concentration	1.11E+3	1.13E+3	1.15E+3	mg/L
Nitrous oxide emissions[2]	3.09	3.39	3.62	metric tons/yr
Methane emissions[2,3]	119	119	119	metric tons/yr

[1] The influent flowrate excludes the RAS flow.

[2] Nitrous oxide and methane emissions are calculated based on TKN and BOD values from GPS-X™.

[3] Methane emissions increase only slightly in the partial and full capacity scenarios. This increase is obscured by the use of three significant figures.

Process GHG emissions of methane and nitrous oxide were estimated for the biological treatment unit based on influent TKN and BOD concentrations. Nitrous oxide emissions were estimated by applying an emission factor of 0.0016 kg N_2O-N/kg influent TKN (Chandran 2012), indicating that 0.16 percent of influent N is released as N_2O. Methane emissions were calculated using a theoretical maximum methane generation rate (B_o) of 0.6 kg CH_4/kg influent BOD, which reflects methane emissions under anaerobic conditions (IPCC 2006). The theoretical maximum methane generation rate was adjusted downwards using the IPCC method and a methane correction factor (MCF) of 0.044. The MCF value was calculated using a methane emission factor of 11 g CH_4/kg influent chemical oxygen demand (COD) reported by Daelman et al. (2013) and discussed in Appendix B. The MCF estimates the share of theoretical methane generation potential that will be realized by the study system. Table 3-7 presents annual emission estimates by feedstock scenario. No chemical use is required for the biological treatment process.

3.3.5 Secondary Clarification

Electricity consumption for this unit includes clarifier drive energy, RAS pumping and WAS pumping. Annual electricity demand for secondary clarification is 1.1 million kWh per year or 0.033 kWh/m^3 of treated wastewater. Electricity use was not scaled depending on the feedstock scenario due to the minimal change in flowrates as displayed in Table 3-8.

Table 3-8. Secondary Clarifier Operational Parameters (GPS-X™ output)

Parameter	Baseline	Partial Capacity	Full Capacity	Units
Influent flowrate	1.60E+5	1.61E+5	1.61E+5	m^3/d
RAS flowrate	6.79E+4	6.79E+4	6.79E+4	m^3/d
WAS flowrate	5.24E+3	5.24E+3	5.23E+3	m^3/d
Surface overflow rate	13.0	13.1	13.1	$m^3/(m^2.d)$
Solids loading rate	26.7	27.1	27.7	$kg/(m^2.d)$
Influent TSS	1.12E+3	1.13E+3	1.15E+3	mg/L
Influent cBOD	373	380	389	mg/L
Effluent TSS	6.69	6.71	6.74	mg/L
Effluent cBOD	10.9	10.3	9.73	mg/L
WAS TSS	2.44E+3	2.48E+3	2.53E+3	mg/L

3.3.6 Plant Water and Disinfection

Effluent is chlorinated and dechlorinated following secondary clarification. A portion of treated effluent is utilized both on and off-site in several reuse applications. The WWTF reuses between two and three MGD (approximately 10 percent) of effluent for on-site applications such as chemical delivery and wash water. Plant records indicate that on average an additional 0.46 MGD of treated wastewater was purchased and reused off-site by a local industrial partner. The electricity requirement for disinfection and plant water distribution is eight percent of annual plant consumption or 0.029 kWh/m^3 of treated wastewater.

Sodium hypochlorite is used for disinfection. Plant records indicate that 1.6 million pounds (734 metric tons) of 15 percent sodium hypochlorite were used in 2016. Sodium bisulfite is used for dechlorination. Plant records indicate that 746 thousand pounds (338 metric tons) of 38 percent sodium bisulfite were used in 2016. Electricity and chemical use associated with these unit processes were held constant across scenarios.

3.3.7 Sludge Thickening and Dewatering

The sludge thickening and dewatering process includes operation of gravity thickeners, gravity belt thickeners (GBT) and centrifuges. Together the sludge thickening and dewatering processes consume 11 percent of plant electricity or 1.41 million kWh in the baseline scenario. Baseline electricity consumption of the gravity thickeners was calculated assuming operation of two out of four thickening units and a collector drive power of five horsepower (HP) per unit (7.5 kW total). Pumping energy requirements were based on an assumed hydraulic head of 40 feet and a pump efficiency of 60 percent (Tarallo et al. 2015). Electricity requirements for the GBTs were estimated based on a combined equipment power requirement of 21.6 kW, which includes the belt drive, polymer pump, mixer, wash booster pump and thickened WAS mixer. Pumping energy requirements for the GBT were based on an assumed hydraulic head of 50 feet and a pump efficiency of 60 percent (Tarallo et al. 2015). One of two centrifuges are typically in operation and have a combined power requirement of 142 kW for the motor and backdrive. Centrifuge pumping energy requirements were based on an assumed hydraulic head of 30 feet and a pump efficiency of 60 percent. These values were input into GPS-X™ and yielded an estimated energy consumption for the three processes of 1.55 million kWh for the baseline scenario (Table 3-9). For partial and full capacity scenarios, thickener power consumption was increased proportionally to the increase in the flowrate of solids to each unit as estimated by GPS-X™ and shown in Table 3-10. Equation 1 was used to adjust GPS-X™ estimated electricity consumption for use in the LCA model.

The solids capture rate for the centrifuge was based on plant specific performance as reported in the 2009 energy evaluation (PES and UTS 2009). Solids capture rates for the gravity thickener and GBT were set at the GPS-X™ default values, 90 and 95 percent respectively. Polymer use in the baseline scenario was based on plant purchasing records. For the co-digestion feedstock scenarios, GBT polymer use was estimated assuming a polymer addition of five kg dry polymer per metric ton of dry solids processed (Tchobanoglous et al. 2014). The centrifuge polymer requirement was estimated assuming a polymer addition of 19.5 kg dry polymer per metric ton of dry solids processed, as reported in the facilities energy feasibility study (CDM Smith 2013).

Table 3-9. Thickening and Dewatering Annual Electricity Consumption (kwh)

	GPS-X™ Output	Baseline[1]	Partial Capacity	Full Capacity
Gravity thickener	74,200	67,600	71,800	76,600
Gravity belt thickener	196,000	178,000	181,000	185,000
Centrifuge	1,240,000	1,130,000	1,460,000	1,800,000
Centrifuge pumping	39,200	35,700	46,200	57,100
Total electricity use	1,550,000	1,410,000	1,760,000	2,100,000

[1] Scaled baseline electricity consumption matches 2016 plant records.

Table 3-10. Thickening and Dewatering Operational Parameters (GPS-X™ Output)

Unit Process	Parameter	Baseline	Partial Capacity	Full Capacity	Units
Gravity Thickener	Primary solids flowrate	5.68E+3	5.68E+3	5.68E+3	m^3/day
	Influent TSS	2.96E+3	3.14E+3	3.35E+3	mg/L
	Solids loading rate	37.9	40.3	43.0	kg/(m^2.d)
	Supernatant flowrate	5.30E+3	5.28E+3	5.25E+3	m^3/day
	Supernatant TSS	296	314	335	mg/L
	Supernatant TN	44.2	48.6	52.2	mg N/L
	Supernatant TP	8.60	8.93	9.27	mg P/L
	Solids capture	90.7	90.7	90.8	%

Table 3-10. Thickening and Dewatering Operational Parameters (GPS-X™ Output)

Unit Process	Parameter	Baseline	Partial Capacity	Full Capacity	Units
	Thickened solids	381	405	432	m^3/day
	Thickened Solids TSS	4.00E+4	4.00E+4	4.00E+4	mg/L
Gravity Belt Thickener	WAS flowrate	5.24E+3	5.24E+3	5.23E+3	m^3/day
	Influent TSS	2.44E+3	2.48E+3	2.53E+3	mg/L
	Supernatant flowrate	4.97E+3	4.96E+3	4.95E+3	m^3/day
	Supernatant TSS	122	124	126	mg/L
	Supernatant TN	30.4	33.9	36.5	mg N/L
	Supernatant TP	6.50	6.66	6.77	mg P/L
	Solids capture	95.3	95.3	95.3	%
	Thickened solids	271	274	280	m^3/day
	Thickened Solids TSS	4.50E+4	4.50E+4	4.50E+4	mg/L
	Polymer use	2.33E+4	2.37E+4	2.41E+4	kg/year
Centrifuge	Digestate flowrate	682	883	1.09E+3	m^3/day
	Influent solids	1.73E+4	2.44E+4	3.27E+4	dry kg/day
	Centrate flowrate	633	815	999	m^3/day
	Centrate TSS	4.30E+3	4.69E+3	5.10E+3	mg/L
	Centrate TN	1.17E+3	1.36E+3	1.40E+3	mg N/L
	Centrate TP	381	328	294	mg P/L
	Solids capture	84.2	84.3	84.4	%
	Thickened solids	1.45E+4	2.05E+4	2.76E+4	dry kg/day
	Thickened Solids TSS	3.00E+5	3.00E+5	3.00E+5	mg/L
	Polymer use	9.83E+5	1.34E+6	1.15E+6	kg/year

3.3.8 Anaerobic Digestion

Thickened primary sludge, WAS and trucked municipal solids are blended and pumped into one of three mesophilic ADs in the baseline scenario. A fourth digester was added to accommodate the SSO material accepted in the partial and full capacity AD performance scenarios. No dewatering is required for the trucked municipal solids or SSO material. Table 3-11 lists basic design parameters for the three AD feedstock scenarios.

Table 3-11. Anaerobic Digester Design and Operational Parameters

Description	Baseline	Partial Capacity	Full Capacity	Unit
Anaerobic digesters	3	4	4	count
Tank diameter	85	85	85	feet
Sidewall depth	39	39	39	feet
Tank volume	1,520,000	1,520,000	1,520,000	gallons per tank
Total storage volume (all tanks)	4,560,000	6,080,000	6,080,000	gallons
Effective volume, total	4,200,000	5,600,000	5,600,000	gallons

Table 3-11. Anaerobic Digester Design and Operational Parameters

Description	Baseline	Partial Capacity	Full Capacity	Unit
Average feed percent solids	4.0%	5.9%	7.0%	solids
Average feed VSS %	70%	79%	82%	ratio
VS loading	4.31E+4	9.20E+4	1.41E+5	lb VSS/day
Effective HRT[1]	23	24	19	days

[1] Calculated using effective volume.

Incoming solids are heated to 95°F using a heat exchanger. Biogas is the preferred fuel source. A glycol boiler system was used to provide thermal energy in the baseline feedstock scenario. CHP thermal energy is preferred for the partial and full capacity scenarios and was found to be sufficient to heat digester solids for all except the partial capacity-low AD performance scenario, where a small quantity of supplementary natural gas is required. Section 3.3.9 includes a description of units used for on-site biogas combustion.

Ferric chloride is added to each digester at a rate of 1.6 gallons per digester per hour (34 percent solution) for biogas H_2S control. The ADs were allocated 13 percent of plant electricity consumption, 1.64 million kWh, in the baseline scenario as reported in Table 3-3. Each digester tank is equipped with one central and three external mixers. Two of the three glycol pumps are allocated to the digesters, with the third providing pumping for building heat delivery. This equipment has a total power demand of 216 and 276 kW in the baseline and SSO feedstock scenarios, respectively. Equation 1 was used to scale GPS-X™ estimated electricity consumption.

LCA results were generated for two AD performance scenarios, reflecting expected (base) and low digester performance. Estimated VSR and biogas yield are varied within the two AD performance scenarios, affecting biogas production and resulting energy generation. Table 3-12 presents these parameter values along with estimates of biogas production. Volatile solids reduction is higher for the partial and full capacity scenarios due to the increased digestibility of fruit and vegetable waste (SSO) as compared to primary sludge and WAS (EBMUD 2008). The low AD performance VSR was calculated assuming 50 and 70 percent reductions for municipal solids and SSO, respectively. The composite VSR for the base AD performance scenario is an output of the GPS-X™ model, corresponding to 55 and 79 percent reductions for municipal solids and SSO. Methane content of biogas is relatively consistent across scenarios ranging from 59.2 to 59.9 percent methane (by volume) depending upon the scenario. Biogas production increases by approximately 230 and 350 percent between the baseline and full capacity feedstock scenarios for the low and base AD performance scenarios, respectively. Available biogas quantity reflects the portion of biogas that is lost as fugitive methane emissions. Fugitive methane emissions were estimated based on an IPCC emission factor for "floating gas holders with no external water-seal" (UNFCCC 2012).

Table 3-12. Anaerobic Digestion Performance Scenarios Parameters and Biogas Production

AD Scenario	Description	Baseline	Partial Capacity	Full Capacity	Units
Base	VS reduction	55%	69%	72%	of influent VS
Low			61%	63%	
Base	Biogas yield	17.4	18.4	18.5	ft^3/lb VSS destroyed
Low			15	15	
Both	Methane content of biogas	59.2	59.4	59.9	% v/v
Both	Fugitive methane losses	5%			of total
Base	Biogas production	4.13E+5	1.17E+6	1.87E+6	ft^3/day
Low			8.40E+5	1.34E+6	
Base	Available biogas	3.93E+5	1.11E+6	1.78E+6	
Low			7.98E+5	1.28E+6	

After exiting the digesters, biogas is cleaned and pressurized before entering the CHP system. Condensation is used to remove excess moisture from the biogas. Iron sponge filters were added during the CHP upgrade to further reduce the presence of sulfur in biogas, which can lead to corrosion of biogas cleaning and CHP equipment as well as undesirable sulfur oxide emissions. Activated carbon filters are used to removed siloxane from the biogas. Biogas is pressurized to four or five psi before entering the CHP engines.

Gas storage is limited to the space available within each digester underneath the floating covers. Due to the timing of biogas production and facility energy demand and CHP maintenance or malfunction, the facility does not expect to utilize 100 percent of available biogas. The term available biogas refers to biogas production minus fugitive losses. The base and low AD performance scenarios assume 90 and 80 percent utilization of available biogas, respectively. The portion of biogas that is not used for facility heat or electricity production was assumed to be combusted in one of two on-site biogas flares. Use of biogas in the pellet drying facility is prioritized over other uses. The pellet drying facility is not set up to utilize thermal energy from the CHP system, requiring direct combustion of biogas in the pellet dryers. In the baseline feedstock scenario, a small quantity of natural gas was required to supplement biogas to satisfy the heat demand of pelletization. The balance of available biogas is combusted in the CHP system in the partial and full capacity scenarios. Table 3-13 and Table 3-14 summarize biogas utilization and facility energy demand for the base and low AD scenarios, respectively. Heat demand and provision are both expressed in terms of fuel energy (primary energy), i.e. prior to the application of equipment conversion efficiencies. Thermal energy production of the CHP system was calculated assuming a thermal conversion efficiency of 39 percent (Wiser et al. 2010), and is expressed in fuel energy equivalents assuming a boiler thermal conversion efficiency of 80 percent. The heat content of biogas is 550 BTU/ft^3 (20.5 MJ/m^3), which is on the lower end of the reported range for biogas from WWTFs (Ong et al. 2017).

Table 3-13. Facility Energy Demand and Production – Base AD Scenario

Category	Description	Baseline	Partial Capacity	Full Capacity	Unit
Biogas utilization	Biogas utilization	82%	90%	90%	of available biogas[1]
	Flaring rate	18%	10%	10%	
	Pellet dryer use	53%	30%	25%	
	Boiler use	29%	0%	0%	
	CHP use	n.a.	60%	65%	
Energy demand	Pellet dryer heat demand	4.4E+7	7.0E+7	9.4E+7	MJ/year (fuel energy)
	Digester heat demand	2.8E+7	3.6E+7	4.3E+7	
	Facility heat demand	1.4E+7	1.4E+7	1.4E+7	
	Electricity demand	1.8E+7	2.0E+7	2.1E+7	kWh/year (delivered)
Biogas energy production and use	Available biogas energy[1]	6.9E+7	2.1E+8	3.4E+8	MJ/year (fuel energy)
	Flare energy losses	1.5E+7	2.4E+7	3.8E+7	
	Pellet dryer heat, from biogas	4.4E+7	7.0E+7	9.4E+7	
	CHP heat, from biogas	n.a.	6.9E+7	1.2E+8	
	Digester heat, from biogas	2.4E+7	3.6E+7	4.3E+7	
	Facility heat, from biogas	-	1.4E+7	1.4E+7	
	Wasted CHP heat, from biogas	n.a.	1.9E+7	6.2E+7	
	Electricity, from biogas	n.a.	1.6E+7	2.7E+7	kWh/year (delivered)
	Electricity, excess production	n.a.	-	6.1E+6	
Energy use summary	Biogas energy recovery[2]	78%	81%	71%	of produced biogas energy[2]
	Electricity demand satisfaction	-	80%	100%	of total facility demand
	Heat demand satisfaction	79%	100%	100%	

[1] Available biogas refers to biogas production minus fugitive losses.

[2] Includes energy losses associated with fugitive emissions.

Table 3-14. Facility Energy Demand and Production – Low AD Scenario

Category	Description	Partial Capacity	Full Capacity	Unit
Biogas utilization	Biogas utilization	80%	80%	of available biogas
	Flaring rate	20%	20%	
	Pellet dryer use	41%	35%	
	CHP use	39%	45%	
Energy demand	Pellet dryer heat demand	7.0E+7	9.4E+7	MJ/year (fuel energy)
	Digester heat demand	3.6E+7	4.3E+7	
	Facility heat demand	1.4E+7	1.4E+7	
	Electricity demand	2.0E+7	2.1E+7	kWh/year (delivered)
Biogas energy	Available biogas energy[1]	1.7E+8	2.7E+8	MJ/year (fuel energy)
	Flare energy losses	3.4E+7	5.4E+7	

Table 3-14. Facility Energy Demand and Production – Low AD Scenario

Category	Description	Partial Capacity	Full Capacity	Unit
production and use	Pellet dryer heat, from biogas	7.0E+7	9.4E+7	
	CHP heat, from biogas	2.9E+7	5.7E+7	
	Digester heat, from biogas	3.2E+7	4.3E+7	
	Facility heat, from biogas	-	1.4E+7	
	Electricity, from biogas	7.3E+6	1.4E+7	kWh/year (delivered)
	Electricity, excess production	-	-	
Energy use summary	Biogas energy recovery[2]	74%	72%	of produced biogas energy[2]
	Electricity demand satisfaction	37%	64%	of total facility demand
	Heat demand satisfaction	85%	100%	

[1] Available biogas refers to biogas production minus fugitive losses.

[2] Includes energy losses associated with fugitive emissions.

Infrastructure requirements for the new AD unit and CHP buildings were estimated based on unit dimensions using generalized CAPDETWorks™ design equations (Harris, et al. 1982). Earthwork, wall and slab concrete, sub-grade gravel and additional piping requirements were included. Combined heat and power building materials were estimated using generalized building LCI information based on building volume assuming 14-foot ceiling height and 12,000 square feet of floor area.

3.3.9 On-Site Combustion Units

Biogas and natural gas are combusted in several on-site combustion units: flare, pellet dryer, glycol boiler, building heat boiler and CHP engine. Table 3-13 and Table 3-14 describe the use of on-site combustion equipment for each feedstock and AD performance scenario. Building heat boilers combust only natural gas and are used exclusively in the baseline feedstock scenario. Emissions from the building heat boiler were approximated using a natural gas boiler unit process adapted from Ecoinvent 2.2. Other combustion unit emissions were based on values reported in an air permit application specific to the GLSD WWTF.

The design capacity of the flare is 800 standard cubic feet per minute (scfm) of biogas. The reported volatile organic compound (VOC) destruction rate is 99 percent. The permit application reports estimated annual emissions when the flare combusts 7.3 million m^3 of biogas. This information was used to calculate flare emission factors in kg/m^3 biogas combusted, as reported in Table 3-15. Methane emissions were estimated using the reported VOC destruction rate. A worst-case estimate of non-methane volatile organic compounds (NMVOCs) and methane emissions was estimated assuming a 95 percent destruction rate, based on facility testing that indicates a potential discrepancy between ideal and realized flare performance (Shah et al. 2011). The worst-case emission factors were analyzed as part of the low AD performance scenario.

Table 3-15. Flaring Emissions, Short Tons Per Year (TPY) and per m^3 Biogas

Pollutant	Emissions (TPY)	Emissions (kg/m^3 biogas combusted)
Nitrogen oxides (NOx)	9.32	1.15E-3
Volatile organic compounds (VOCs), base AD performance	6.52	8.07E-4
Volatile organic compounds (VOCs), low AD performance	n.a.	4.04E-3
Sulfur dioxide (SO_2)	10.2	1.26E-3
Particulate matter (PM)	4.69	5.81E-4
Carbon monoxide (CO)	28.0	3.47E-3
Methane (CH_4), base AD performance	n.a.	3.90E-3
Methane (CH_4), low AD performance	n.a.	1.95E-2

Two new internal combustion engines are used for CHP generation. Each engine has a design capacity of 12.9 MMBtu/hr (13.6 GJ/hr), which equates to a biogas combustion rate of 390 scfm (11.4 m^3/minute) per engine. The engines utilize oxidation catalyst and selective catalytic reduction emission control technologies to minimize VOC and CO and nitrogen oxide emissions, respectively. The oxidation catalyst system is expected to remove 50 and 96 percent of VOC and CO emissions by weight, respectively. The selective catalytic reduction system is expected to remove 98.2% of NOx emissions by weight. The permit application reports estimated annual emissions when the flare is operating at design capacity. Table 3-16 reports CHP emission factors in kg/m^3 biogas combusted.

Table 3-16. CHP Engine Emissions, Short Tons Per Year (TPY) and per m^3 Biogas

Pollutant	Emissions (TPY)	Emissions (kg/m^3 biogas combusted)
NOx	2.10	1.64E-4
VOCs	20.2	1.58E-3
SO_2	0.18	1.41E-5
PM	0.44	3.44E-5
CO	13.7	1.07E-3
NH_3	0.82	6.41E-5
CH_4[1]	n.a.	4.30E-3
N_2O[1]	n.a.	1.02E-4

[1] Values are based on Ecoinvent 2.2 unit process: "natural gas, burned in cogen one MWe lean burn", and are converted to be on a per m^3 biogas basis.

The facility has three dual-fuel glycol boilers that are used to provide digester heat in the baseline feedstock scenario. Each boiler has a design capacity of 8.31 MMBtu/hr (8.77 GJ/hr).

The units are not equipped with pollution control devices. Emission factors were calculated based on design capacity and annual emissions (Table 3-17).

Table 3-17. Glycol Boiler Emissions, Short Tons Per Year (TPY) and per m^3 Biogas

Pollutant	Emissions (TPY)	Emissions (kg/m^3 biogas combusted)
NOx	1.36	4.08E-4
VOCs	0.310	9.29E-5
SO_2	1.72	5.15E-4
PM	0.400	1.20E-4
CO	0.800	2.40E-4
N_2O	n.a.	1.02E-5
CH_4	n.a.	4.10E-5

The facility operates two pellet driers each with a design capacity of 15 MMBtu/hr (15.8 GJ/hr), which equates to a maximum annual biogas combustion rate of 13.5 million m^3 per year. Pellet driers are equipped with cyclone separators and scrubber/condensers for emission control. Emission factors were calculated based on design capacity and estimated annual emissions (Table 3-18).

Table 3-18. Pellet Drier Emissions, Short Tons Per Year (TPY) and per m^3 Biogas

Pollutant	Emissions (TPY)	Emissions (kg/m^3 biogas combusted)
NOx	10.5	1.12E-3
VOCs	1.93	2.05E-4
SO_2	11.4	1.21E-3
PM	5.58	5.93E-4
CO	7.76	8.25E-4
Arsenic (As)	2.48E-4	2.64E-8
Cadmium (Cd)	1.56E-3	1.66E-7
N_2O	n.a.	2.05E-6
CH_4	n.a.	4.10E-5

3.3.10 Biosolids Pelletization

An on-site biosolids pelletization facility is operated by an outside contractor to turn dewatered biosolids from the centrifuge into a dry, stabilized agricultural amendment. Table 3-19 lists the quantity of centrifuge cake processed per day, associated pellet production and pellet nutrient content. Biosolids pelletization requires 8,500 MJ of thermal energy and 350 kWh of electrical energy per dry short ton of biosolids processed. Sludge drying requires 16, 20 and 25 percent of facility electricity demand, excluding influent pump station electricity requirements, for the baseline, partial and full capacity feedstock scenarios, respectively (Table 3-3). Section

3.3.8 discusses the ability of biogas to satisfy pellet drying energy demand. Section 3.3.9 describes pellet drying equipment and emissions.

Table 3-19. Pellet Production and Nutrient Content

Parameter	Baseline	Partial Capacity	Full Capacity	Units
Centrifuge cake, dry mass	1.45E+4	2.05E+4	2.76E+4	kg/day
Pellet production	5.16E+6	7.30E+6	9.81E+6	kg/year
Pellet N Content	2.06E+5	2.92E+5	3.92E+5	kg/year as N
Pellet P Content	4.51E+4	6.37E+4	8.56E+4	kg/year as P

3.3.11 Land Application of Pelletized Biosolids

Pelletized biosolids were assumed to be transported an average of 121 km to farm fields for application as a fertilizer and soil amendment. Table 3-20 lists basic biosolids pellet specifications. Nutrient content information was provided by the drying facility. Carbon content was estimated assuming a carbon to nitrogen ratio of 7:1 (Parnaudeau et al. 2004; Rigby et al. 2016).

Table 3-20. Biosolid Fertilizer Pellet Specifications

Parameter	Value	Units
Moisture content	2.5%	moisture
Nitrogen content	4%	by weight
Phosphorus content	2%	by weight
Potassium content	0%	by weight
Carbon content	28%	by weight

Fertilizer pellets are loaded into a manure spreader and distributed on agricultural fields at the average 2015 U.S. nitrogen (N) and phosphorus (P_2O_5) application rate for winter wheat (NASS 2016). It was assumed that 1.06 liters of diesel fuel are required to spread one ton of pellets (ROU 2007). Pellets are applied such that they provide 61 lb N per acre (68.4 kg N/ha) and 31 lb P_2O_5 per acre (34.9 kg P_2O_5/ha) of plant available nutrients. The estimate of plant available nutrients is equivalent to the fertilizer replacement value. A nitrogen fertilizer replacement value for the pelletized biosolids of 55 percent was used in this analysis (Smith and Durham 2002; Rigby et al. 2016). The value is based on the total quantity of mineralized nitrogen available over a three-year period. Negligible additional mineralization typically occurs after three years when biosolids are applied at typical agronomic rates (Rigby et al. 2016). A fertilizer replacement value of 95 percent was used for P_2O_5 (Boldrin et al. 2009). Table 3-21 compares typical application rates for chemical fertilizers to the pelletized biosolid nutrient application rates used in this study, designed to achieve equivalent plant availability. The pelletized biosolids are also a source of carbon.

Table 3-21. Comparison of Chemical and Pelletized Biosolid Nutrient Applications

Parameter	Chemical Fertilizer Application (kg/ha/yr)	Pelletized Biosolid Application (kg/ha/yr)	Units
Nitrogen	68.4	124	as N
Phosphorus	34.7	62.2	as P_2O_5
Potash	43.7	-	as K_2O
Carbon	-	870	as C

The benefits of avoided fertilizer production were estimated assuming the replacement of urea and single superphosphate for the plant available portion of pellet nutrients. Urea and single superphosphate are 46 and 21 percent N and P_2O_5 by weight, respectively.

Typical agricultural emissions such as nitrous oxide (N_2O), NOx, NH_3, NO_3 and P 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. 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 total nutrient application rates and therefore lead to higher estimates of agricultural emissions due the increased total nutrient application rate (Table 3-21) of pelletized biosolids that is required to achieve equivalent plant available nutrient applications. Impacts were assessed based on the net change in agricultural emissions that would be expected based on the assumed fertilizer replacement rates.

Table 3-22 lists the calculated emission per kg of land applied nutrient. Phosphorus emissions to surface water and groundwater were estimated using the Ecoinvent methodology (Nemecek and Kägi 2007). Ammonia emissions were estimated assuming that 8.5 percent of applied nitrogen is released as NH_3 (Goedkoop et al. 2009). Nitrogen oxide emissions were estimated assuming that 21 percent of land applied nitrogen is lost via this route (Nemecek and Kägi 2007). Nitrate and N_2O emissions were estimated using the IPCC method (De Klein et al. 2006). Direct N_2O emissions associated with land use were excluded as these emissions remain consistent regardless of fertilizer type. The carbon sequestration estimate assumes that 0.32 kg of CO_2 are sequestered per kg of carbon land applied, equating to a long-term carbon sequestration rate of 9 percent (Boldrin et al. 2009).

Environmental impacts based on these values should be viewed as reasonable estimates, however significant variability in these values is expected in practice.

Table 3-22. Estimated Agricultural Emissions

Parameter	Value	Units
NH_3, to air	0.103	kg NH_3/kg applied N
N_2O, to air	0.025	kg N_2O/kg applied N
NOx, to air[1]	0.011	kg NO_x/kg applied N
NO_3, to water	1.33	kg NO_3/kg applied N
P, to groundwater	2.99E-3	kg P/kg applied P

Table 3-22. Estimated Agricultural Emissions

Parameter	Value	Units
P, to surface water	0.087	kg P/kg applied P
C, Sequestered	0.32	kg CO_2/kg C applied

[1] Excludes nitrous oxide.

3.3.12 Effluent Release

Table 3-23 lists effluent quality for each of the three feedstock scenarios in the base AD performance scenario. Baseline effluent characteristics were calculated using 2016 DMR data (U.S. EPA 2016). Effluent concentrations for the partial and full capacity scenarios were estimated using percent removal values corresponding to baseline plant operations and scenario specific primary clarifier loading estimates drawn from the GPS-X™ model. The WWTF has no permitted nutrient requirements and is not operated for nutrient removal.

GPS-X™ modeling indicates that the partial and full capacity scenarios yield nine and 16 percent, respective, increases in nitrogen load to the primary clarifier. This increased load corresponds to 61 and 55 percent of SSO nitrogen content for the partial and full capacity scenarios. The low AD performance scenario assumes that 80 percent of SSO nitrogen is returned to the primary clarifier as part of a sensitivity analysis to quantify the effect on eutrophication potential (EP) impact. The 80 percent nitrogen return flow estimate was based on the reasoning that organic nitrogen is solubilized in proportion to the realized volatile solid reduction in the AD, which can be 75-80 percent for fruit and vegetable waste (EBMUD 2008).

Nitrous oxide emissions from receiving streams were 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 Appendix B.

Table 3-23. Effluent Emissions by Feedstock Scenario

Parameter	Baseline	Partial Capacity	Full Capacity	Units
Flowrate	8.73E+4	8.75E+4	8.76E+4	m^3/day
TSS, to water	6.05	6.28	6.55	mg/L
BOD_5, to water	17.7	18.0	18.5	mg O_2/L
TN, to water	20.6	22.4	23.8	mg N/L
NH_3-N, to water	18.5	20.1	21.4	mg N/L
NO_3-N, to water	0.644	0.701	0.746	mg N/L
Organic N, to water	1.44	1.57	1.67	mg N/L
TP, to water	0.367	0.378	0.389	mg P/L
N_2O, to air	0.162	0.176	0.187	mg N_2O/L

3.3.13 Facilities

Administrative, laboratory and maintenance facilities (i.e. control buildings) were allocated two percent of annual electricity consumption in the baseline scenario. This value was increased by five percent in the SSO scenarios to account for the additional electricity requirements of the new CHP building. Building heating requirements were allocated 72 percent of natural gas purchases based on the energy efficiency evaluation (PES and UTS 2009). The plant purchased approximately 17,000 Dekatherms (DTH) of natural gas in 2016. Control buildings were allocated 100 percent of purchased potable water consumption, which totals 3.87 million gallons per year. Potable water consumption was estimated based on the annual water bill of $17,236 and a unit water cost of $3.10 per 100 ft^3 (municipal rate schedule). For facility heating, the analysis assumed that CHP heat is the preferred building heat source following installation of the new facilities. CHP heat production is sufficient to provide 100 percent of building heat requirements for all except the partial capacity-low AD performance scenario, for which supplementary natural gas is required. Building heat requirements were held constant across scenarios.

3.3.14 Avoided Waste Processes

Several states have implemented a landfill ban on organic waste including Massachusetts, Vermont and Connecticut (Henricks 2014). Food waste diverted from the landfill is expected to be alternatively disposed of via AD, composting or as animal feed among other options. This study examines the net environmental impact of shifting SSO EOL treatment from disposal in landfills and WTE facilities to beneficial reuse as an AD feedstock. Baseline results, presented in Section 5, are based on 2016 Massachusetts waste diversion, where 32 percent of diverted SSO avoids landfill disposal. The remaining 68 percent of food waste is diverted from WTE facilities. Appendix A includes the results of an additional analysis where AD of food waste is compared to composting as an alternative EOL management strategy.

3.3.14.1 Avoided Food Waste Landfilling

Avoided burdens were calculated relative to national average and Massachusetts landfills, which were differentiated by the share of landfills that practice energy recovery, flaring or venting of generated landfill gas as depicted in Table 3-24.

Table 3-24. National and Massachusetts Average Landfill Gas Management Practice[1]

Gas Management Practice	National[1]	Massachusetts[2]
Flaring	24%	19%
Energy recovery	68%	81%
Venting	8%	-

[1] (U.S. EPA 2017b; U.S. EPA 2017c)

[2] (Commonwealth of Massachusetts 2017b)

The share of Massachusetts landfills that employ energy recovery are reported in the Master List of Solid Waste Facilities in Massachusetts (Commonwealth of Massachusetts 2017b). In total there were 14 operational landfills in the State of Massachusetts in 2014. Seven of the operational landfills were equipped with energy recovery. The remaining facilities were assumed to flare their landfill gas. The share of landfill gas produced at each facility was calculated based on the mass of waste landfilled in 2014, the most recent available data year.

The share of national landfills that employ each gas management practice was determined by analyzing landfill and energy project level technical data collected by EPA's Landfill Methane Outreach Program (LMOP) (U.S. EPA 2017c; U.S. EPA 2017b). The 2017 LMOP database lists 2,452 U.S. landfills, of which 1,165 are open. Only open facilities were considered in this analysis. The database reports landfill gas generation for 822 of the open facilities. All active landfills with landfill gas estimates were classified as energy recovery, flare or venting facilities. Project level LMOP data (2017) lists 849 operational energy recovery projects. Facilities that do not report an operational energy recovery project and have a gas collection and flaring facility were classified as flare facilities. All other facilities were assumed to vent landfill gas.

Of the 822 open facilities, 361 report energy recovery projects, accounting for 68 percent of reported landfill gas generation. While 223 facilities were classified as venting, they account for only eight percent of reported landfill gas generation. The remaining 238 facilities were classified as flare facilities and account for 24 percent of reported landfill gas generation.

The LCI for landfill disposal of food waste, or SSO, was developed using the Municipal Solid Waste Decision Support Tool (MSW DST), version 1.0 (RTI International 2012). Separate LCIs were generated for facilities venting, flaring and recovering energy from landfill gas. The MSW DST tool models each landfill over a 100-year period. All scenarios assume no gas capture system is in place during the first two years of operation. Years two to thirty are specified such that landfill gas is either vented, flared or piped to an internal combustion engine (ICE) electrical generator, according to the scenario. All landfill gas is vented following year 30 once gas production has slowed. The assumed electrical efficiency of the landfill ICE is 33 percent. Heat from the ICE is not recovered for reuse. The oxidation rate of methane that escapes through the cover material was held constant across scenarios and was set to 0.038 (unitless) (U.S. EPA 2015a). The LCI for each facility category was combined using the gas management practices specified in Table 3-24 as weighting factors. The full LCI is available in Appendix B, Table B-1.

3.3.14.2 Avoided Food Waste Incineration

Avoided burdens were calculated relative to national average and Massachusetts WTE facilities, which were differentiated based on plant heat rate and emissions per unit of waste combusted as presented in Table 3-25.

The full LCI is available in Appendix B, Table B-2.

Table 3-25. National and Massachusetts Average WTE Facility Specifications

WTE Parameter	National[1]	Massachusetts[2]
Food waste heat value (BTU/lb)	1,800	1,800
Plant heat rate (BTU/kWh)	18,000	19,214
Sulfur dioxide (ppmv @ 7% oxygen, dry)	8.0	2.8
Hydrochloric acid (ppmv @ 7% oxygen, dry)	8.9	8.9
Nitrogen oxides (ppmv @ 7% oxygen, dry)	1.4E+2	56
Carbon monoxide (ppmv @ 7% oxygen, dry)	26	4.8
Particulate matter (mg/dscm @ 7% oxygen, dry)	4.0	0.63

Table 3-25. National and Massachusetts Average WTE Facility Specifications

WTE Parameter	National[1]	Massachusetts[2]
Dioxins/furans (mg/dscm @ 7% oxygen, dry)	4.5	4.5
Methane (lb emitted/ton MSW)	3.0E-3	3.0E-3
Ammonia (lb emitted/ton MSW)	-	8.0E-3
Hydrocarbons (lb emitted/ton MSW)	-	-

1 MSW DST default values

2 Variations from MSW DST defaults are based on records for the North Andover Massachusetts, Wheelabrator WTE facility

3.4 Background LCI Databases

In addition to the primary data sources described in the preceding sections, several background LCI databases were used to model life cycle impacts of upstream processes such as electricity generation and distribution, transportation, and manufacturing of chemical and material inputs. Ecoinvent 2.2 served as the basis for many of the upstream infrastructure inputs, chemical and avoided fertilizer manufacturing (Frischknecht et al. 2005). The U.S. Life Cycle Inventory (U.S. LCI) database was used to represent the manufacture of some chemical inputs and most of the electricity unit processes, in cases where applicable U.S. specific processes were available in the database (NREL 2012). A U.S. EPA LCI database was used for electricity from solar and wind, transportation processes and additional infrastructure materials (U.S. EPA 2015b).

3.5 LCI Limitations and Data Quality

In accordance with the project's Quality Assurance Project Plan (QAPP) entitled *Quality Assurance Project Plan for Life Cycle Considerations and Systems Analyses of Municipal Water Sustainability Assessments* approved by EPA on March 21, 2017 (ERG 2017), ERG collected existing data[1] to develop the LCA and cost estimates for the GLSD WWTF and associated scenario/sensitivity analysis. ERG evaluated the collected information for completeness, accuracy and reasonableness. In addition, ERG considered publication date, accuracy/reliability and cost completeness when reviewing data quality. Finally, ERG performed developmental and final product internal technical reviews of the LCA and costing methodology and calculations for this study.

Table 3-26 presents the data quality criteria ERG used when evaluating collected cost data. All capital costs associated with the AD and CHP expansion project were drawn from an engineering feasibility study and are specific to the case-study facility. Current and ongoing operational, maintenance and material purchase costs were based on budget data from the GLSD WWTF or facility-specific unit costs that were applied to estimated LCI and LCCA parameters documented in this report (e.g. electricity production/value).

[1] *Existing data* means information and measurements that were originally produced for one purpose that are recompiled or reassessed for a different purpose. Existing data are also called secondary data. Sources of existing data may include published reports, journal articles, LCI and government databases, and industry publications.

Table 3-26. Cost Data Quality Criteria

Quality Criterion: Cost Data	Description/Definition	Acceptance Specifications
Current	Report the time period of the data.	Costs are converted to a standard year using the Bureau of Labor Services 2017 Consumer Price Index (Crawford et al. 2017)
Complete	Ensure all aspects of the technology costs are reported.	Cost estimates are completed using all input costs for energy, labor, chemicals and waste disposal.
Representative	Report if the costs used are representative of the technology studied.	Costs are based on data from peer reviewed literature, vendor information and engineering software specific to the technologies studied.
Accurate/Reliable	Document the sources of the data. Confirm calculations are based on sound methodology and technically correct.	Data sources and calculations were documented and reviewed.

Table 3-27 presents the data quality criteria ERG used when evaluating collected or developed LCI data. ERG documented qualitative descriptions of the source reliability, completeness, temporal correlation, geographical correlation and technological correlation in Appendix E, for EPA's use in determining whether the LCI data are acceptable for use. Structuring the analysis as a case-study allows for high data quality. Completeness, temporal correlation, geographic correlation and technological correlation for entries based on plant records were all assigned data quality scores of one. Plant records were not able to furnish all information required for the LCI, leading to source reliability scores of two or below for some data in the baseline scenario. The partial and full capacity scenarios rely on modeling and engineering/scientific estimation methods that rely on numerous assumptions, leading to a data quality score of three for source reliability. The same data quality rubric was applied both to LCI development and the use of unit process data from existing databases listed in Section 3.4. Some entries in Table E-1 have been marked as n.a., not applicable, for LCI development entries that use engineering/scientific estimation methods that are applied to future, potential co-digestion scenarios.

Table 3-27. Life Cycle Inventory Data Quality Criteria[1,2]

Indicator	Reporting Criteria	Score
Source Reliability[3]	Data verified based on measurements.	**1**
	Data verified based on some assumptions and/or standard science and engineering calculations.	**2**
	Data verified with many assumptions, or non-verified but from quality source.	**3**
	Qualified estimate.	**4**
	Non-qualified estimate.	**5**
Completeness	Representative data from a sufficient sample of sites over an adequate period of time.	**1**
	Smaller number of sites, but an adequate period of time.	**2**
	Sufficient number of sites, but a less adequate period of time.	**3**
	Smaller number of sites and shorter periods or incomplete data from an adequate number of sites or periods.	**4**

Table 3-27. Life Cycle Inventory Data Quality Criteria[1,2]

Indicator	Reporting Criteria	Score
	Representativeness unknown or incomplete data sets.	**5**
Temporal Correlation	Less than 3 years of difference to year of study/current year.	**1**
	Less than 6 years of difference.	**2**
	Less than 10 years of difference.	**3**
	Less than 15 years of difference.	**4**
	Age of data unknown or more than 15 years of difference.	**5**
Geographical Correlation	Data from area under study.	**1**
	Average data from larger area or specific data from a close area.	**2**
	Data from area with similar production conditions.	**3**
	Data from area with slightly similar production conditions.	**4**
	Data from unknown area or area with very different production conditions.	**5**
Technological Correlation	Data from technology, process, or materials being studied.	**1**
	Data from a different technology using the same process and/or materials.	**2**
		3
	Data on related process or material using the same technology.	**4**
	Data or related process or material using a different technology.	**5**

[1] The baseline scenario represents 2016 operational conditions and costs, based on plant records.

[2] The partial and full capacity scenarios refer to the prospective feedstock scenarios and modeled performance for both the low and base AD performance scenarios.

[3] Values based on plant records are assigned a Source Reliability data quality score of one, while data based on GPS-X™ model output or engineering based estimation methods are assigned a score of two.

ERG input all LCI data developed into the openLCA software (GreenDelta 2016). A team member knowledgeable of the project, but who did not develop the model, reviewed the OpenLCA model to ensure the accuracy of the data transcribed into the software.

LCI information that falls outside of the system boundary was 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 WWTFs of similar size and design, the data presented here relates to a specific U.S. WWTF in Massachusetts. Further work is recommended to understand the variability of key parameters across different conditions, permit requirements, 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 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 scenario-based sensitivity analysis was conducted in lieu of a formal uncertainty assessment and was intended to produce results within a range that is representative of the facilities potential performance. However, there is still uncertainty and variability associated with individual LCI values, and the reader should keep this in mind when interpreting the results. Comparative conclusions should not be drawn based on small differences in impact results.

- **Modeled vs. Actual WWTF Performance.** Given the complexity of the processes occurring within the WWTF and the minimal data available for proper characterization, several assumptions were made regarding the expected effects of SSO co-digestion on those processes. One source of uncertainty is the effect on WWTF effluent, especially with respect to nutrient concentrations and eutrophication potential. For this study, effects were estimated based on past, demonstrated performance under baseline conditions (see Section 3.3.12 for detailed discussion), taking into consideration the increase in nutrient loading associated with co-digestion. Ultimately, evaluation of long-term monitoring data will help answer these questions. A preliminary analysis has been conducted in Appendix B, though given the limited data available at the time of publishing, results are inconclusive.

4. LCCA METHODOLOGY

This section presents the methodology used to develop life cycle costs for the three feedstock scenarios. Cost data was collected and adjusted from several sources as described in Section 4.1. Basic LCCA methods are described in Section 4.2. Life cycle cost assessment results are presented according to two cost scenarios, which span a reasonable range of variation for parameters that affect estimates of system net present value (NPV). Parameter values for the low and base cost scenarios are listed in Section 4.2.6.

4.1 LCCA Data Sources

Cost data were obtained from the following sources:

- Annual budget for the GLSD WWTF (2016);
- Engineering report assessing the feasibility of several AD expansion, CHP and SSO acceptance scenarios (CDM Smith 2013);
- Plant purchasing records for: electricity, natural gas, chemicals, potable water and grit disposal (2016).

The above information, in addition to literature cited throughout this document, was used to develop life cycle costs.

4.2 LCCA Methods

The LCCA uses NPV to consider capital costs and annual or otherwise periodic costs associated with operation, maintenance and material replacement over a 30-year time horizon. The goal of the LCCA is to compare the present value of several operational alternatives for the GLSD WWTF. The analysis compares the NPV of operating the WWTF according to historical patterns, without CHP and SSO acceptance, to alternatives that include varying levels of co-digestion and AD performance.

4.2.1 Total Capital Costs

Total capital costs include purchased equipment, direct and indirect costs. Direct costs are physical or material costs associated with capital projects, such as the installation of a new treatment process. Direct costs include mobilization, site preparation, site electrical, yard piping, instrumentation and control and lab and administration building. Indirect costs include legal costs, engineering design fee, inspection costs, contingency, technical services, interest during construction, profit and miscellaneous cost (Harris, et al. 1982). All capital costs associated with the AD and CHP expansion project were drawn from a previous energy feasibility study (CDM Smith 2013) and were inclusive of purchased equipment, direct and indirect costs. As these costs were inclusive, no additional calculation was required to estimate capital cost.

Additional, ongoing capital costs were estimated as the sum of annual capital expenditures and ongoing debt service, which is how GLSD budgets for equipment replacement, non-routine maintenance projects and capital upgrades. Estimated annual capital expenditures were available for the period from 2015 to 2017. Average capital expenditures over this period were used to approximate this budget item in all future years. Annual capital expenditures are not subject to interest payments and averaged approximately 10 percent of the total annual budget over the period from 2015 to 2017.

The GLSD provided estimates of their expected debt service payments over a 25-year period (Table C-4). Debt service data shows that the capital cost of the AD expansion and CHP project will be paid down over a 20-year period, from 2021 to 2040. These capital costs are separated out and applied only to the partial and full capacity scenarios. Only the first 10 years of debt service projections were expected to be accurate, as additional large maintenance or expansion projects may occur after this 10 year period, but are not currently being projected. Rather than use only the projected values, which decrease towards the end of the 25-year projection period, we used the average debt service payment, excluding the CHP project, over the first 10 years as an estimate of on-going capital debt service. Annual debt service averaged approximately 18 percent of the total annual budget over the period from 2015 to 2017. Annual debt service payments include the assessment of interest.

4.2.2 Cost Escalation

Per NIST LCCA guidelines, the analysis does not assume escalation rates beyond the standard inflation rate for any cost categories except for energy costs (Fuller and Petersen 1996). The LCCA was performed in constant (non-inflated) dollars and uses a real discount rate corresponding to the constant dollar method. Electricity and natural gas costs were escalated according to 2017 annual energy escalation factors specific to fuel type, in the Northeastern U.S. (Lavappa et al. 2017). Energy escalation factors were applied by multiplying base year energy cost by the escalation factor corresponding to the appropriate calendar year. Energy escalation factors are included in Appendix C, Table C-1.

4.2.3 Total Annual Costs

Total annual costs include operation and maintenance labor, materials, chemicals, energy and plant revenue. Equation 2 was used to calculate total annual costs.

$$\text{Total Annual Costs} = \text{Operation Costs} + \\ \text{Material Costs} + \text{Chemical Costs} + \text{Energy Costs - Plant Revenue}$$

Equation 2

where:

Total annual costs (2016 $/year) = Total annual operation and maintenance costs

Operation costs (2016 $/year) = Labor and non-material ancillary costs required to operate the WWTF, including operation, administrative, laboratory labor and routine equipment maintenance

Materials costs (2016 $/year) = Material and physical service costs (e.g. grit disposal) costs required to operate and maintain the WWTF, including equipment replacement

Chemical costs (2016 $/year) = Cost of chemicals required for WWTF operation (e.g., ferric chloride, polymer)

Energy costs (2016 $/year) = Cost of electricity required for WWTF operation

Plant revenue (2016 $/year) = Revenue received associated with waste tipping fees, renewable energy credits, alternative energy credits and industrial cost sharing programs

Operational labor cost associated with primary and secondary treatment remain the same regardless of the scenario considered. Additional personnel are required to manage the AD and CHP expansion. Regular plant maintenance is carried out by plant staff and does not require additional labor costs beyond their annual salary and benefits. Annual operation and maintenance costs were based on the 2016 budget, which includes costs associated with typical preventive maintenance.

4.2.4 Net Present Value

Equation 3 was used to calculate system NPV (Fuller and Petersen 1996). A real discount rate of three percent was used in the base cost scenario.

$$Net\ Present\ Value = \sum \frac{Cost_x}{(1+i)^x}$$

Equation 3

where:

NPV (2016 \$) = Net present value of all costs and revenues necessary to construct and operate the WWTF

$Cost_x$ = Cost in future year x

i (%) = Real discount rate

x = number of years in the future

4.2.5 AD and CHP Expansion Payback Period

Equation 4 was used to calculate a discounted payback period for the combined AD expansion and CHP installation. Payback period measures the duration of time that is required to recover initial investment cost of a particular project or project alternative (Fuller and Petersen 1996). A payback period will only exist if unit annual revenue exceeds annual cost. System NPV estimates include capital cost of the AD and CHP expansion project using debt service projections so that both interest and the timing of payment is accurately modeled. However, discounted payback period was estimated using capital cost projections from the energy feasibility study, detailed in Table 4-1.

$$\boldsymbol{Payback\ period\ (x) = \sum_{t=1}^{x} \frac{Rev_t - Cost_t}{(1+i)^t} \geq Capital\ Investment}$$

Equation 4

where:

x = Payback period, measured in years

Rev_t = Revenue in year t

$Cost_t$ = Operational expenditure in year t

i (%) = Real discount rate

Table 4-1. Capital Costs of the Anaerobic Digester and CHP Expansion Project

Cost Category	Capital Cost (2016 $s)
New AD tank & ancillary equipment	4,700,000
Digester feed pumps	710,000
Foam control and site improvements	490,000
CHP engines	10,400,000
Siloxane treatment	1,900,000
Waste blending tank	380,000
Collection, flare and safety upgrade	1,800,000
Waste receiving station	380,000
Total	20,760,000

4.2.6 LCCA Cost Scenario Parameters

Cost parameter assumptions can have a significant effect on total life cycle costs or the cost performance of any unit within the WWTF. Table 4-2 documents parameters used in the low and base cost scenarios. The low cost scenario corresponds to parameter values that will yield a lower system NPV than the base cost scenario.

The study period remains consistent across scenarios, while the real discount rate varies between three and five percent for the base and low cost scenarios, respectively. 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 system NPV. Electricity cost per kWh was based on plant utility records, including all fees. Electricity revenue is 10 and 14 percent below the purchased electricity cost to account for customer service fees that are not covered by the Massachusetts net metering program (Commonwealth of Massachusetts 2017c). Renewable energy credits (RECs) and alternative energy credits (AECs) values are determined as a function of supply and demand in the marketplace. Base cost REC and AEC values were provided by GLSD staff. Low cost REC and AEC values were based on personal communication with the program manager of the Massachusetts renewable and alternative portfolio standard programs (Wassam 2018). Natural gas price was based on plant utility records and the energy feasibility study for the base and low cost scenarios, respectively. Expected SSO tipping fees were based on feedback from GLSD staff.

Table 4-2. Low and Base Cost Scenario Parameters

Parameter Value	Low Cost	Base Cost
Planning period (years)	30	30
Real discount rate (%)	5%	3%
Electricity cost ($/kWh)[1]	0.143	0.143
Electricity, avoided cost ($/kWh)[2]	0.129	0.123
Renewable energy credit ($/MWh)[3]	25	12
Alternative energy credit ($/MWh)[3]	20	14
Natural gas cost ($/DTH)[4]	10.5	9.88

Table 4-2. Low and Base Cost Scenario Parameters

Parameter Value	Low Cost	Base Cost
SSO tipping fee ($/gallon)	0.02	0.005

[1] 2016 plant utility bills, includes all fees.

[2] Low cost value based on the energy feasibility study (CDM Smith 2013). Base value assumes a 10% reduction in the 2016 utility rate to account for customer charges and system benefit not offset by net metering.

[3] Low cost REC and AEC values based on personal communication with RPS and APS Program Manager (Wassam 2018). Base cost REC and AEC values based on correspondence with GLSD staff.

[4] Base cost from plant utility records, Low scenario cost based on energy feasibility study

Table Acronym: DTH – dekatherm = 1,000,000 British thermal units

4.3 Treatment Group and Unit Process Costs

The following sections describe data sources and cost estimation assumptions for individual unit processes. Electricity, natural gas and chemical costs were allocated to the treatment groups listed in Table 4-3, as described in Section 3.3 and the following subsections. Costs that are unable to be allocated to specific unit processes were allocated to the full plant treatment group when presenting LCCA results.

Table 4-3. LCCA Treatment Groups

Treatment Groups	Unit Process Name
Full plant	Control building
Preliminary/Primary treatment	Wastewater collection; operation and infrastructure
	Influent pump station
	Screening and grit removal
	Primary clarification
	Waste receiving and holding
Biological treatment	Pre-anoxic tank
	Aeration basins
Secondary clarification	Secondary Clarification
Plant water and disinfection	Plant Water and Disinfection
Sludge thickening and dewatering	Gravity belt thickener
	Gravity thickener
	Centrifuge
AD and CHP	Anaerobic digestion
	Combined heat and power
Pellet drying	Biosolids drying and pelletization

4.3.1 General Facility and Administration (Full Plant treatment group)

General facility and administrative costs were based on the 2016 budget. Table 4-4 summarizes annual plant costs that were assigned to the Full Plant treatment group. Plant labor costs are divided among administration, monitoring (laboratory), maintenance and operations personnel. Based on budget granularity it was not possible to allocate maintenance and operation personnel costs to specific unit processes. Fringe benefits, such as health care and workers compensation are included in plant labor costs.

The facility budget includes a line item for general mechanical and electrical supplies, which was assumed to include the material requirements for routine preventive maintenance. Additional preventive maintenance costs for the AD and CHP system were developed specifically for those unit processes. The majority (72 percent) of purchased natural gas is used for general building heating. GLSD receives several small sources of revenue including REC sales from an on-site solar electricity installation as well as industrial surcharge and industrial cost recovery programs.

Annual capital expenditures and debt service, which were used to estimate life cycle costs associated with equipment replacement and process upgrades were not able to be assigned to specific treatment processes based on the available information. Plant staff provided projections of existing and planned debt service expenditures.

Table 4-4. Annual Cost Summary by Feedstock Scenario for the Full Plant Treatment Group – Base Cost Scenario

Annual Cost	Feedstock Scenario		
	Baseline	Partial Capacity	Full Capacity
Plant labor	$4,709,488		
Administrative, miscellaneous	$737,213		
Operations, miscellaneous	$102,150		
Monitoring	$113,530		
Materials, general maintenance	$418,483		
Capital projects	$1,800,000		
Debt service[1]	$3,316,494		
Electricity	$35,768	$37,556	$37,556
Natural gas	$121,793	-	-
Water	$17,236		
Diesel	$19,000		
Revenue, solar RECs	$15,000		
Revenue, other	$120,200		
Miscellaneous, other	$246,000		

[1] The value shown is for 2016 debt service. Debt service estimates change annually over the course of the 30-year analysis period. See Table C-2 for year-by-year debt service estimates.

4.3.2 Preliminary and Primary Treatment

This treatment group includes the influent pump station, grit removal, bar screen and primary clarifier. Table 4-5 summarizes annual plant costs that were assigned to the Preliminary and Primary treatment group. Preliminary and primary treatment was allocated seven percent of facility electricity expenditures (excluding pump station electricity). The influent pump station consumes an additional five million kWh per year. Septage and municipal solids tipping fees were allocated to this treatment group and amount to 1.56 million dollars in the base year (2016). The Preliminary and Primary treatment group requires annual material inputs of activated carbon and potassium permanganate as well as grit disposal.

Ongoing maintenance of the new waste receiving station was assessed as two percent of capital expenditures listed in Table 4-1. One additional staff member was assumed to be required to cover the additional workload of accepting SSO and increased operational requirements associated with the AD and CHP expansion. The cost of this employee was included in the AD and CHP process group.

Table 4-5. Cost Summary by Feedstock Scenario for the Preliminary and Primary Treatment Group – Base Cost Scenario

Cost Category	Feedstock Scenario		
	Baseline	Partial Capacity	Full Capacity
Electricity	$935,931		
Chemical, potassium permanganate	$11,000		
Revenue, septage	$1,500,000		
Revenue, municipal solids	$60,000		
Material, activated carbon	$12,681		
Grit disposal	$47,500		
Maintenance, receiving station	-	$7,600	$7,600

4.3.3 *Biological Treatment*

The biological treatment group accounts for 35 percent of electricity cost in the baseline scenario. Electricity consumption, and associated cost, was increased in the partial and full capacity scenarios proportional to increased BOD loading (Table 4-6).

Table 4-6. Annual Cost Summary by Feedstock Scenario for the Biological Treatment Group – Base Cost Scenario

Cost Category	Feedstock Scenario		
	Baseline	Partial Capacity	Full Capacity
Electricity	$621,612	$632,518	$644,981

4.3.4 *Secondary Clarification*

The four secondary clarifiers and RAS pumping account for eight percent of electricity cost in the baseline scenario. Electricity consumption for secondary clarification remains constant across scenarios (Table 4-7).

Table 4-7. Annual Cost Summary by Feedstock Scenario for the Secondary Clarifier Treatment Group – Base Cost Scenario

Cost Category	Feedstock Scenario		
	Baseline	Partial Capacity	Full Capacity
Electricity	$151,203		

4.3.5 Sludge Thickening and Dewatering

Table 4-8 summarizes annual plant costs associated with the Sludge Thickening and Dewatering treatment group. Sludge thickening and dewatering accounts for 11 percent of electricity cost in the baseline scenario. Electricity consumption by the gravity thickeners and GBTs increases slightly as the facility accepts increased quantities of SSO. Centrifuge electricity consumption was scaled proportionally to the increase in digester solids processed. Polymer use is required for centrifuges and GBTs and was calculated for each scenario based on the quantity of solids processed by the respective dewatering process. The unit cost of polymer is $1.49 per pound ($3.28 per kg).

Table 4-8. Annual Cost Summary by Feedstock Scenario for the Sludge Thickening and Dewatering Treatment Group – Base Cost Scenario

Cost Category	Feedstock Scenario		
	Baseline	Partial Capacity	Full Capacity
Electricity	$201,604	$251,643	$300,162
Chemical, polymer	$447,148	$647,377	$843,865

4.3.6 Plant Water and Disinfection

Table 4-9 summarizes annual plant costs associated with the Plant Water and Disinfection treatment group. All annual costs for this treatment group remain constant across scenarios. Plant water and disinfection accounts for eight percent of electricity cost in the baseline scenario. Unit chemical costs in dollars per pound are $0.093 and $0.117 for sodium hypochlorite and sodium bisulfite, respectively. GLSD receives revenue for the sale of treated effluent to a local industrial partner.

Table 4-9. Annual Cost Summary by Feedstock Scenario for the Plant Water and Disinfection Treatment Group – Base Cost Scenario

Cost Category	Feedstock Scenario		
	Baseline	Partial Capacity	Full Capacity
Electricity	$134,403		
Chemical, sodium hypochlorite	$100,000		
Chemical, sodium bisulfite	$100,000		
Revenue, effluent sale	$72,000		

4.3.7 Anaerobic Digestion and CHP

The costs of unit construction and mechanical equipment associated with the AD expansion and CHP installation were based on debt service estimates provided by facility staff. Capital costs include one additional digester, waste blending tank, new digester feed pumps, upgraded flare and biogas collection system, siloxane treatment system and two 1.6 MW cogeneration engines. One additional full-time staff member will be required to help with operation of the AD units and acceptance of the SSO material. Several large maintenance projects including digester cleaning, fixing a draft tube leak, biogas metering and monitoring, and foam control improvements were included in the cost estimate. Table 4-10 summarizes annual plant costs associated with the AD and CHP treatment group.

Ongoing maintenance cost associated with the AD and CHP expansion was estimated to be two percent of capital cost for AD and biogas processing equipment. CHP engine maintenance costs were estimated using a factor of $0.019 per kWh of electricity production (Wiser et al. 2010). These costs were considered in addition to maintenance costs based on the 2016 budget, introduced in Section 4.3.1.

The AD and CHP system accounts for 14 percent of electricity cost in the baseline scenario. Electricity consumption increases by approximately 28 percent with the addition of a fourth digester. Net metering in the State of Massachusetts allows the facility to offset the cost of purchased electricity following installation of the CHP system. Under the Massachusetts net metering system, electricity production beyond the customers demand is credited to the electricity bill and can be used to pay for future utility expenditures. Net metered electricity production off-sets basic service charges, distribution, transmission and transition costs on the customers electricity bill (Commonwealth of Massachusetts 2017c).

The GLSD's CHP system is classified as a Class III net metering facility, and could be eligible for payment for excess electricity production, at the discretion of the electric utility (Commonwealth of Massachusetts 2018). However, this was deemed to be unlikely, therefore the only financial benefit ascribed to electricity production more than the facilities' demand comes from the sale of RECs. Only the full capacity-base AD performance scenario is expected to produce electricity in excess of facility demand (Table 3-13, Table 3-14). The economic value of net metered electricity was used in the calculation of the discounted payback period for the AD and CHP expansion project.

The CHP system is eligible to be classified as class I generation unit within the Massachusetts Renewable Portfolio Standard program (Commonwealth of Massachusetts 2016), allowing for an additional source of revenue from the sale of environmental benefits associated with electricity production. Renewable energy credits, corresponding to one MWh of net electricity production, can be sold at current market prices. The facility is also eligible for classification as a Renewable Thermal Generation Unit within the Massachusetts Renewable Portfolio Standard program, which allows for revenue from the sale of AECs for useful thermal energy. Alternative energy credits, corresponding to one MWh equivalent of thermal energy production, can also be sold at current market prices. Revenue from the sale of RECs and AECs was assessed less the internal (parasitic) energy demand (i.e. net production) of the AD and CHP expansion (DOER 2016).

Revenue from acceptance of SSO material was allocated to the AD and CHP treatment group. GLSD staff report an SSO tipping fee of between 0.5 and 2 cents per gallon.

The GLSD purchased 124 thousand pounds (56 metric tons) of ferric chloride in 2016 at a unit cost of $0.255 per pound.

Table 4-10. Annual Cost Summary by Feedstock Scenario for the AD and CHP Treatment Group – Base Cost Scenario

	Feedstock Scenario		
Cost Category	**Baseline**	**Partial Capacity**	**Full Capacity**
Additional labor	-	$104,000	$104,000
Electricity	$235,205	$300,539	$300,539
Natural gas	$37,214	-	-
Avoided cost, electricity	-	$2,051,175	$3,545,027
Capital, annual debt service[1]	-	$1,427,317	$1,428,317
Chemical, defoamant	$20,000		
Chemical, ferric chloride	$31,797	$35,772	$39,746
Revenue, SSO tipping fee	-	$83,950	$167,900
Revenue, RECs	-	$162,900	$301,143
Revenue, AECs	-	$292,182	$385,802
Maintenance, CHP[2]	-	$303,225	$524,061
Maintenance, AD[3]	-	$175,600	$175,600

[1] This cost corresponds to the first annual debt service payment. See Table C-2 for year-by-year debt service estimates.

[2] Maintenance costs were estimated in addition to plant maintenance costs listed in the 2016 budget.

[3] Maintenance of ADs in the baseline scenario are included in the Full Plant treatment group.

4.3.8 Biosolids Pelletization and Sale

The pellet drying facility is operated by a separate entity that is contracted to dry digestate from the GLSD WWTF. No additional offsite material is processed in the pellet drying facility. An annual base drying fee is paid to the contracting company regardless of the quantity of solids processed by the facility. An additional fee of $24.97 is charged per wet short ton of material in excess of 20,000 short tons per year. GLSD is separately responsible for the energy cost of operating the pellet drying facility. The pellet drying facility accounts for 16 percent of electricity cost in the baseline scenario. Additional electricity costs were estimated for the partial and full capacity scenarios based on an additional electricity requirement of 350 kWh per short dry ton of solids processed. The increased heat demand associated with SSO feedstock scenarios was also estimated on a per ton basis. Biogas can satisfy 100 percent of pellet drying heat demand for all feedstock and AD performance scenarios, avoiding expenditures on natural gas. No revenue is currently generated or expected from the sale of biosolid pellets, however disposal costs are avoided.

Table 4-11. Annual Cost Summary by Feedstock Scenario for the AD and CHP Treatment Group – Base Cost Scenario

Cost Category	Feedstock Scenario		
	Baseline	Partial Capacity	Full Capacity
Base drying fee	$2,293,445		
Processing charge	$66,462	$300,619	$575,785
Electricity	$293,162	$414,474	$557,033
Natural gas	$6,766	-	-

5. LCA AND LCCA RESULTS BY TREATMENT GROUP

This section presents comparative LCA results for the GLSD WWTF scenarios by impact category.

5.1 Guide to Results Interpretation

Results for this project were calculated for all combinations of the following parameters.

- ***Feedstock Scenarios*** – Results were calculated for baseline, partial capacity and full capacity feedstock scenarios. The partial and full capacity scenarios demonstrate the effect of accepting and digesting SSO waste on impact potential of the treatment system. Feedstock quantities associated with the scenarios are presented in Table 2-4.
- ***Anaerobic Digestion*** – Results were calculated for a set of parameters defining low and base (expected) operational performance of the AD units, as presented in Table 3-12.
- ***Avoided SSO Disposal*** – Results were calculated for the MA disposal mix of avoided SSO disposal processes, avoided landfill only, avoided WTE only and without any avoided disposal (i.e., avoided disposal is outside system boundaries). Background information on avoided disposal scenarios is available in Section 3.3.14.

Section 5 presents results for all feedstock scenario options assuming base AD performance and avoided SSO disposal impacts using the MA disposal mix. Section 6 presents all results as part of the scenario and sensitivity analysis.

The above model parameters were varied over the ranges defined in Section 2.3.2 to convey the potential variability in impact results that might be realized by wastewater treatment systems of the type considered in this analysis. The trends observed and the key variables that drive environmental impacts as discussed in Sections 5 and 6 can be used by facilities during the design process to estimate potential impacts and areas for potential improvement by examining 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 group, as shown in Table 2-8. Global warming potential and CED also show impacts aggregated according to the process categories listed in Section 2.4. Relative change values, quoted in this section, comparing impact between the baseline scenario and the partial and full capacity scenarios were calculated relative to the baseline scenario, using Equation 5.

$$\textbf{Relative Change} = \frac{\textbf{SSO Scenario}_{impact} - \textbf{Baseline}_{impact}}{\textbf{Baseline}_{impact}}$$

Equation 5

5.2 Eutrophication Potential

Eutrophication potential is a critical metric for measuring the comparative environmental performance of wastewater treatment systems. Figure 5-1 presents EP results organized by treatment group. Eutrophication potential impacts are presented in g N eq/m^3 wastewater treated. Nitrogen equivalents present the EP of both nitrogen and phosphorus compounds together in a single unit and are therefore, not comparable to typical parameters used to measure and report effluent quality. Eutrophication potential is primarily driven by effluent release, with over 92 percent of eutrophication impact attributable to this treatment group for all feedstock scenarios.

Eutrophication potential increases by 10 and 20 percent as more SSO material is processed in the partial and full capacity scenarios. SSO material contains additional nitrogen and phosphorus that is returned to the primary and secondary treatment unit processes. In theory, a fraction of these nutrients is ultimately released in the effluent, contributing to EP. However, the actual quantity of nitrogen and phosphorus that is returned, and thus ultimately contributes to effluent concentrations, has not been well studied and is a source of uncertainty in the current results. Preliminary water quality monitoring is ongoing to determine what affect, if any, the addition of SSO material may have on final effluent nutrient concentrations (further discussed in Appendix B).

Land application of pelletized biosolids is the other visible contributor to EP impact, accounting for between four and six percent of impact. The eutrophication contribution of land applied biosolid pellets is a source of uncertainty and is included as a conservative estimate of the net change in EP that could result from switching from chemical fertilizers to organic nutrient sources. Increased field emissions were based on the 55 percent fertilizer replacement value, which indicates that greater quantities of nitrogen and phosphorus need to be land applied for an equivalent crop response due to lower plant availability of nutrients in the pelletized biosolids.

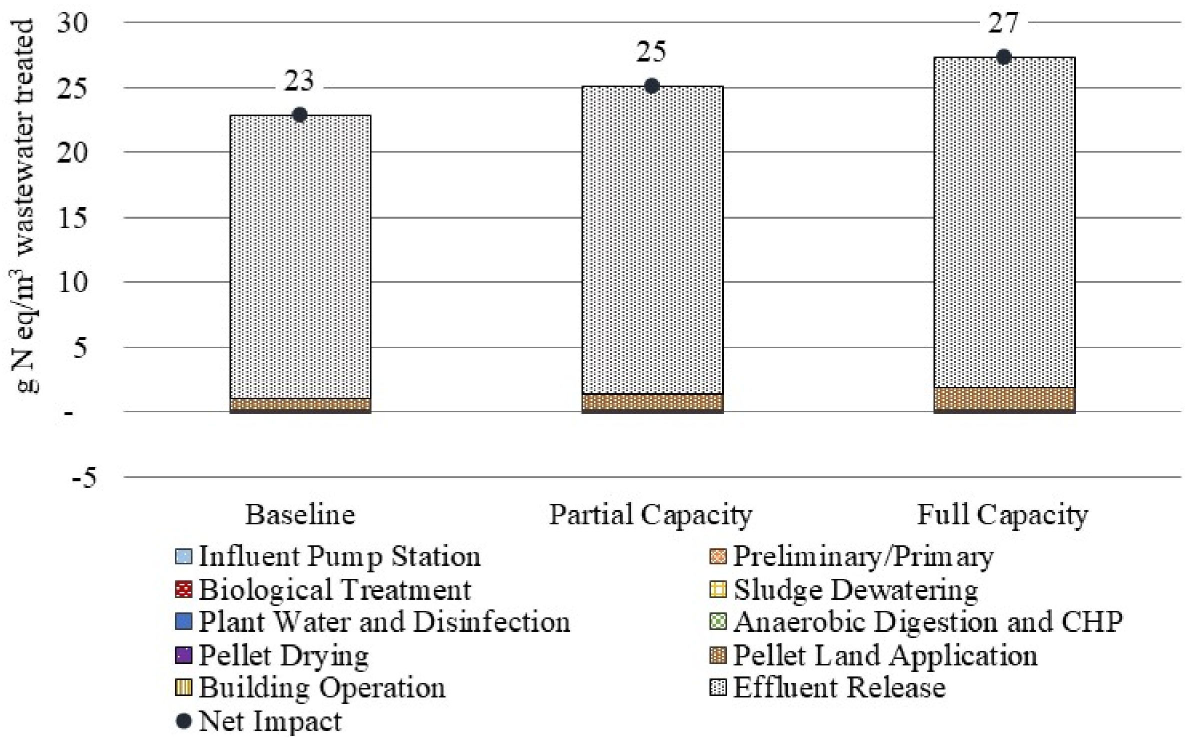


Figure 5-1. Eutrophication potential results by treatment group.

5.3 Cumulative Energy Demand

Figure 5-2 and Figure 5-3 present CED results organized according to treatment group and by process category, respectively. Cumulative energy demand decreases from a maximum of 5.0 MJ per m^3 of wastewater treated in the baseline feedstock scenario to a minimum of -6.4 MJ per m^3 for the full capacity scenario. If the full capacity of the digesters is used for co-digestion of municipal solids and SSO material, the WWTF avoids more energy use than is required for its own operation.

Figure 5-3 illustrates the 55 percent increase in gross positive CED that is associated with the full capacity scenario. The increase is largely associated with avoided SSO disposal in landfills and WTE facilities, both of which are also energy producers. The full capacity scenario experiences a 20 percent increase in CED associated with plant electricity consumption due to the processing requirements of the additional organic waste. The figure shows that this increase in gross, positive CED is offset by avoided electricity production and natural gas combustion. Avoided electricity production produces the largest CED credit for the partial and full capacity scenarios, amounting to six and 11 MJ, respectively. Energy content of combusted biogas is excluded from the analysis for all feedstock scenarios and avoided disposal processes, because it enters the WWTF as a waste product, while CED measures energy extractions from nature.

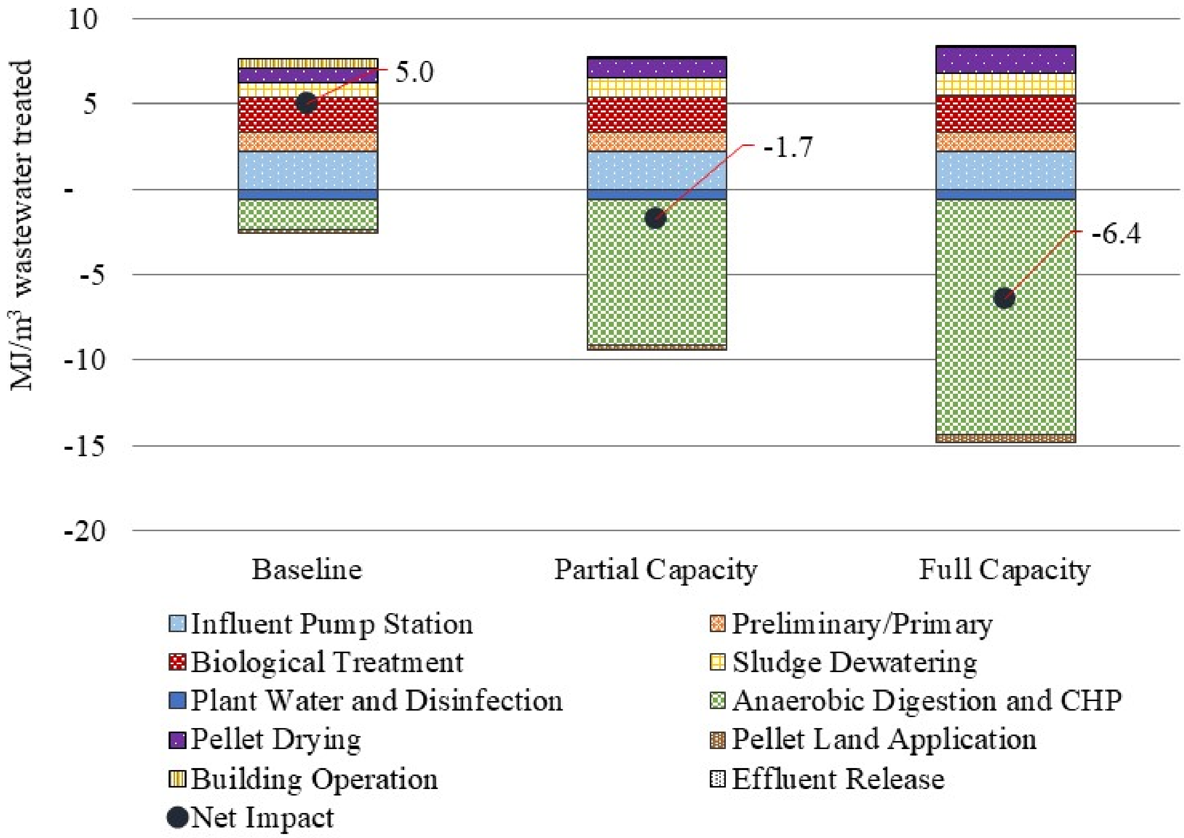


Figure 5-2. Cumulative energy demand results by treatment group.

The analysis shows that a significant energy resource is forfeited when food waste, in the form of SSO, is disposed of in landfills and WTE facilities. Each kg of food waste generates approximately 0.025 kWh of electricity when disposed of in MA landfills due to landfill gas capture, whereas that same kg of material will generate approximately 0.09 kWh when incinerated with energy recovery. When food waste is digested in this analysis it generates up to 0.48 kWh per kg of food waste plus recovered thermal energy. It has been shown that the theoretical energy potential of the organic material in typical domestic wastewater is on the order of 1.9 kWh/m^3 of wastewater treated (McCarty et al. 2011). Through the application of co-digestion to boost the quantity of volatile solids processed, this system realizes approximately 2.6 MJ of energy recovery per m^3 of wastewater treated in the full capacity-base AD performance scenario.

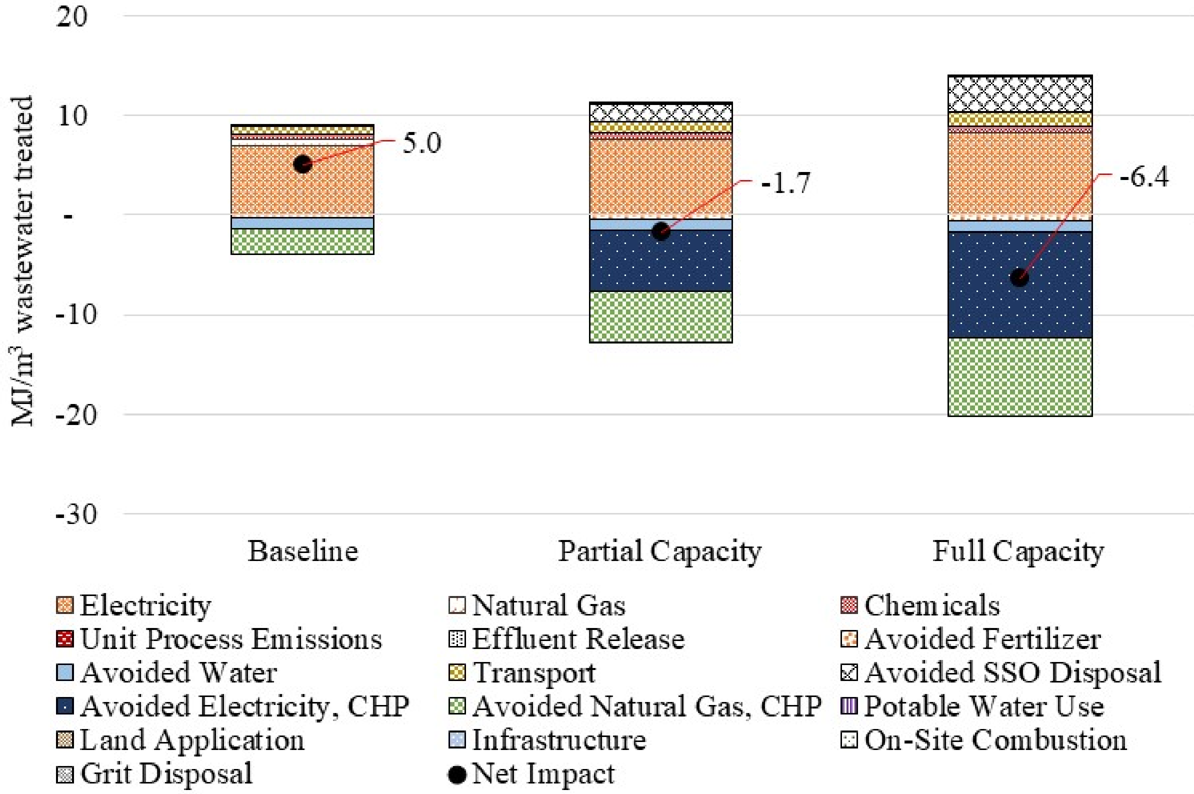


Figure 5-3. Cumulative energy demand results by process category.

5.4 <u>Global Warming Potential</u>

Figure 5-4 presents GWP results organized according to treatment group, while Figure 5-5 presents results according to process category. Global warming potential decreases from a maximum of 0.36 kg CO_2-eq per m^3 of wastewater in the baseline feedstock scenario to a minimum of -0.28 kg CO_2-eq per m^3 within the full capacity scenario. Figure 5-4 demonstrates that the marked decrease in net GWP is largely due to environmental credits associated with AD. Results by process category show that gross, positive GWP increases as more SSO is accepted. The GWP of increased material and energy consumption and process emissions associated with the co-digestion feedstock scenarios are more than offset by avoided product credits. The effect on net impacts is such that the WWTF achieves a net zero GWP impact in the partial capacity scenario. Environmental benefits (negative impact results) are realized by accepting and processing SSO to boost biogas energy and biosolids production in the full capacity-base AD scenario.

The increases in GWP that occur due to increased process GHG emissions, are primarily associated with fugitive methane emissions from the digesters. The analysis assumes that five percent of biogas methane is lost through the floating cover based on guidance provided in Clean Development Mechanism literature (UNFCCC 2012). Other types of digesters can have lower rates of fugitive emissions, but Clean Development Mechanism guidance does not suggest a fugitive emission rate below 2.8 percent. On-site combustion emissions (biogas equipment), increases in facility electricity demand, and increased nitrous oxide emissions associated with elevated effluent nitrogen emissions also contribute to increases in gross, positive GWP.

Figure 5-5 shows that avoided natural gas production and combustion is the largest single contributor to reductions in net GWP, yielding an environmental credit of 0.45 kg CO_2 eq. per m^3 wastewater treated in the full capacity scenario. Avoided SSO disposal also contributes substantially to reductions in net GWP for the co-digestion scenarios. An examination of detailed process results, presented in Appendix D, reveals that avoided landfill disposal is responsible for the impact reduction. The GWP credit associated with avoided SSO disposal in landfills primarily accrues due to avoided landfill gas methane emissions. Avoided WTE incineration contributes to net GWP at a rate of approximately 0.09 kg CO_2 eq. per m^3 of wastewater treated (full capacity). The magnitude of the GWP benefit is therefore strongly dependent on avoiding landfill disposal, and the assumed gas capture rate of the landfill. The sensitivity results in Section 6.1 present comparative results that illustrate the effect of avoided SSO disposal assumptions.

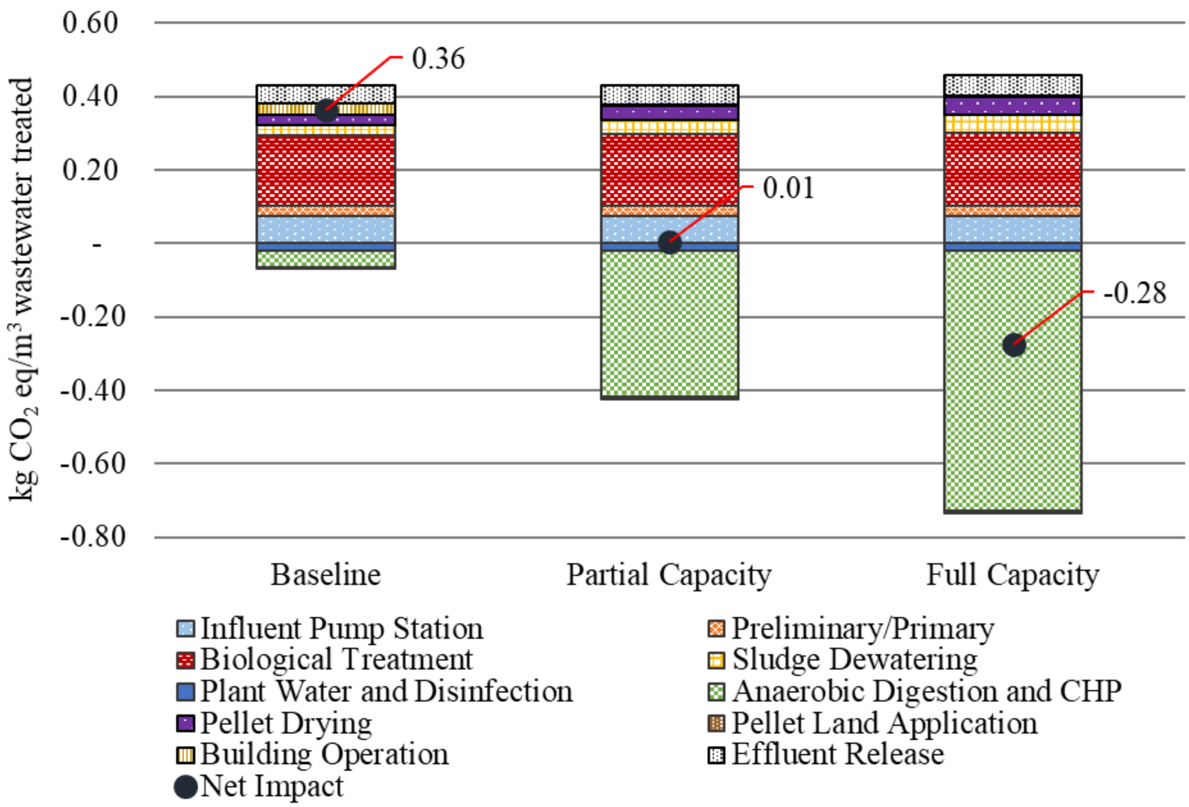


Figure 5-4. Global warming potential results by treatment group.

Figure 5-5 indicates considerable environmental credits associated with avoided electricity production and natural gas consumption. Avoided natural gas consumption is credited to AD in all three feedstock scenarios. For the partial and full capacity scenarios, only the portion of biogas heat production that can be utilized by the facility contributes to avoided natural gas consumption. In the full capacity scenario, over 60 terajoules of additional thermal energy is available for utilization[2]. Wasted thermal energy constitutes 20 percent of available biogas fuel energy and 50 percent of CHP thermal output in the full capacity scenario. Further environmental benefits, not assessed in this report, can be realized in the future if the facility is able to identify additional uses of thermal energy. The LCA assumes all electricity can be utilized at the facility or exported to the grid with each kWh of electricity production yielding one kWh of avoided electricity production. Avoided electricity production leads to GWP credits of 0.20 and 0.35 kg CO_2 eq. per m^3 wastewater treated in the partial and full capacity scenarios. The full capacity scenario is a net exporter of electricity, producing an annual surplus of over six million kWh. All electricity production was assumed to offset energy from the ISO-NE network shown in Table 2-2.

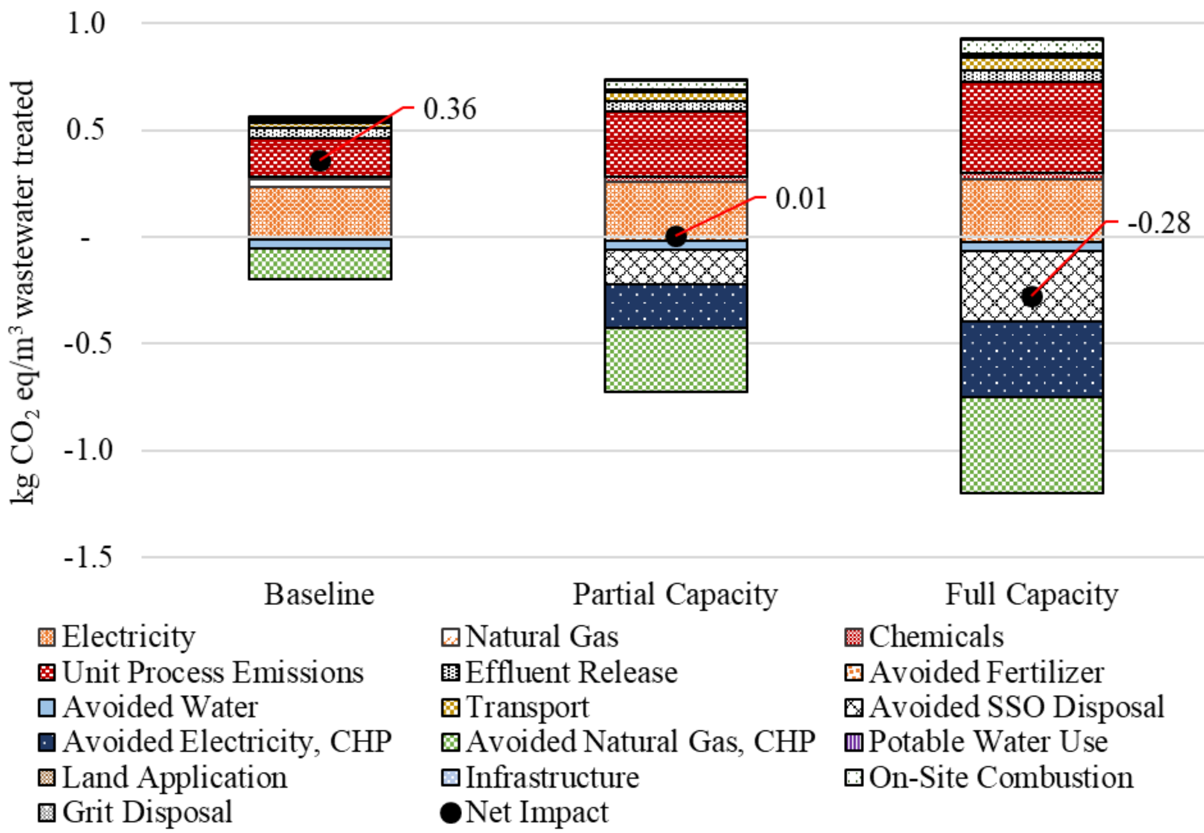


Figure 5-5. Global warming potential results by process category.

[2] Expressed as natural gas equivalent fuel energy (HHV). Assumes 39% CHP thermal efficiency and 80% boiler efficiency. Boiler efficiency is used to convert CHP thermal energy into natural gas equivalent energy.

5.5 Acidification Potential

Figure 5-6 presents the impact assessment results for acidification potential organized according to treatment group. Relative acidification potential impact is reduced by 35 and 50 percent by accepting SSO material according to the partial and full capacity scenario assumptions, respectively. The figure shows a significant environmental credit attributable to AD avoided products. A review of detailed process results reveals that over 80 percent of this environmental credit is due to avoided energy production. Avoided SSO disposal contributes the remaining 20 percent of acidification potential reductions. Pellet land application is shown to contribute prominently to acidification potential impact. Acidification potential of land application is due primarily to field emission of ammonia. A nitrogen fertilizer replacement value of 55 percent was used to estimate this impact due to lower nutrient availability in pelletized biosolids as compared to chemical fertilizers as described in Section 3.3.11. Operation of the pellet dryer also contributes to noticeable increases in acidification potential as the quantity of dried biosolids increases.

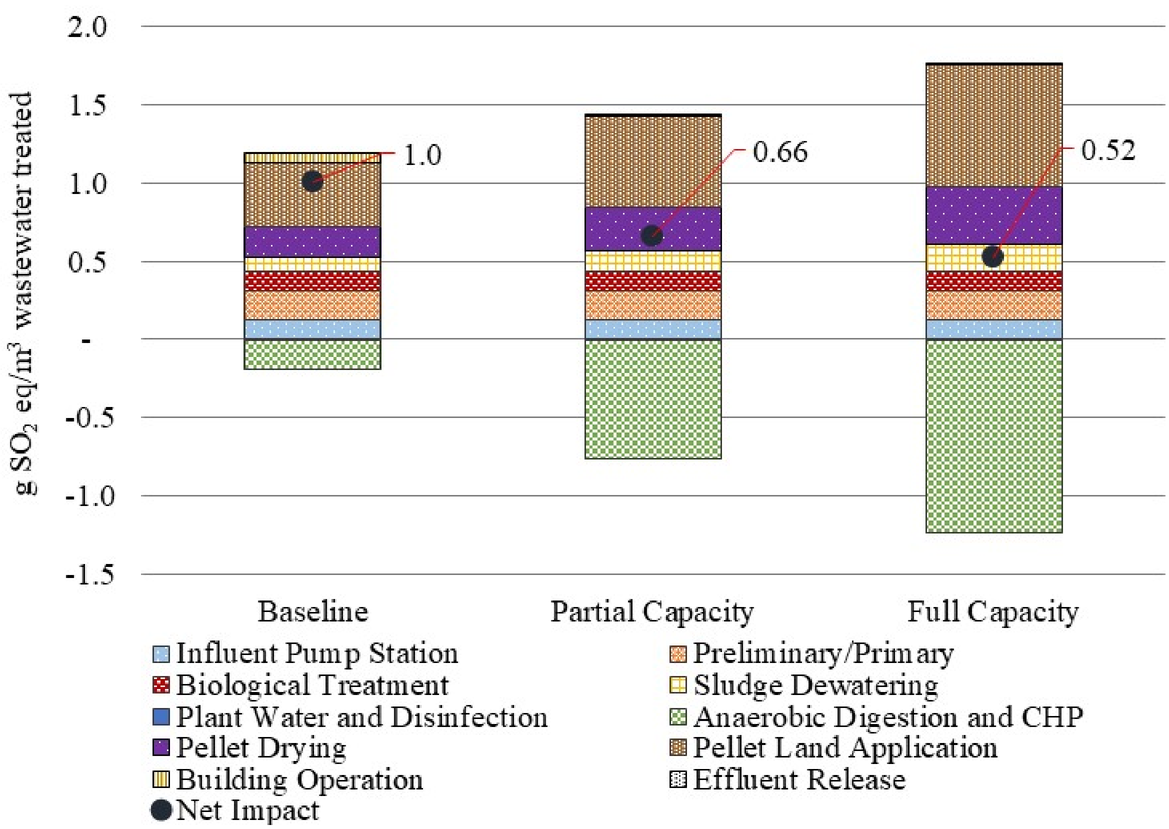


Figure 5-6. Acidification potential results by treatment group.

5.6 Fossil Depletion Potential

Figure 5-7 presents fossil depletion potential results organized according to treatment group. The use of biogas as an energy source leads to a net reduction in fossil fuel consumption. Increased biogas production attributable to co-digestion and the installation of CHP eliminates the need for on-site natural gas combustion in both the partial and full capacity scenarios. If the full capacity of the fourth digester is utilized, the facility becomes a net exporter of electricity, despite a 20 percent increase in facility electricity demand. Combined heat and power electricity production in the partial capacity scenario satisfies 80 percent of facility electricity demand. Sixty percent of available biogas is combusted in the CHP system in the partial capacity scenario, 30 percent is used in the pellet driers and 10 percent is flared. Figure 5-7 reflects the increase in energy demand for sludge dewatering and pellet drying that accompanies SSO acceptance. Avoided energy products associated with digestion more than offset increased facility energy demand, substituting natural gas and grid electricity with a non-fossil energy alternative.

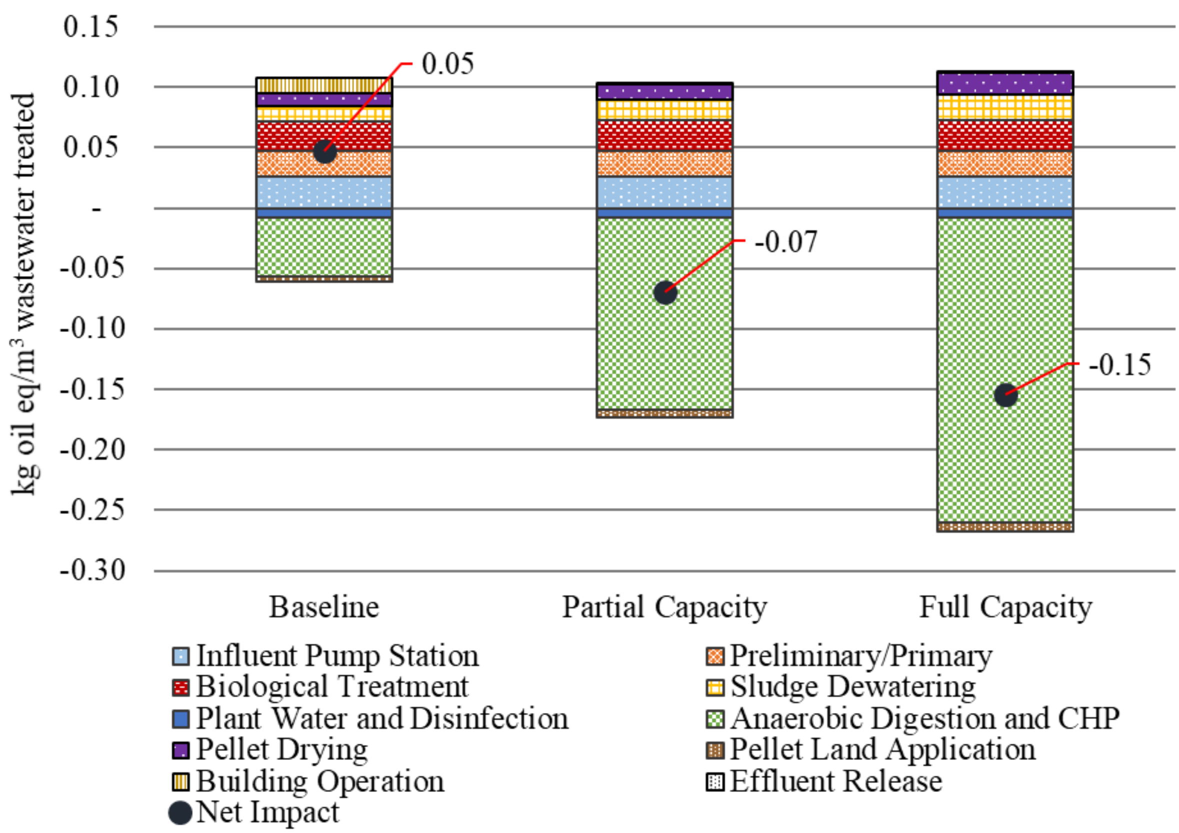


Figure 5-7. Fossil depletion potential results by treatment group.

5.7 Smog Formation Potential

Figure 5-8 presents the smog formation potential results organized according to treatment group. The partial and full capacity scenarios yield 50 and 80 percent reductions in smog formation potential relative to the baseline scenario. This is due to the environmental credit attributable to AD avoided products. Review of detailed process results reveals that avoided electricity production yields the greatest reduction in smog formation potential. Environmental impacts and credits are nearly balanced for the AD treatment group in the baseline feedstock scenario leading to a negligible net contribution to smog formation potential. Emissions associated with biogas combustion in the pellet drying facility lead to increasing gross, positive smog formation potential impacts from operation of the WWTF. Avoided products and EOL disposal methods associated with digestion more than offset increases in smog formation potential associated with increased pellet production.

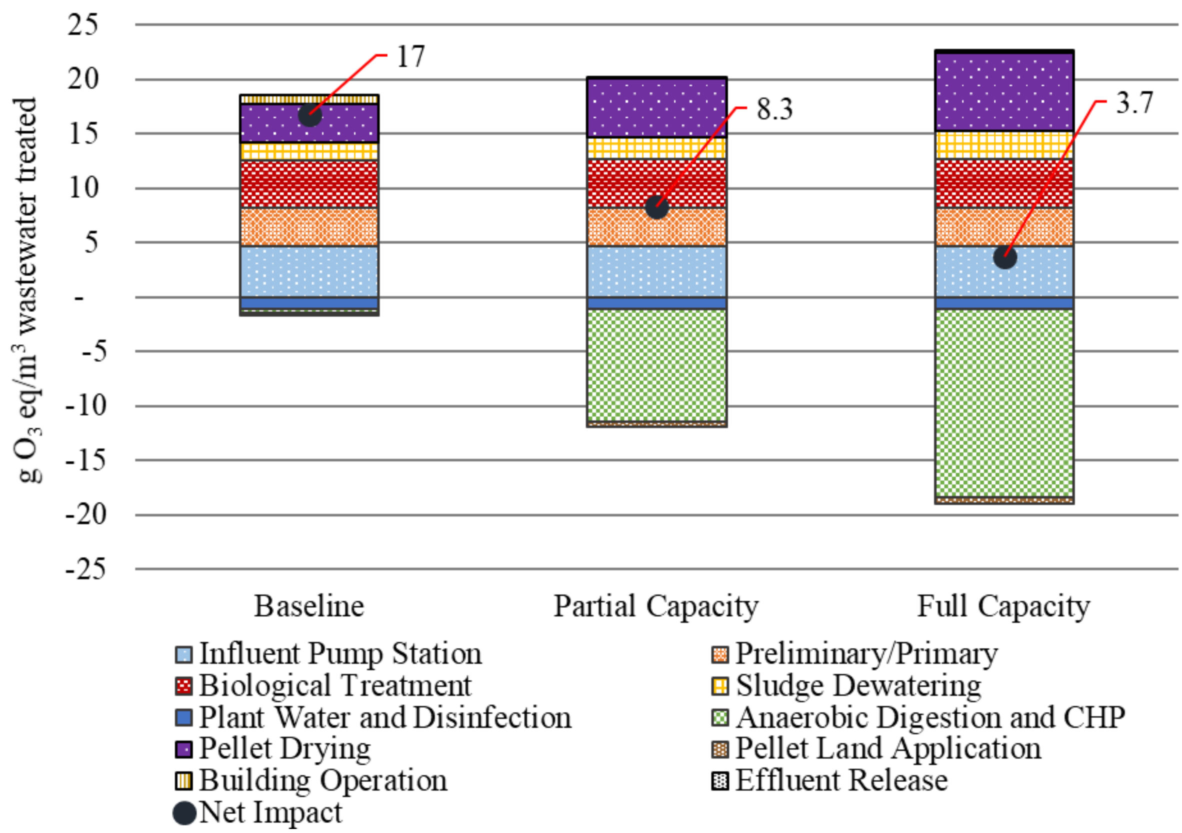


Figure 5-8. Smog formation potential results by treatment group.

5.8 Particulate Matter Formation Potential

Figure 5-9 presents particulate matter formation potential results organized according to treatment group. Partial and full capacity scenarios yield 65 and 110 percent reductions in particulate matter formation potential relative to the baseline feedstock scenario. This is due to the environmental credit attributable to AD avoided products. Review of detailed process results reveals that avoided natural gas combustion yields the greatest reduction in particulate matter formation potential. Biogas flaring is the largest contributor to particulate matter formation potential impact within the AD treatment group for the partial and full capacity scenarios. Emission of particulates and SO_2 from biogas combustion in the pellet drier are the dominant contributor to increasing gross, positive particulate matter formation potential impacts from operation of the WWTF. Increased electricity demand associated with biosolids dewatering also contributes to increased gross, positive impact as the facility accepts larger quantities of SSO. Overall, the trend is towards decreasing net particulate matter formation potential impact as more SSO is accepted.

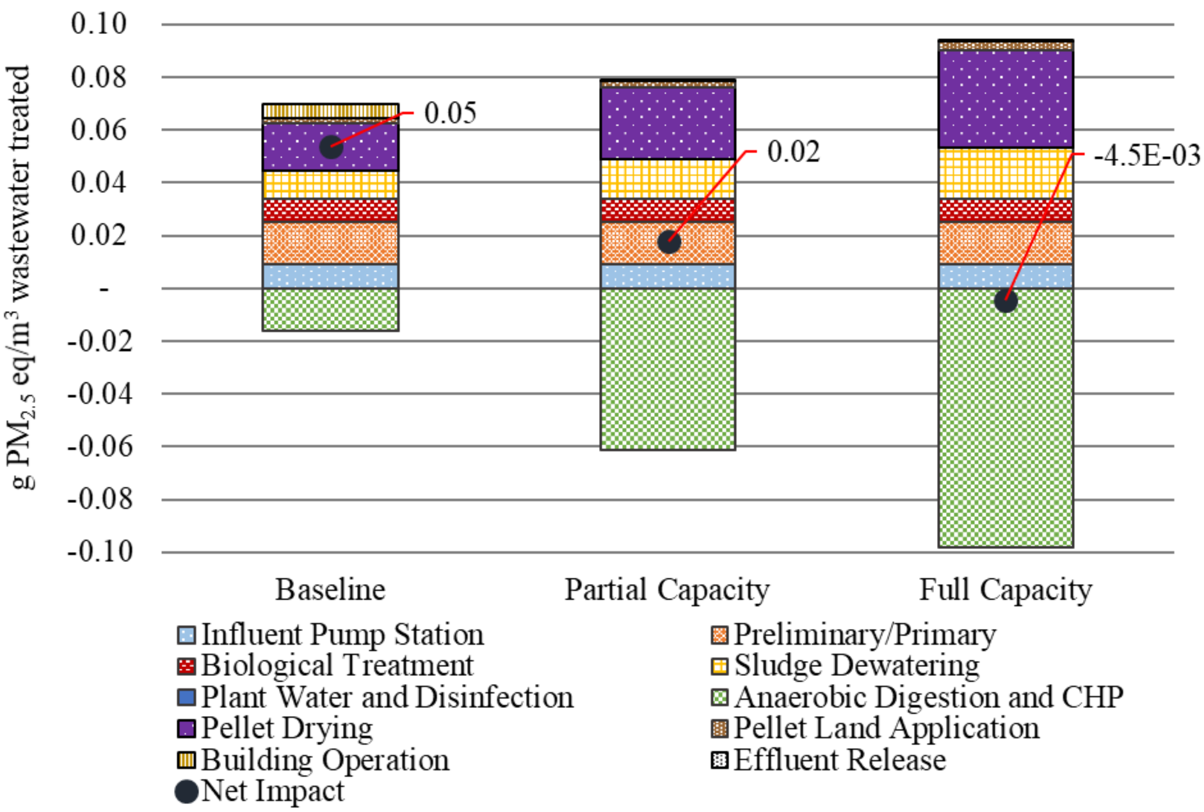


Figure 5-9. Particulate matter formation potential results by treatment group.

5.9 Water Use

Figure 5-10 presents water use results grouped according to treatment group. The avoided water extraction associated with on-site and industrial reuse of treated wastewater dominates all other sources of water use within the product system. The quantity of reuse water remains constant across scenarios and constitutes approximately 13 percent of treated wastewater by volume. A split axis scale is used to facilitate viewing water use not associated with avoided potable water consumption. Examination of detailed process results indicates that water use during SSO slurry production, avoided SSO disposal and electricity consumption are the three primary contributors to gross, positive water use potential. Avoided electricity production reduces gross, positive water use potential by approximately 40 percent.

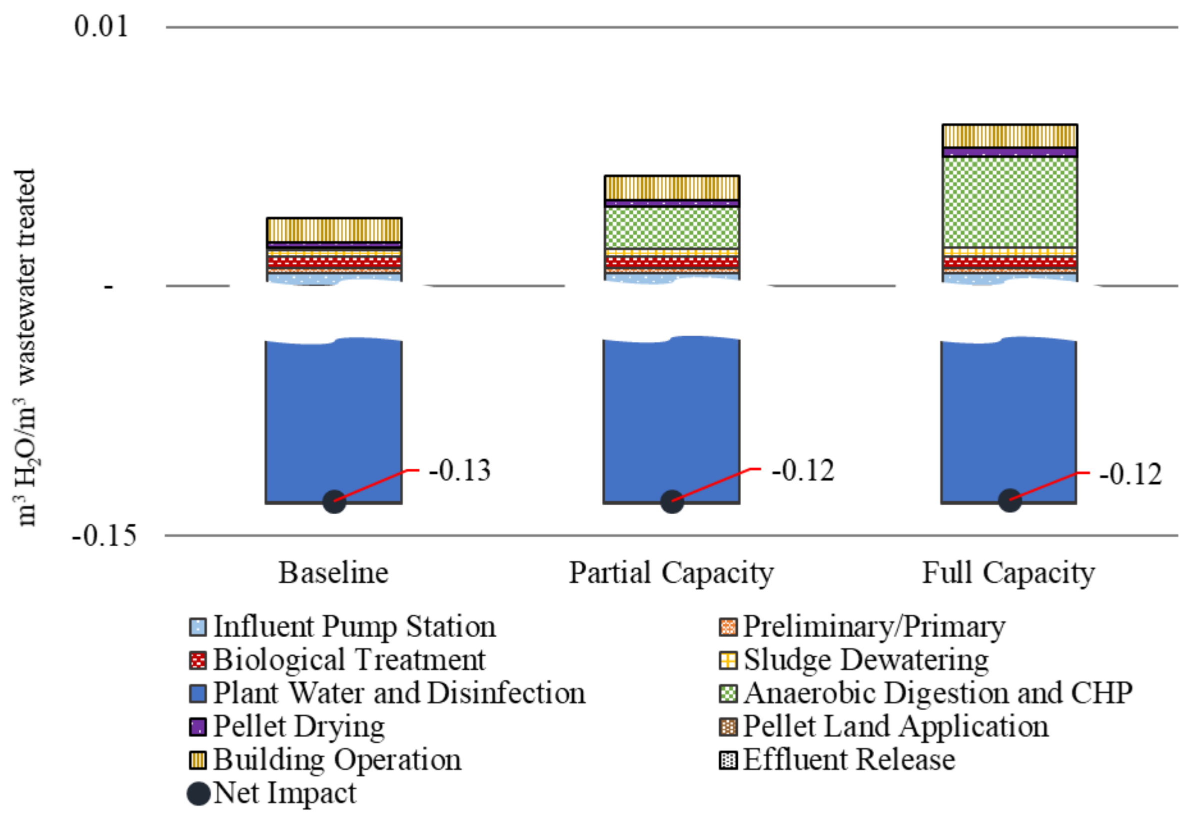


Figure 5-10. Water use results by treatment group.

5.10 Life Cycle Cost Assessment

Figure 5-11 presents system NPV for the baseline, partial capacity and full capacity feedstock scenarios assuming base AD performance and cost parameters. The partial and full capacity scenarios realize four and 10 percent reductions in NPV relative to the base cost scenario over a 30-year period. Capital costs increase by 20 percent for both scenarios that include AD and CHP expansion. SSO tipping fee revenues help to limit the increase in operational costs associated with the facilities. Annual chemical costs increase by 30 and 55 percent for the partial and full capacity scenarios, due primarily to increased polymer consumption. The biggest shift in life cycle cost is from increased energy production in the partial and full capacity scenarios. Baseline energy cost is 61 million dollars over the 30-year analysis period. The partial capacity scenario realizes an 83 percent reduction in energy expenditure. The full capacity scenario receives net revenue from the sale of REC and AECs associated with electrical and thermal energy production, respectively. The discounted payback period within the base AD performance scenarios for investment in the fourth anerobic digester and the CHP system is 14 and 27 years for the full and partial capacity scenarios, respectively. Payback period is not applicable for the baseline scenario.

This report presents results such that the environmental benefit of energy recovery accrues to the WWTF, reducing the impact of treating a unit of wastewater. However, when the facility sells RECs and AECs associated with its energy products, they are selling those benefits to other facilities. The LCA quantifies this environmental benefit and presents the results per cubic meter of treated wastewater.

A detailed breakdown of life cycle costs that were used to develop Figure 5-11 are included in Appendix C, Table C-3 and Table C-4.

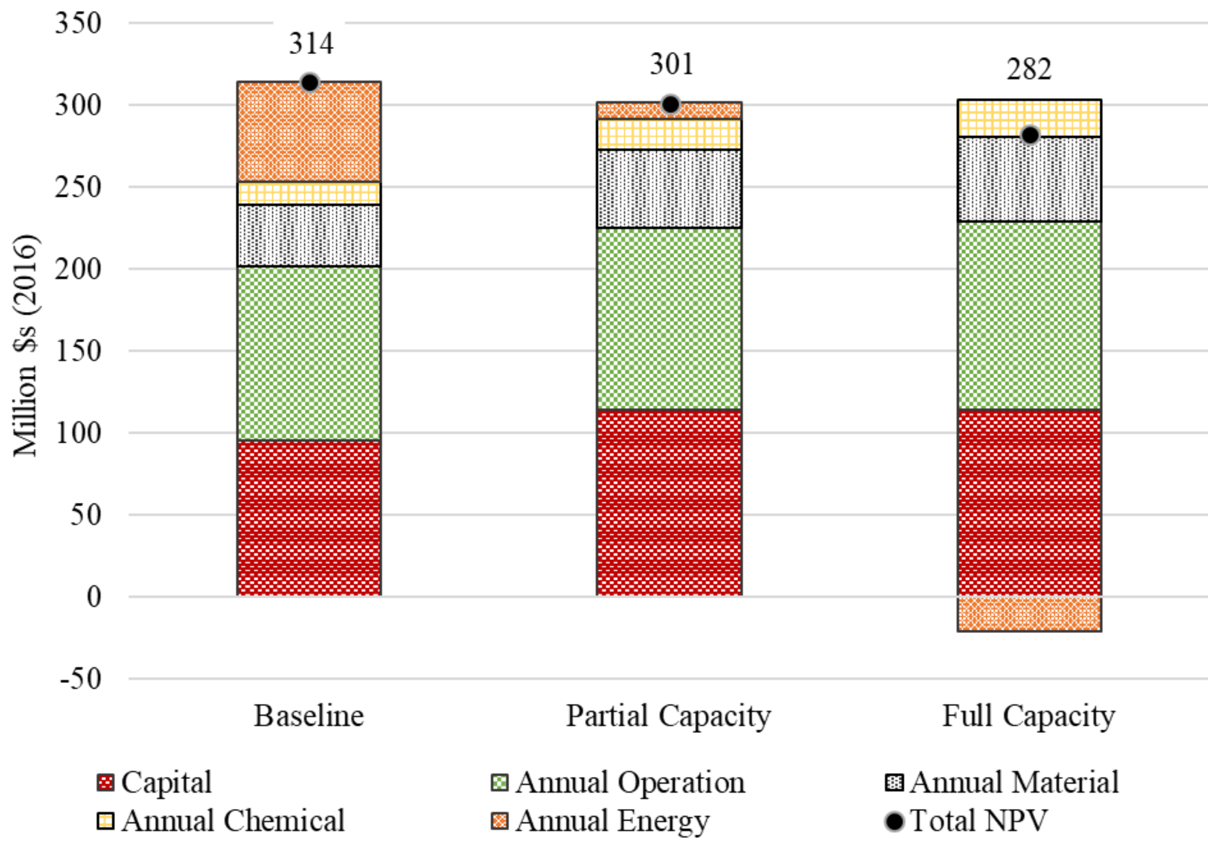


Figure 5-11. Base life cycle costs by cost category for the case-study wastewater treatment facility.

6. SCENARIO AND SENSITIVITY ANALYSIS

Sensitivity and scenario analysis help determine the influence of model assumptions and parameters on the study findings. The sensitivity and scenario analysis covered in this work were previously introduced in Section 2.3.2.

6.1 Anaerobic Digestion Performance

Results presented in this section demonstrate the sensitivity of EP, GWP and CED impact results to assumptions regarding anaerobic digester performance. Section 6.3 includes summary results for all impact categories.

Figure 6-1 presents comparative EP results for three feedstock and two AD performance scenarios. The trend in results shows that increasing acceptance of SSO material is likely to increase the plant's contribution to eutrophication in the absence of nutrient removal and recovery strategies. The GLSD WWTF is not permitted on nitrogen or phosphorus and is not designed for nutrient removal. The highest EP is exhibited by the full capacity-low AD performance and represents a 24 percent increase in EP impact relative to the baseline feedstock scenario. Nitrogen emission estimates in the low AD performance scenario assume that 80 percent of nutrient content in SSO material is solubilized and returned to the primary and secondary treatment units leading to increased effluent emissions. In the base AD scenario, approximately 60 percent of nitrogen in the SSO returns to the primary clarifier in centrifuge supernatant. A consistent 20 percent increase in phosphorus return was also applied in the low AD scenario. The difference in EP between the base and low AD performance scenarios is approximately four percent in both co-digestion scenarios.

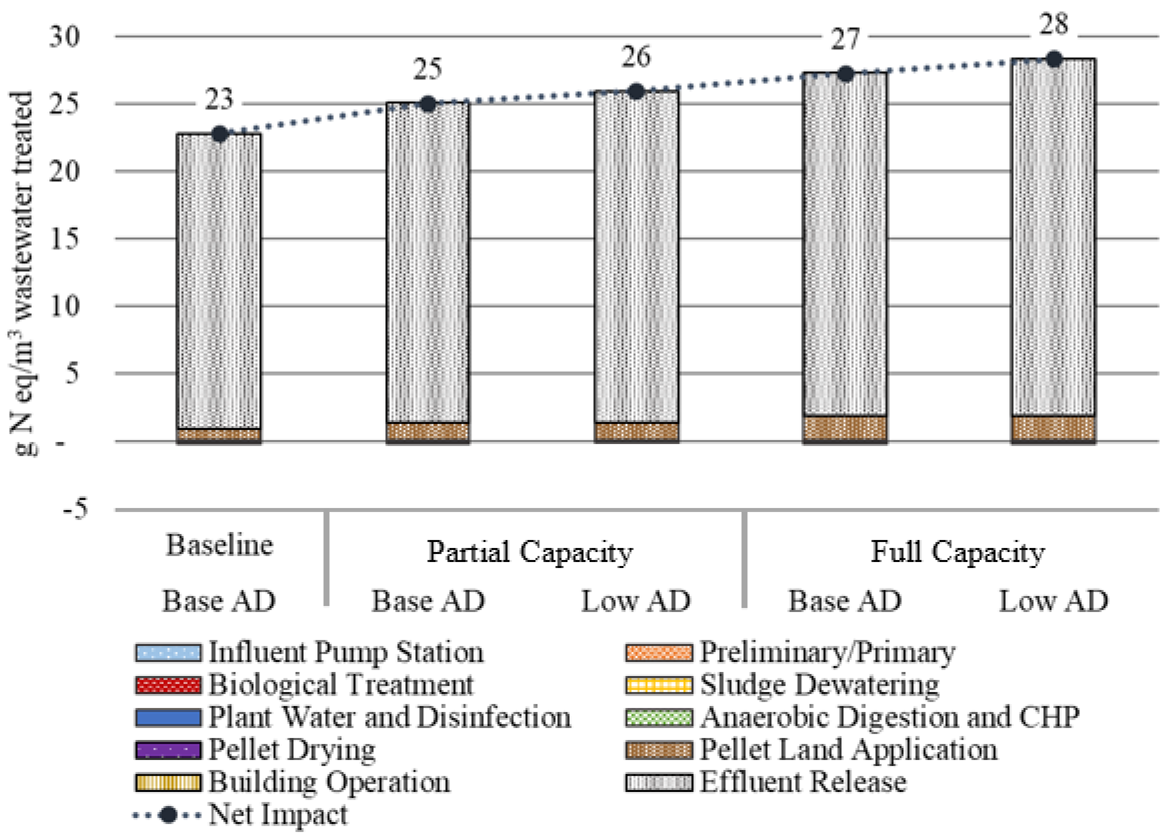


Figure 6-1. Eutrophication potential by treatment group for all feedstock and AD performance scenarios.

Figure 6-2 presents comparative GWP results for three feedstock and two AD performance scenarios. Both partial capacity scenarios yield net reductions in GWP relative to the base scenario. The partial capacity-low AD scenario yields a 50 percent reduction in GWP impact relative to the baseline scenario, while the partial capacity-base AD scenario has very close to net zero GWP impact. Both full capacity-AD performance scenarios produce GWP benefits (i.e. net negative impact results). The full capacity-base AD performance scenario leads to a reduction in GWP of 175 percent relative to the baseline scenario. Both avoided SSO disposal and avoided energy products contribute considerable reductions in GWP impact. The magnitude of the avoided SSO disposal impact/credit is the same regardless of AD performance scenario.

In the partial capacity-base AD performance scenario, the environmental credit associated with avoided energy products totals 0.50 kg CO_2 eq per m^3 wastewater treated. Avoided landfill disposal reduces GWP impact by 0.20 kg CO_2 eq per m^3 wastewater treated, while avoided WTE disposal leads to slight increases in GWP. Although avoided WTE disposal itself yields slight increases in impact, the benefits of digesting food waste outweigh the forfeited benefits of WTE incineration.

The quantity of biogas flared increases to 20 percent in the low AD performance scenario, increasing on-site combustion emissions and reducing energy production. Fugitive emissions decrease in the low AD performance scenario, given that emissions were estimated as a set five percent fraction of biogas produced.

Global warming potential impact per m^3 of wastewater treated was found to be sensitive to assumptions related to capacity utilization and AD performance, however the downward trend in GWP impact remains consistent regardless of AD performance as SSO co-digestion is adopted and SSO quantities increase. Overall, Figure 6-2 demonstrates that utilizing the full digester capacity for SSO co-digestion produces the greatest GWP benefit, by avoiding the use of fossil-based energy products and methane emissions associated with landfill disposal of food waste.

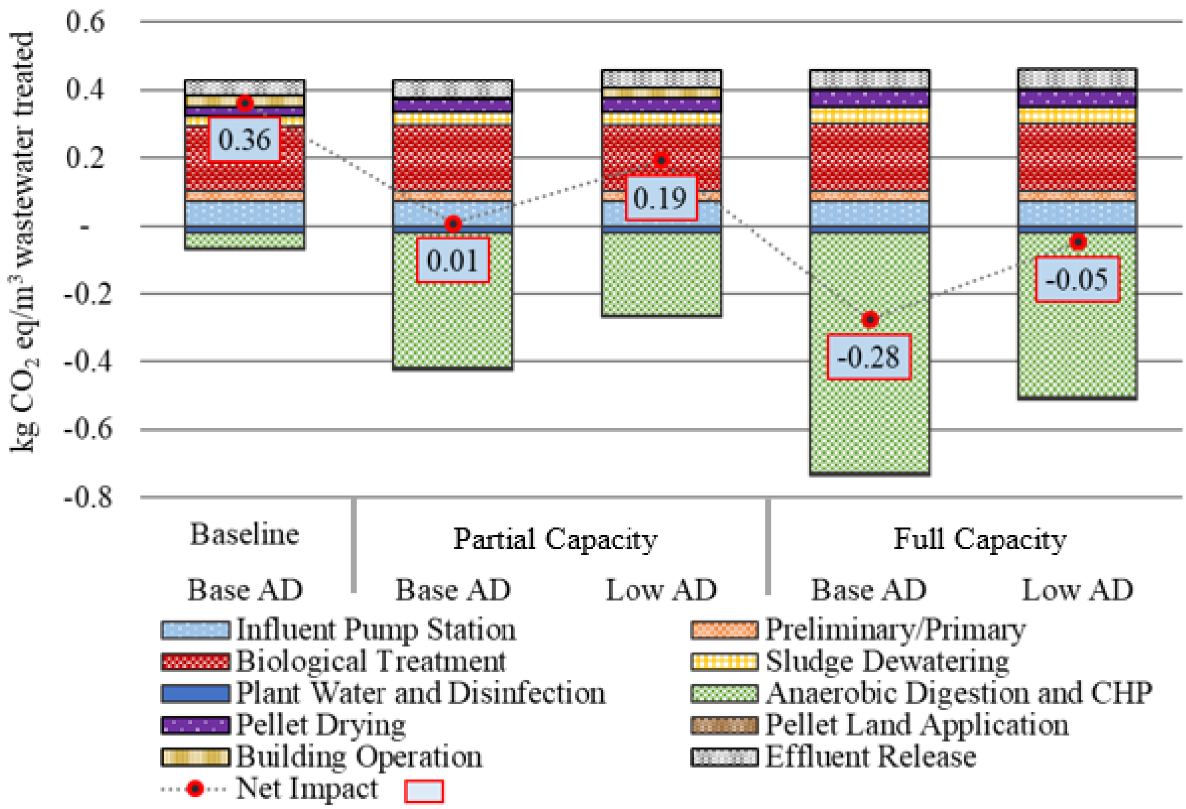


Figure 6-2. Global warming potential by treatment category for all feedstock and AD performance scenarios.

Figure 6-3 presents comparative CED results for three feedstock and two AD performance scenarios. All four SSO feedstock scenarios yield lower net CED than was associated with the WWTF prior to AD expansion and SSO co-digestion. The partial capacity-low AD performance scenario demonstrates the most modest reduction in CED, reducing net CED by approximately 30 percent relative to the baseline scenario. In the full capacity-base AD scenario, a CED environmental benefit is achieved, corresponding to a 225 percent reduction relative to the baseline scenario. Like the trend in GWP results, net CED was found to be sensitive to both feedstock acceptance and assumptions regarding AD performance, however the relative reduction in CED as SSO co-digestion is adopted is clear in all the developed scenarios.

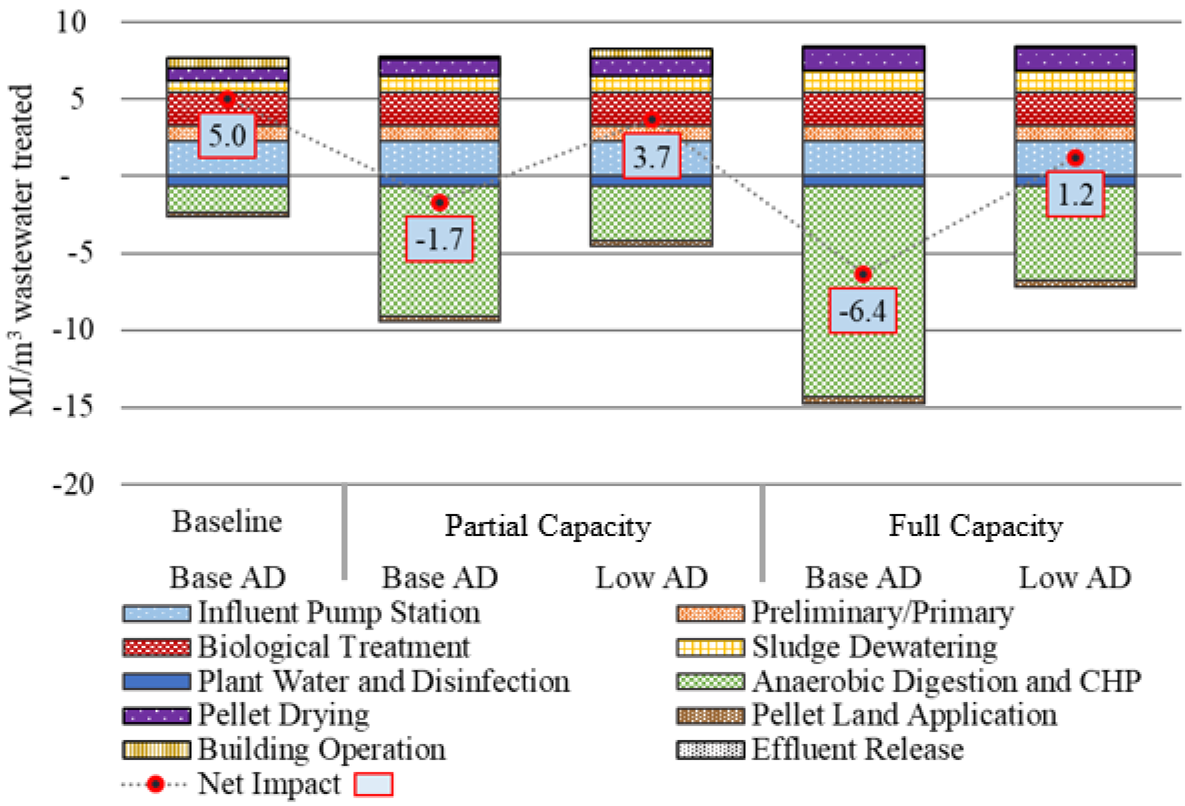


Figure 6-3. Cumulative energy demand by treatment group for all feedstock and AD performance scenarios.

6.2 SSO Avoided End-of-Life Disposal

This section presents results of the sensitivity analysis focusing on avoided EOL disposal processes. Baseline results, presented in Section 5, include the net environmental benefits and burdens of avoiding SSO EOL disposal according to current disposal practices in Massachusetts (MA disposal mix). Results excluding avoided EOL processes are labeled "None" in Figure 6-4 and Figure 6-5. The figures also present results for hypothetical scenarios where each kg of SSO waste digested avoids 100% landfill or 100% WTE disposal routes. Section 6.3 includes summary results for all impact categories. Appendix A includes the results of an additional analysis where anaerobic digestion of food waste is compared to composting as an alternative EOL disposal strategy.

Figure 6-4 presents GWP results by treatment group for all avoided EOL options and the base AD performance scenario. The magnitude of global warming potential impact results is strongly affected by selection of the avoided EOL disposal option. Avoiding landfill disposal of

SSO waste yields a significant environmental credit, which drives the negative impact score demonstrated for the AD and CHP treatment group. The predominant contribution of landfill disposal in the national disposal mix, 82 percent, is responsible for the significant decrease in GWP within this scenario. This avoided GWP burden is primarily due to avoided landfill fugitive methane emissions. Avoiding WTE disposal of SSO has the opposite effect, which works to reduce the GWP benefits associated with avoided energy and fertilizer products. This makes sense intuitively, given that substitution of one energy producing process for another has a more limited net effect on results. However, the net GWP impact of the AD and CHP treatment group is negative for all avoided SSO disposal scenarios, indicating that the net benefits of anaerobically digesting food waste are greater than the benefits associated with WTE combustion, making AD an environmentally preferable option for the GWP impact category.

Excluding avoided EOL disposal still leads to a net reduction in GWP impact for both the partial and full capacity feedstock scenarios, indicating that the environmental benefits of SSO co-digestion are not dependent on avoided EOL disposal credits.

Figure 6-5 presents CED results by treatment group for all avoided EOL options and the base AD performance scenario. Both the full and partial capacity scenarios yield net reductions in facility energy demand regardless of assumptions concerning avoided EOL disposal. The magnitude of net reduction in CED is less sensitive than GWP impact results. Avoiding WTE disposal tends to reduce CED benefits, due to the energy production associated with WTE incineration. Avoided landfill disposal has a limited effect on CED.

The national disposal scenario yields a greater CED reduction relative to the MA disposal mix due to the lower quantity of avoided WTE combustion in the national disposal scenario. The “None” scenario, that excludes avoided EOL disposal, shows that avoided waste disposal processes tend to reduce the CED benefits of food waste anaerobic digestion. However, the benefits of AD considerably outweigh those of the avoided disposal processes, making AD an environmentally preferable option to either landfill or WTE disposal of food waste from the perspective of CED.

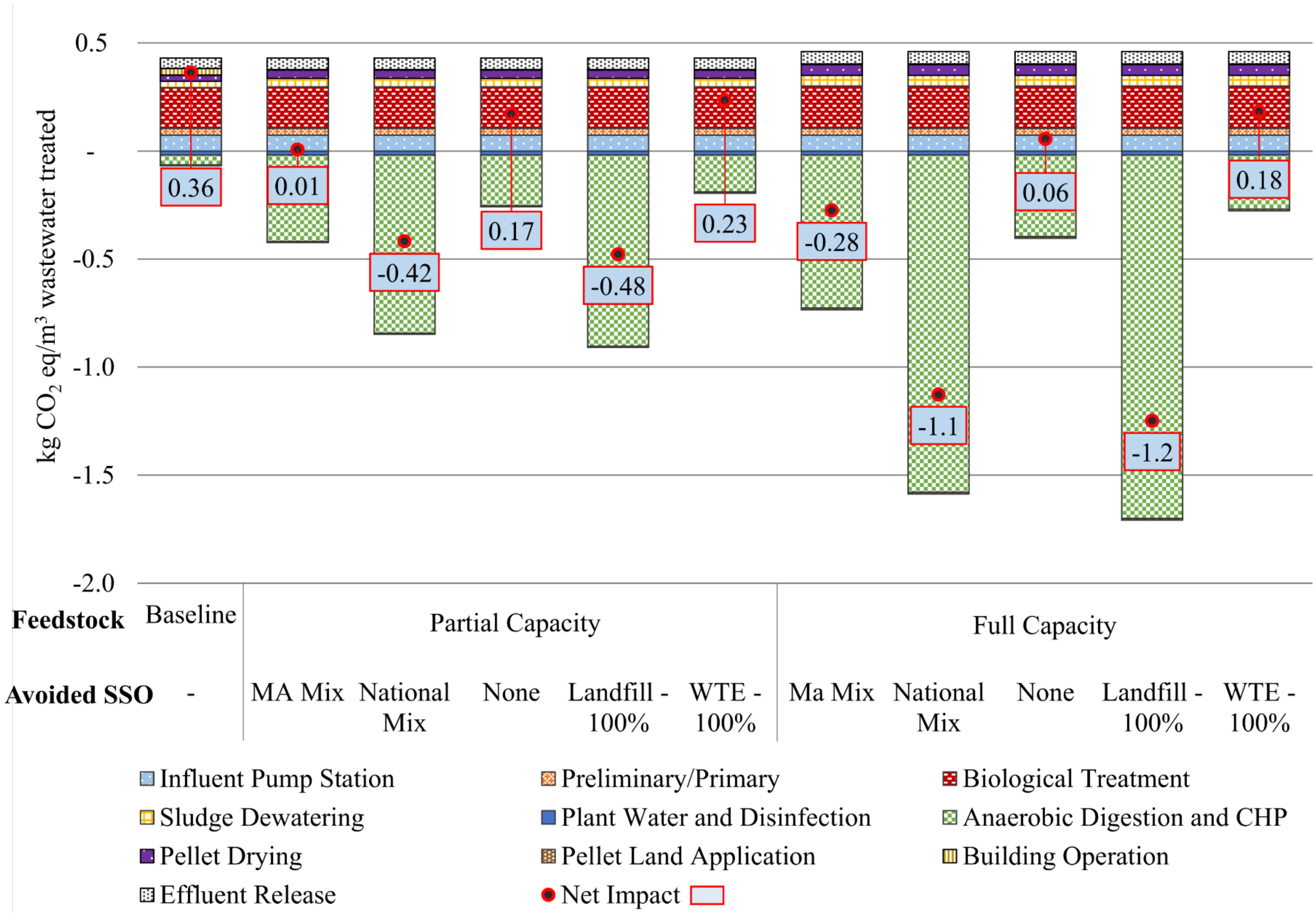


Figure 6-4. Global warming potential results by treatment group for all feedstock and avoided EOL scenarios.

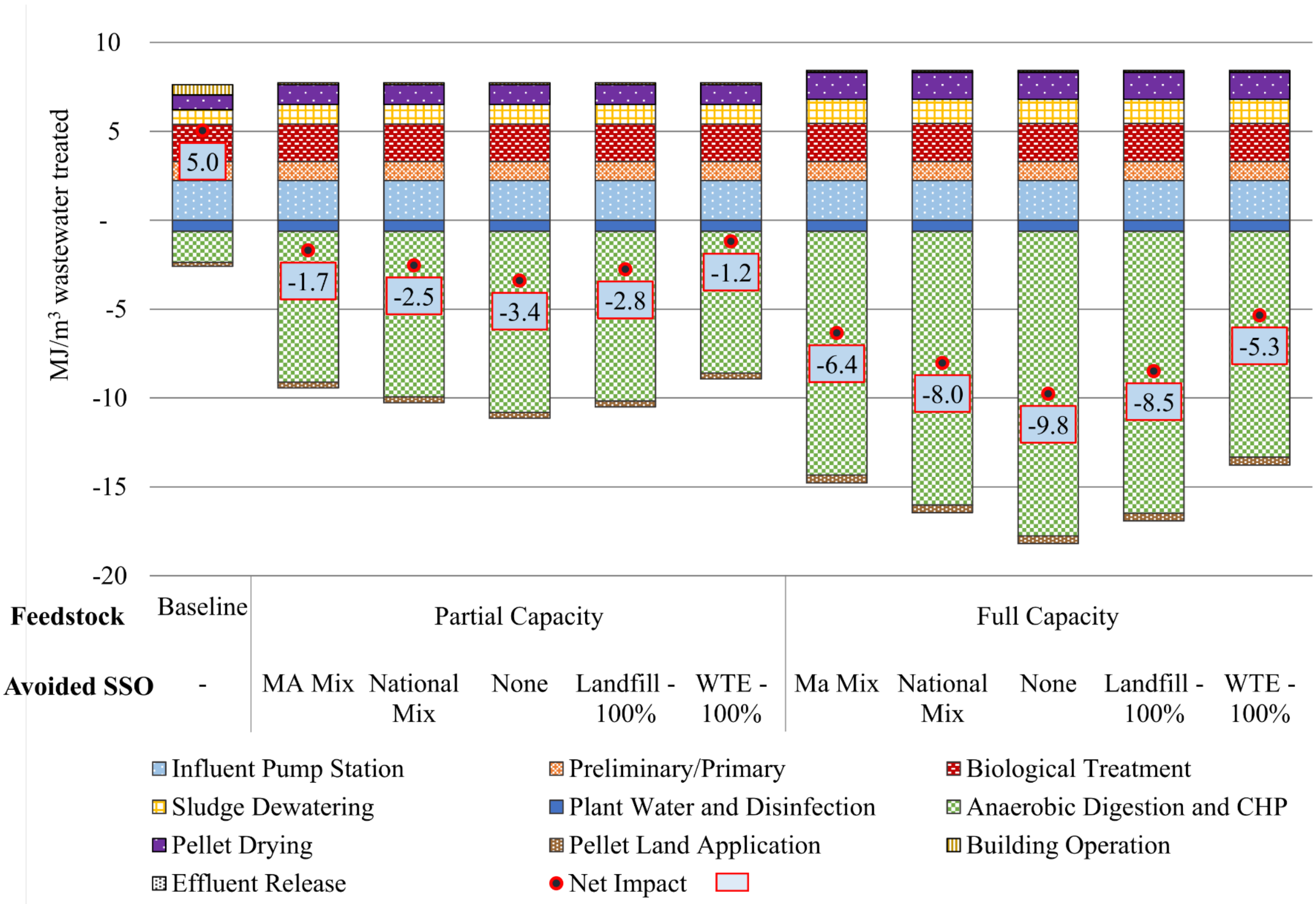


Figure 6-5. Cumulative energy demand by treatment group for all feedstock and avoided EOL scenarios.

6.3 Summary Results – All Impact Categories and EOL Scenarios

Table 6-1 presents net impact results for all feedstock-AD performance scenarios for each avoided SSO disposal scenario. Positive impact results for feedstock-AD performance scenarios that are less than the baseline value indicate a net reduction in environmental impact relative to the baseline scenario. Negative impact results indicate an environmental benefit due to a combination of avoided product and SSO disposal process benefits. Table 6-2 presents LCIA results relative to the baseline scenario. Positive percentages that are less than 100 percent indicate a net reduction in environmental impact relative to the baseline scenario, while values greater than 100 percent indicate a net increase in impact. Negative values indicate an environmental benefit.

Table 6-1. Net Impact Results for all Feedstock and AD Performance Scenarios (per m^3 Wastewater Treated)

Impact Category	EOL Scenario	Baseline	Partial Capacity, Base AD	Partial Capacity, Low AD	Full Capacity, Base AD	Full Capacity, Low AD
Global Warming Potential - kg CO_2 eq	MA Disposal Mix	0.36	0.01	0.19	-0.28	-0.05
	National Disposal Mix	n.a.	-0.4	-0.2	-1.1	-0.9
	No Avoided SSO Disposal	n.a.	0.17	0.36	0.06	0.28
	Avoided Landfill - 100%	n.a.	-0.5	-0.3	-1.2	-1.0
	Avoided WTE - 100%	n.a.	0.23	0.42	0.18	0.41
Eutrophication Potential - kg N eq	MA Disposal Mix	0.02	0.03	0.03	0.03	0.03
	National Disposal Mix	n.a.	0.03	0.03	0.03	0.03
	No Avoided SSO Disposal	n.a.	0.03	0.03	0.03	0.03
	Avoided Landfill - 100%	n.a.	0.03	0.03	0.03	0.03
	Avoided WTE - 100%	n.a.	0.03	0.03	0.03	0.03
Cumulative Energy Demand - MJ	MA Disposal Mix	5.0	-1.7	3.7	-6.4	1.2
	National Disposal Mix	n.a.	-2.5	2.9	-8.03	-0.5
	No Avoided SSO Disposal	n.a.	-3.4	2.0	-9.77	-2.2
	Avoided Landfill - 100%	n.a.	-2.8	2.6	-8.5	-0.9
	Avoided WTE - 100%	n.a.	-1.20	4.2	-5.3	2.2
Fossil Depletion Potential - kg oil eq	MA Disposal Mix	0.05	-0.07	0.02	-0.15	-0.04
	National Disposal Mix	n.a.	-0.08	0.01	-0.17	-0.06
	No Avoided SSO Disposal	n.a.	-0.09	0.00	-0.19	-0.08
	Avoided Landfill - 100%	n.a.	-0.08	0.01	-0.18	-0.06
	Avoided WTE - 100%	n.a.	-6.4E-2	0.02	-0.14	-0.03
Particulate Matter Formation Potential - kg $PM_{2.5}$ eq	MA Disposal Mix	5.4E-5	1.8E-5	5.6E-5	-4.5E-6	4.4E-5
	National Disposal Mix	n.a.	1.3E-5	5.1E-5	-1.4E-5	3.4E-5
	No Avoided SSO Disposal	n.a.	2.0E-5	5.8E-5	-9.0E-8	4.8E-5
	Avoided Landfill - 100%	n.a.	1.1E-5	4.9E-5	-1.7E-5	3.1E-5
	Avoided WTE - 100%	n.a.	2.1E-5	5.9E-5	1.6E-6	5.0E-5
Acidification Potential - kg SO_2 eq	MA Disposal Mix	1.0E-3	6.6E-4	1.1E-3	5.4E-4	1.1E-3
	National Disposal Mix	n.a.	5.9E-4	1.1E-3	3.8E-4	9.8E-4
	No Avoided SSO Disposal	n.a.	7.2E-4	1.2E-3	6.6E-4	1.3E-3
	Avoided Landfill - 100%	n.a.	5.8E-4	1.1E-3	3.7E-4	9.8E-4
	Avoided WTE - 100%	n.a.	7.0E-4	1.2E-3	6.1E-4	1.2E-3

Table 6-1. Net Impact Results for all Feedstock and AD Performance Scenarios (per m^3 Wastewater Treated)

Impact Category	EOL Scenario	Baseline	Partial Capacity, Base AD	Partial Capacity, Low AD	Full Capacity, Base AD	Full Capacity, Low AD
Smog Formation Potential - kg O_3 eq	MA Disposal Mix	0.02	8.3E-3	0.02	3.7E-3	0.02
	National Disposal Mix	n.a.	4.9E-3	0.01	0.00	1.0E-2
	No Avoided SSO Disposal	n.a.	0.01	0.02	5.7E-3	0.02
	Avoided Landfill - 100%	n.a.	4.4E-3	1.4E-2	0.00	9.3E-3
	Avoided WTE - 100%	n.a.	0.01	0.02	0.01	0.02
Water Use - m^3 H_2O	MA Disposal Mix	-0.13	-0.12	-0.12	-0.12	-0.12
	National Disposal Mix	n.a.	-0.12	-0.12	-0.12	-0.12
	No Avoided SSO Disposal	n.a.	-0.12	-0.12	-0.12	-0.12
	Avoided Landfill - 100%	n.a.	-0.12	-0.12	-0.12	-0.12
	Avoided WTE - 100%	n.a.	-0.12	-0.12	-0.12	-0.12

Table 6-2. Relative Impact Results for all Feedstock and AD Performance Scenarios (Relative to Baseline Scenario)

Impact Category	EOL Scenario	Baseline	Partial Capacity, Base AD	Partial Capacity, Low AD	Full Capacity, Base AD	Full Capacity, Low AD
Global Warming Potential	MA Disposal Mix	100%	2%	53%	-76%	-13%
	National Disposal Mix	n.a.	-115%	-64%	-311%	-248%
	No Avoided SSO Disposal	n.a.	47%	99%	16%	78%
	Avoided Landfill - 100%	n.a.	-132%	-81%	-344%	-281%
	Avoided WTE - 100%	n.a.	65%	116%	50%	113%
Eutrophication Potential	MA Disposal Mix	100%	110%	114%	120%	124%
	National Disposal Mix	n.a.	110%	114%	119%	124%
	No Avoided SSO Disposal	n.a.	110%	114%	120%	124%
	Avoided Landfill - 100%	n.a.	110%	114%	119%	124%
	Avoided WTE - 100%	n.a.	110%	114%	120%	124%
Cumulative Energy Demand	MA Disposal Mix	100%	-34%	73%	-126%	24%
	National Disposal Mix	n.a.	-50%	57%	-160%	-9%
	No Avoided SSO Disposal	n.a.	-68%	39%	-194%	-44%
	Avoided Landfill - 100%	n.a.	-55%	52%	-169%	-18%
	Avoided WTE - 100%	n.a.	-24%	83%	-106%	44%
Fossil Depletion Potential	MA Disposal Mix	100%	-148%	40%	-330%	-84%
	National Disposal Mix	n.a.	-168%	19%	-371%	-125%
	No Avoided SSO Disposal	n.a.	-190%	-2%	-414%	-168%
	Avoided Landfill - 100%	n.a.	-174%	14%	-382%	-136%
	Avoided WTE - 100%	n.a.	-136%	52%	-305%	-59%
Particulate Matter Formation Potential	MA Disposal Mix	100%	33%	103%	-8%	81%
	National Disposal Mix	n.a.	24%	94%	-26%	64%
	No Avoided SSO Disposal	n.a.	37%	107%	0%	90%
	Avoided Landfill - 100%	n.a.	21%	91%	-32%	57%
	Avoided WTE - 100%	n.a.	39%	109%	3%	93%
Acidification Potential	MA Disposal Mix	100%	66%	113%	54%	114%
	National Disposal Mix	n.a.	59%	105%	38%	98%
	No Avoided SSO Disposal	n.a.	72%	119%	66%	126%
	Avoided Landfill - 100%	n.a.	58%	105%	37%	98%

Table 6-2. Relative Impact Results for all Feedstock and AD Performance Scenarios (Relative to Baseline Scenario)

Impact Category	EOL Scenario	Baseline	Partial Capacity, Base AD	Partial Capacity, Low AD	Full Capacity, Base AD	Full Capacity, Low AD
	Avoided WTE - 100%	n.a.	70%	116%	61%	121%
Smog Formation Potential	MA Disposal Mix	100%	50%	105%	22%	102%
	National Disposal Mix	n.a.	29%	84%	-18%	62%
	No Avoided SSO Disposal	n.a.	56%	111%	34%	115%
	Avoided Landfill - 100%	n.a.	26%	81%	-25%	55%
	Avoided WTE - 100%	n.a.	61%	116%	44%	125%
Water Use	MA Disposal Mix	100%	99%	99%	99%	98%
	National Disposal Mix	n.a.	100%	99%	99%	98%
	No Avoided SSO Disposal	n.a.	100%	99%	99%	99%
	Avoided Landfill - 100%	n.a.	100%	99%	99%	98%
	Avoided WTE - 100%	n.a.	99%	99%	99%	98%

6.4 Normalized LCIA Results

Normalization is a process of standardizing impact results such that the contribution of impact results associated with the functional unit can be investigated relative to total national or global impact for a given impact category. Table 6-3 shows normalization factors and U.S. national per capita impacts in the year 2008. This is the most recent year that LCA normalization factors are available (Lippiatt et al. 2013; Ryberg et al. 2014). A CED normalization factor was developed for U.S. 2008 conditions based on reported total primary energy consumption data (Enerdata 2017). A normalization factor was not available for the fossil depletion potential impact category; therefore, this category is excluded from the normalization step. The normalization factor is the total U.S. impact for the specified category in 2008. Impact per person was estimated by dividing the normalization factor by the U.S. population. The U.S. population in 2008 was estimated as 304,100,000 people (World Bank 2017). So, for example, the second row of Table 6-3 indicates that average per capita GHG emissions from all U.S. sources was just over 24 metric tons of CO_2 eq. in 2008.

Table 6-3. 2008 U.S. Normalization Factors and Per Capita Annual Impacts

Impact Category [1]	Unit	Normalization Factor (US-2008)	Impact per Person [2]	Source
Eutrophication potential	kg N eq/yr	6.6E+9	22	(Ryberg et al. 2014)
Global warming potential	kg CO_2 eq/yr	7.4E+12	2.4E+4	(Ryberg et al. 2014)
Acidification potential	kg SO_2 eq/yr	2.8E+10	92	(Ryberg et al. 2014)
Smog formation potential	kg O_3 eq/yr	4.2E+11	1.4E+3	(Ryberg et al. 2014)
Particulate matter formation potential	kg $PM_{2.5}$ eq/yr	7.4E+9	24	(Ryberg et al. 2014)
Cumulative energy demand	MJ	9.5E+13	3.1E+5	(Enerdata 2017)
Water Depletion	liter H_2O eq/yr	1.7E+14	5.6E+2	(Lippiatt et al. 2013)

[1] Normalization factor not available for fossil depletion, so these categories are excluded from normalization step.

[2] Impact per person calculated using 2008 population of 304,100,000 (World Bank 2017)

The process of normalization allows us to better assess the significance of impacts by comparing against absolute benchmarks at the national level. The functional unit for this study is a cubic meter of wastewater treated. To provide a gross, general context to these numbers, this presentation of normalized results calculates values based on the range of per capita municipal wastewater that is generated each year. The average generation of domestic municipal wastewater in the U.S. was estimated to be between 50 and 89 gallons per person per day (Tchobanoglous et al. 2014). This is a large range, reflecting the wide variation in use patterns as determined by factors such as climate, household size, and home and community conservation measures. This level of daily use translates to an annual domestic wastewater generation rate of between 70 and 120 cubic meters per person per year. By multiplying impact results calculated in this study by the annual cubic meters of domestic wastewater treated each year at municipal wastewater facilities and dividing by per capita normalization factors, we calculated the approximate annual contribution of domestic wastewater treatment to total per capita impact in each of the included impact categories for conditions presented in this study. The calculation excludes wastewater generated by commercial, public and industrial sources, and therefore overestimates the impact from individuals and does not reflect the full national burden of wastewater treatment. Normalized results for the three feedstock and two AD performance scenarios are presented in Table 6-4 for seven environmental impact categories.

Normalized results show that wastewater treatment makes the largest contribution to eutrophication per capita emissions. Normalized impact for all other categories is relatively small, less than one percent, due to environmental credits attributable to avoided energy and disposal products. Avoided product credits work to reduce net impact, and the associated normalized impact. Avoided potable water use contributes notably to normalized water use impact, off-setting between one and three percent of per capita water consumption. Negative normalized impact results indicate that operation of the WWTF, in the associated operational mode, reduces national emissions contributing to that impact category (i.e. an environmental benefit).

Normalized results are by their nature a highly generalized metric that overlooks nuance in favor of developing a high level indicator that provides guidance pertaining to results interpretation and the study systems contribution to individual impact categories. Normalized results should always be considered in this context.

Table 6-4. Estimated Annual Contribution of Municipal Wastewater Treatment Per Capita Impact in Seven Impact Categories

		Partial Capacity Feedstock		Full Capacity Feedstock	
Impact Category1,2	**Baseline**	**Base AD**	**Low AD**	**Base AD**	**Low AD**
Eutrophication potential	7 to 13%	8 to 14%	8 to 15%	9 to 15%	9 to 16%
Global warming potential	0.1 to 0.2%	0%	0.05 to 0.1%	-0.08 to -0.1%	-0.01 to -0.02%
Acidification potential	0.08 to 0.1%	0.05 to 0.1%	0.08 to 0.2%	0.04 to 0.1%	0.09 to 0.2%
Smog formation potential	0.08 to 0.1%	0.04 to 0.1%	0.09 to 0.2%	0.02 to 0.03%	0.09 to 0.2%
Particulate matter formation potential	0.02 to 0.03%	0.01 to 0.01%	0.02 to 0.03%	0%	0.01 to 0.02%
Water use	-1.6 to -2.8%	-1.5 to -2.8%	-1.5 to -2.7%	-1.5 to -2.7%	-1.5 to -2.7%
Cumulative energy demand	0.1 to 0.2%	-0.04 to -0.1%	0.08 to 0.1%	-0.14 to -0.2%	0.03 to 0.05%

1 Normalization factor not available for fossil depletion, so this category is excluded from normalization step.
2 Negative values indicate reductions in impact as result of WWTF operation.

6.5 LCCA Cost Scenarios

Figure 6-6 presents a summary of life cycle cost results for all feedstock, AD and cost scenarios by cost category. Discount rate selection is largely responsible for the difference in NPV magnitude between the low and base cost scenario, while the changes in relative relationships between cost categories is determined by capacity utilization, tipping fee and energy revenue assumptions. The shift in relative energy cost/revenue between scenarios is more dependent on AD capacity utilization and performance than it is on realized tipping fees and energy prices. Within the base cost scenario, the partial capacity-low AD performance scenario yields a 33 percent reduction in annual energy expenditures. The partial capacity-base AD performance scenario however realizes an 83 percent reduction in energy cost, demonstrating that relatively small reductions in biogas yield, VS reduction and biogas utilization can considerably affect the balance of system costs.

Table 6-5 emphasizes this point through the calculation of payback period for investments made as part of the AD and CHP expansion project for all feedstock, AD performance and cost scenarios. The low cost scenario is associated with parameter values that increase revenue potential of SSO acceptance and energy production, leading to shorter payback periods. Both the partial and full capacity scenarios have a payback period that is less than the system lifespan (30 years) in the base AD performance scenario. Neither feedstock scenario yields a payback period of less than 30 years within the low AD performance scenario. Several aspects of the low AD performance scenario combine to explain this result.

The most obvious aspects of the low AD performance scenario that reduce system revenue are the lower rate of volatile solids destruction and lower biogas yield. Together these two factors reduce biogas production by nearly 30 percent. This result is also a function of prioritizing biogas first for use in the pellet driers, where heat is the only beneficial end product. The low AD performance scenario also assumes an elevated flaring rate of 20 percent. When considered together these factors lead to a 50 percent reduction in the quantity of biogas that goes to the CHP system in the full capacity scenario. Greater utilization of the CHP system in the base AD performance scenario provides access to increased revenue potential from the sale of both RECs and AECs in addition to net metering benefits. The full capacity-base AD performance scenario shifts the WWTF for a net energy consumer to a net producer of energy.

Additional financial benefits may be realized as a function of the shift from traditional disposal routes of food waste to its anaerobic digestion at WWTFs. Beneficial use of this former waste product, has the potential to reduce tipping fees associated with landfill disposal. These benefits are likely to be captured by waste generators and waste collection and hauling companies. The plant also avoids disposal fees that would previously have been associated with biosolids disposal, while local farms get access to a low or no cost source of soil amendment.

Table 6-5. AD and CHP System Payback Period (years)

Scenario	Base Cost	Low Cost
Baseline	None	None
Partial Capacity-Low AD	None	None
Partial Capacity-Base AD	27	19
Full Capacity-Low AD	None	None
Full Capacity-Base AD	14	10

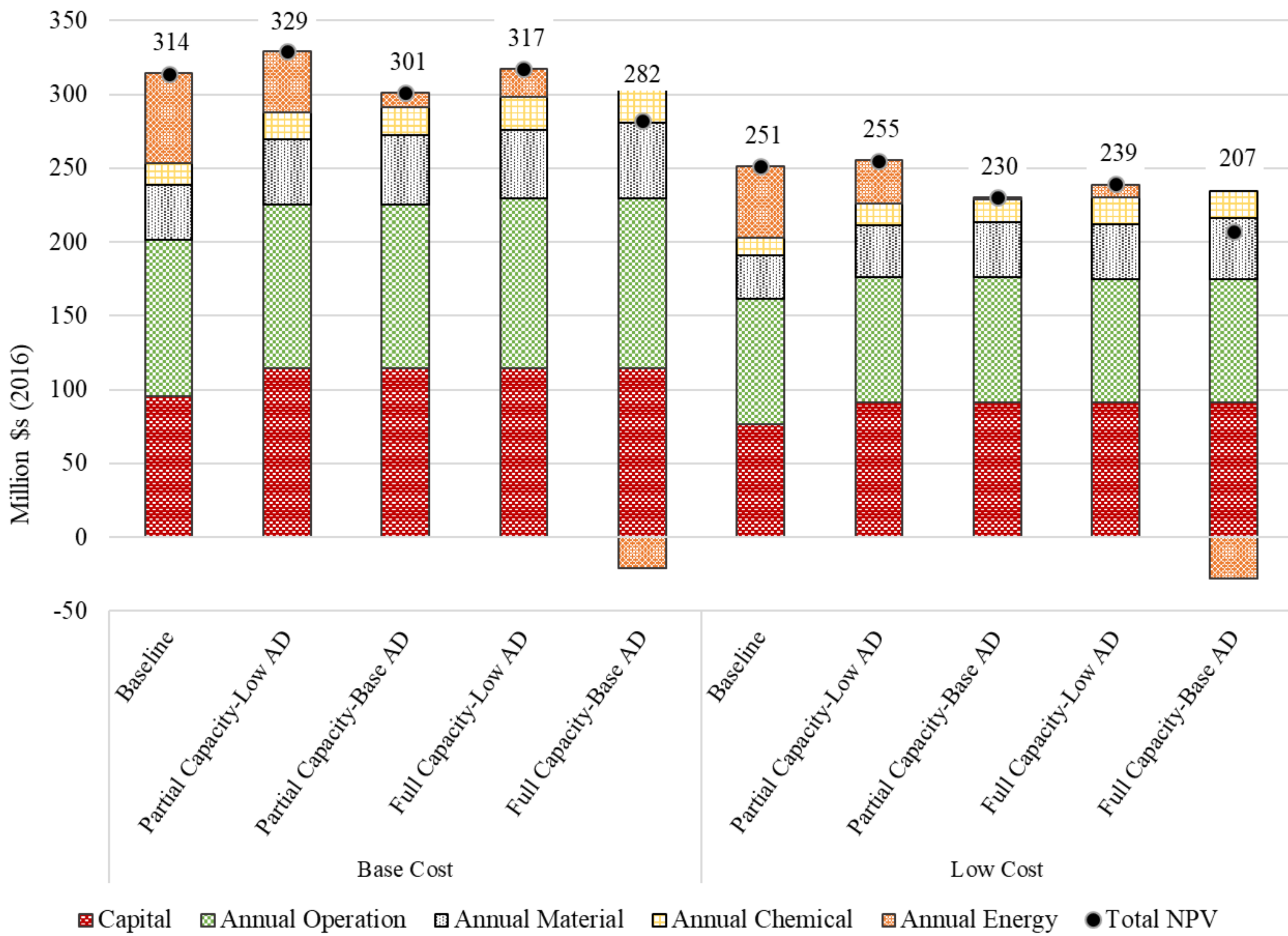


Figure 6-6. Life cycle cost assessment summary showing results for each Feedstock-AD performance scenario by cost scenario.

7. CONCLUSIONS

This report describes the effort to use recent purchasing records (2016), engineering design documents, the MSW DST and the GPS-X™ modeling software to develop LCI data for GLSD's wastewater treatment processes, biogas combustion units and avoided SSO disposal processes. Using the developed LCI data in combination with existing inventory data for upstream production processes the analysis quantifies environmental impacts in eight impact categories.

LCA results presented in this study highlight the environmental and economic benefits available to medium-scale WWTFs willing to invest in additional AD capacity, CHP equipment and personnel for co-digestion of SSO waste. Reductions in environmental impact or the generation of environmental benefit, judged relative to the baseline scenario prior to co-digestion, are possible in all impact categories assessed, except eutrophication. The possibility of achieving reduced environmental impact, even as the facility processes increased quantities of waste in the form of SSO, is robust for most impact categories, given that reductions are realized for all (or most) feedstock and AD performance scenarios investigated.

The magnitude of reductions and benefits in most categories is sensitive to AD utilization and performance and avoided SSO EOL disposal assumptions. In particular, net GWP benefits are greatest when avoiding landfill disposal of source separated food waste. As U.S. EOL disposal practices change either in the form or environmental impact of avoided disposal routes, the applicability of the environmental benefits currently assessed will need to be revisited. However, given the relatively early stage of U.S. efforts to shift away from landfill and WTE disposal routes for organic material, these avoided benefits are expected to be reasonable for many areas of the country for years to come.

The main environmental trade-off identified in this analysis was between increasing eutrophication potential, 10 to 20 percent increase for the partial and full capacity scenarios, and all other impact categories as the facility processes more SSO. Given the location and permit requirements of the GLSD WWTF, no specific nutrient removal efforts are made to mitigate contribution to eutrophication potential. Facilities that are bound by nutrient limitations are likely to require a simultaneous investment in nutrient removal capacity assuming static or decreasing permitted nutrient effluent quantity. The magnitude of normalized eutrophication potential impact, relative to that of other impact categories, indicates that this aspect of AD expansion for co-digestion should be carefully considered.

The energy analysis of AD presented in Section 3.3.8 indicates that the level of SSO co-digestion described in both the partial and full capacity scenarios was able to meet the thermal energy demand of GLSD's WWTF. In fact, significant excess thermal energy is available (i.e. currently wasted) in both scenarios. If GLSD, or other municipalities considering similar projects, can find additional productive uses for all thermal energy, additional environmental and economic benefits are available. Due to the net-metering program, environmental benefits are captured for all produced electricity, even the portion that exceeds plant electricity demands.

LCCA results are favorable for the GLSD WWTF, and likely for other medium-scale treatment facilities with similar energy consumption profiles. All base AD performance scenarios demonstrate a discounted payback period of less than the expected system lifespan. Payback period for the AD and CHP upgrades, assuming full capacity utilization, is 14 or less years in the base AD performance scenario. Economic benefits were not identified under conditions of low AD performance and capacity utilization for either cost scenario. Energy expenditures are significantly reduced in all co-digestion scenarios, yielding a source of net energy revenue within the full capacity-base AD performance scenarios. Previous work by the authors of this report demonstrated that economic payback of investment in AD and CHP technology are more difficult to achieve at the one MGD system scale (Morelli et al. 2017).

The use of biosolids drying and pelletization is a relatively unique aspect of this facility that should be considered by other facilities looking to translate results to their own context. Biosolids drying and pelletization is a source of significant energy demand within the facility, which provides a corresponding opportunity to benefit the economics of digestion paired with CHP. The most reliable economic benefit of Massachusetts's net metering program comes from off-setting facility electricity purchasing cost, as discussed in Section 4.3.7. Likewise, AECs are only applicable to useful thermal energy, i.e. that which is put to use. The significant energy demand of biosolid drying and pelletization allows the case-study facility to capture economic benefits that may not be available to all facilities. More importantly, net metering, AEC and REC or equivalent programs must be available to a specific WWTF for them to capture similar benefits.

This report presents results such that the environmental benefit of energy recovery accrues to the WWTF, reducing the impact of treating a unit of wastewater. However, when the facility sells RECs and AECs associated with its energy products, they are selling those environmental benefits to other facilities. The LCA quantifies this environmental benefit and presents the results per cubic meter of treated wastewater. Sale of RECs and AECs does not diminish the environmental benefit of co-digestion and the AD expansion project but instead shifts the facility that is able to claim those environmental benefits as an off-set to their production impacts.

For medium-scale WWTFs with a ready source of SSO, or similar high strength organic waste, investment in AD capacity and CHP systems provides an opportunity to reduce net environmental impact, while reducing energy expenditures over time. The analysis demonstrates sensitivity to capacity utilization and avoided EOL disposal assumptions that should be considered by facilities as they endeavor to assess applicability of case-study results within their own context.

8. REFERENCES

1. AACEI. 2016. Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Process Industries. Recommended Practice No. 18R-97. TCM Framework: 7.3 - Cost Estimating and Budgeting. American Association of Cost Engineers International.

2. Amlinger, F., S. Peyr, and C. Cuhls. 2008. Greenhouse Gas Emissions from Composting and Mechanical Biological Treatment. Waste Management and Research 26: 47–60. doi:10.1177/0734242X07088432.

3. Bare, J. 2011. TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and other Environmental Impacts. Clean Technologies and Environmental Policy 13: 687–696. doi:10.1007/s10098-010-0338-9.

4. Bare, J. C., G. A. Norris, D. W. Pennington, and T. E. McKone. 2003. TRACI: The tool for the reduction and assessment of chemical and other environmental impacts. Journal of Industrial Ecology 6: 49–78. Scopus.

5. Bayer, P., E. Heuer, U. Karl, and M. Finkel. 2005. Economical and ecological comparison of granular activated carbon (GAC) adsorber refill strategies. Water Research 39: 1719–1728.

6. Boldrin, A., J. K. Andersen, Møller, Jacob, H. Thomas, and E. Favoino. 2009. Composting and compost utilization: accounting of greenhouse gases and global warming contributions. Waste Management and Research 27: 800–812. doi:10.1177/0734242X09345275.

7. Brewer, L., A. D. Sullivan, and W. Gehr. 2013. Agricultural Composting and Water Quality. EM 9053. Oregon State University Extension.

8. CDM Smith. 2013. Technical Memorandum Report: Greater Lawrence Sanitary District, Organics to Energy Feasibility Study.

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

10. Christensen, E. M. 2009. Best Management Practices (BMPs) for Incorporating Food Residuals into Existing Yard Waste Composting Operations. Bethesda, MD: U.S. Environmental Protection Agency and The US Composting Council.

11. Commonwealth of Massachusetts. 2016. RENEWABLE ENERGY PORTFOLIO STANDARD - CLASS I. 225 CMR 14.00.

12. Commonwealth of Massachusetts. 2017a. Commercial Food Waste Disposal Ban. Massachusetts Government. Commercial Food Waste Disposal Ban.

13. Commonwealth of Massachusetts. 2017b. Master List of Solid Waste Facilities in Massachusetts, 2017.

14. Commonwealth of Massachusetts. 2017c. Net Metering. Vol. 220 CMR 18.00.

15. Commonwealth of Massachusetts. 2018. Net Metering Guide.

16. Cook, J. 2017. Sites Accepting Diverted Food Waste. Massachusetts Department of Environmental Protection.

17. Cousens, C. R. 2016. MassDEP Non-major Comprehensive Plan Application. Air Permit Application Transmittal No.: X268418, Application No.: NE-15-017. Greater Lawrence Sanitary District.

18. Crawford, M., J. Church, and B. Akin. 2017. CPI Detailed Report: Data for January 2017. Bureau of Labor Services.

19. Daelman, M. R., E. M. van Voorthuizen, L. G. van Dongen, El. Volcke, and M. C. van Loosdrecht. 2013. Methane and Nitrous Oxide Emissions from Municipal Wastewater Treatment–Results from a Long-Term Study. Water Science Technology 67: 2350–2355. doi:10.2166/wst.2013.109.

20. De Klein, C., R. S. A. Novoa, S. Ogle, K. A. Smith, P. Rochette, and T. C. Wirth. 2006. N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application. Volume 4: Agriculture, Forestry and Other Land Use. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC.

21. DOER. 2016. Guideline on Metering and Calculating the Useful Thermal Output of Eligible Renewable Thermal Generation Units - Part 2. Commonwealth of Massachusetts.

22. EBMUD. 2008. Anaerobic Digestion of Food Waste. U.S. Environmental Protection Agency EPA-R9-WST-06-004. East Bay Municipal District.

23. Emmerson, R. H. C., G. K. Morse, J. N. Lester Ph. D., and D. R. Edge. 1995. The Life-Cycle Analysis of Small-Scale Sewage-Treatment Processes. Water and Environment Journal 9: 317–325. doi:10.1111/j.1747-6593.1995.tb00945.x.

24. Enerdata. 2017. Global Energy Statistical Yearbook 2017.

25. ERG. 2017. Quality Assurance Project Plan for Life Cycle Considerations and Systems Analyses of Municipal Water Sustainability Assessments. EP-C-16-015; 0003. U.S. Environmental Protection Agency.

26. Favoino, E., and D. Hogg. 2008. The potential role of compost in reducing greenhouse gases. Waste Management and Research 26: 61–69. doi:10.1177/0734242X08088584.

27. Fillmore, L. 2017. Personal communication: Lauren Fillmore, of WE&RF.

28. Fischer, J. 2017. Personal Communication: John Fischer.

29. Frischknecht, R., N. Jungbluth, H.-J. Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, et al. 2005. The ecoinvent Database: Overview and Methodological Framework. The International Journal of Life Cycle Assessment 10: 3–9. doi:10.1065/lca2004.10.181.1.

30. 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. doi:10.1016/S0960-8524(03)00060-9.

31. Fuller, S. K., and S. R. Petersen. 1996. Life-Cycle Costing Manual for the Federal Energy Management Program. U.S. Department of Commerce NIST handbook 135. Washington, D.C.: National Institute of Standards and Technology.

32. Goedkoop, M., R. Heijungs, M. Huijbregts, A. De 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 the endpoint level: Report 1 Characterization.

33. Goedkoop, M., R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. van Zelm. 2013. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report 1 Characterisation. ReCiPe version 1.08.

34. GreenDelta. 2016. OpenLCA Version 1.6.3. English (version 1.6.3). Berlin, Germany: GreenDelta.

35. Harris, R. W., M. J. Cullinane, and P. T. Sun. 1982. Process Design and Cost Estimating Algorithms for the Computer Assisted Procedure for Design and Evaluation of Wastewater Treatment Systems (CAPDET). U.S. Environmental Protection Agency PB82-190455. Washington, D.C.: U.S. Environmental Protection Agency.

36. Hellebrand, H. J. 1998. Emission of Nitrous Oxide and other Trace Gases during Composting of Grass and Green Waste. Journal of Agricultural Engineering Research 69: 365–375. doi:10.1006/jaer.1997.0257.

37. 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: 1011–1018.

38. Henricks, M. 2014. More states ban organic waste in landfills. Trade. American Recycler News, Inc.

39. Hischier, R., B. Weidema, H.-J. Althaus, C. Bauer, G. Doka, R. Dones, R. Frishknecht, S. Hellweg, et al. 2010. Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3. St. Gallen: Ecoinvent Centre.

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

41. Hydromantis. 2017. GPS-X® Version 7.0.1 Software.

42. IPCC. 2006. IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Japan: Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme.

43. ISO. 2006a. ISO 14040: Environmental management — Life cycle assessment — Principles and framework. ISO 14040:2006(E). The International Organization for Standardization.

44. ISO. 2006b. ISO 14044: 2006 Environmental management -- Life cycle assessment -- Requirements and guidelines. ISO 14044:2006(E). ISO 14044. The International Organization for Standardization.

45. Komilis, D. P., and R. K. Ham. 2004. Life-Cycle Inventory of Municipal Solid Waste and Yard Waste Windrow Composting in the United States. Journal of Environmental Engineering 130: 1390–1400. doi:10.1061/(ASCE)0733-9372(2004)130:11(1390).

46. Lavappa, P. D., J. D. Kneifel, and E. O'Rear. 2017. Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis – 2017 Annual Supplement to NIST Handbook 135. NISTIR 85-3273-32. National Instititute of Standards and Technology.

47. Layzer, J. A., and A. Schulman. 2014. Municipal Curbside Compostables Collection: What Works and Why? Massachusetts Institute of Technology.

48. Lippiatt, B. C., J. Kneifel, P. Lavappa, S. Suh, and A. L. Greig. 2013. Building Industry Reporting and Design for Sustainability (BIRDS): Technical Manual and User Guide. NIST Technical Note 1814. National Institute of Standards and Technology.

49. MA DLS. 2019. Municipal Database: Tax Rates by Class. Massachusetts Department of Revenue, Division of Local Services. Municipal Database: Tax Rates by Class. February 11.

50. Ma, J., K. Wilson, Q. Zhao, G. Yorgey, and C. Frear. 2013. Odor in Commercial Scale Compost: Literature Review and Critical Analysis. 13-07–066. Washington State Department of Ecology.

51. MassDEP. 2012. 310 CMR 16.00: Site Assignment Regulations for Solid Waste Facilities.

52. MassDEP. 2015. Loans from the Massachusetts State Revolving Fund. Massachusetts Department of Environmental Protection.

53. MassDEP. 2017. MassDEP Organics Study and Action Plan. Massachusetts Department of Environmental Protection.

54. 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. doi:10.1016/j.biortech.2013.07.118.

55. McCarty, P. L., J. Bae, and J. Kim. 2011. Domestic Wastewater Treatment as a Net Energy Producer–Can This be Achieved? Environmental Science & Technology 45: 7100–7106. doi:10.1021/es2014264.

56. MDAR. 2011. Guide to Agricultural Composting. Boston, MA: Massachusetts Department of Agricultural Resources.

57. Morelli, B., S. Cashman, C. Ma, J. Garland, D. Bless, and J. Cashdollar. 2017. Environmental Life Cycle Assessment and Cost Analysis of Bath, NY Wastewater Treatment Plant: Potential Upgrade Implications. EPA/600/R-17/207. U.S. Environmental Protection Agency.

58. NASS. 2016. 2015 Agricultural Chemical Use Survey Wheat. United States Department of Agriculture.

59. Nemecek, T., and T. Kägi. 2007. Life Cycle Inventories of Agricultural Production Systems. Ecoinvent No. 15. Zurich and Dubendorf: Agrosope Research Station (ART).

60. 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: 79–101.

61. NREL. 2012. U.S. Life Cycle Inventory Database.

62. O2 Compost. 2015. Aerated Static Pile Compost Pilot Project and Operator Training Program. City of Walla Walla, Washington.

63. Ong, M. D., R. B. Williams, and S. R. Kaffka. 2017. Comparative Assessment of Technology Options for Biogas Clean-up. 500-11–020. Davis, California: California Energy Commission.

64. Pachauri, R. K., and A. Reisinger. 2007. IPCC Fourth Assessment Report. Intergovernmental Panel on Climate Change.

65. Parnaudeau, V., B. Nicolardot, and J. Pagès. 2004. Relevance of Organic Matter Fractions as Predictors of Wastewater Sludge Mineralization in Soil. Journal of Environment Quality 33: 1885–1894.

66. PES and UTS. 2009. Energy Evaluation for the Greater Lawrence Sanitary District Wastewater Treatment Facility and Riverside Pump Station. Process Energy Services, LLC and UTS Energy Engineering, LLC.

67. Pipatti, R., J. W. S. Alves, Q. Gao, C. Cabrera, K. Mareckova, H. Oonk, E. Scheehle, C. Sharma, et al. 2006. Biological Treatment of Solid Waste. In IPCC Guidelines for National Greenhouse Gas inventories. Vol. 5. Intergovernmental Panel on Climate Change.

68. Razza, F., M. Fieschi, F. D. Innocenti, and C. Bastioli. 2009. Compostable cutlery and waste management: an LCA approach. Waste Management 29: 1424–1433. doi:10.1016/j.wasman.2008.08.021.

69. Richard, T. 2014. Moisture and Carbon/Nitrogen Ratio Calculation Spreadsheet. Cornell University.

70. Rigby, H., B. Clarke, D. L. Pritchard, B. Meehan, F. Beshah, S. R. Smith, and N. A. Porter. 2016. A critical review of nitrogen mineralization in biosolids-amended soil, the associated fertilizer value of crop production and potential for emissions to the environment. Science of The Total Environment 541: 1310–1338.

71. ROU. 2007. Life Cycle Inventory and Life Cycle Assessment for Windrow Composting Systems. New South Wales Department of Environment and Conservation.

72. RSMeans; 2016. Building Construction Cost Data.

73. RTI International. 2012. Municipal Solid Waste Decision Support Tool. Windows (version 1.0). RTI International.

74. Ryberg, M. W., J. Bare, M. D. M. Vieira, and R. K. Rosenbaum. 2014. Updated US and Canadian normalization factors for TRACI 2.1. Clean Technologies and Environmental Policy 16: 329–339. doi:10.1007/s10098-013-0629-z.

75. Saer, A., S. Lansing, N. H. Davitt, and R. E. Graves. 2013. Life cycle assessment of food waste composting system: environmental impact hotspots. Journal of Cleaner Production 52: 234–244. doi:10.1016/j.jclepro.2013.03.022.

76. Shah, A., M. Joiner, L. Fillmore, D. Checkel, J. Willis, and D. Handford. 2011. Quantifying Fugitive Methane Emissions From Gas Flares: WERF's New Flare Efficiency Estimator. In , 13:486–498. Water Environment Federation.

77. Smith, S. R., and E. Durham. 2002. Nitrogen Release and Fertiliser Value of Thermally-Dried Biosolids. Water and Environment Journal 16. 121-126.

78. Sundberg, C., I. H. Franke-Whittle, S. Kauppi, D. Yu, M. Romantschuk, H. Insam, and H. Jönsson. 2011. Characterisation of source-separated household waste intended for composting. Bioresource Technology 102: 2859–2867. doi:10.1016/j.biortech.2010.10.075.

79. SYLVIS. 2011. Biosolids Emissions Assessment Model (BEAM): Version 1.1. Canadian Council of Ministers of the Environment.

80. Tarallo, S., A. Shaw, P. Kohl, and R. Eschborn. 2015. A Guide to Net-Zero Energy Solutions for Water Resource Recovery Facilities. IWA Publishing.

81. Tchobanoglous, G., H. D. Stensel, R. Tsuchihashi, F. Burton, M. Abu-Orf, G. Bowden, and W. Pfrang. 2014. Wastewater Engineering Treatment and Resource Recovery. 5th ed. New York, NY: McGraw-Hill Education.

82. Tiquia, S. M., T. L. Richard, and M. S. Honeyman. 2002. Carbon, nutrient, and mass loss during composting. Nutrient Cycling in Agroecosystems 62: 15–24. doi:10.1023/A:1015137922816.

83. UNFCCC. 2012. Clean Development Mechanism: Methodological Tool, Project and leakage emissions from anaerobic digestion. UNFCCC EB 66, Annex 32. CDM Methodology.

84. U.S. DOL. 2016. May 2016 Natioanl Industry-Specific Occupational Employment and Wage Estimates, NAICS 325300 - Pesticide, Fertilizer, and Other Agricultural Chemical Manufacturing. U.S. Department of Labor. United States Department of Labor Bureau of Labor Statistics.

85. US EIA. 2019. Gasoline and Diesel Fuel Update. U.S. Energy Information Administration. Gasoline and Diesel Fuel Update. February 11.

86. U.S. EPA. 1984. Septage Treatment and Disposal. U.S. Environmental Protection Agency.

87. U.S. EPA. 2014. Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Tables and Figures for 2012.

88. U.S. EPA. 2015a. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013. EPA 430-R-15-004.

89. U.S. EPA. 2015b. ORD LCA Database. LCA Research Center, National Risk Management Research Laboratory.

90. U.S. EPA. 2016. Discharge Monitoring Report Pollutant Loading Tool. Environmental Protection Agency.

91. U.S. EPA. 2017a. Examples and Resources for Transforming Waste Streams in Communities (#1-50). Government. Managing and Transforming Waste Streams - A Tool for Communities. November 24.

92. U.S. EPA. 2017b. Landfill Gas Energy Project Data: Detailed file of currently operational projects. Landfill Methane Outreach Program (LMOP). June.

93. U.S. EPA. 2017c. Landfill Technical Data: Landfill-level data only. Government. Landfill Methane Outreach Program (LMOP). June.

94. U.S. EPA, and MADEP. 2005. National Pollutant Discharge Elimination System Permit No. MA0100447: Greater Lawrence Sanitary District. U.S. Environmental Protection Agency and Massachusetts Department of Environmental Protection.

95. Varnier, D. J., and R. Saidur. 2004. Life Cycle Cost Analysis as a Decision Support Tool for Managing Municipal Infrastructure. In .

96. Wassam, J. 2018. Personal Communication with John Wassam, RPS and APS Program Manager.

97. van Welie, G. 2017. State of the Grid: 2017 January 30.

98. Wiser, J. R., P. E., J. W. Schettler P. E., and J. L. Willis P. E. 2010. Evaluation of Combined Heat and Power Technologies for Wastewater Treatment Facilities. EPA 832-R-10-006. U.S. Environmental Protection Agency.

99. World Bank. 2017. Population, Total.

Appendix A:
Composting and Land Application of Food Waste:
A Comparison with Anaerobic Co-Digestion at a Wastewater Treatment Facility

Appendix A
Composting and Land Application of Food Waste: A Comparison with Anaerobic Co-Digestion at a Wastewater Treatment Facility

Introduction

As industries and institutions shift from the paradigm of waste disposal to that of resource recovery, it becomes apparent that EOL decisions shift from a conversation centered on minimizing impact to one that productively considers opportunities to maximize environmental benefit. This new paradigm looks at "waste" as a resource.

In light of the Massachusetts landfill and incineration ban on organic materials from large industrial and institutional producers, several industries are vying for the opportunity to utilize abundant organic waste streams. In this Appendix to the main report, we analyze composting as an alternative disposal pathway for SSO waste (i.e., food waste). To do this we isolate inputs, emissions and costs associated with GLSD's WWTF that can be directly attributed to the addition of co-digestion capacity and the processing of SSO waste. We then compare co-digestion impacts and costs against food waste management through windrow and aerated static pile (ASP) compost systems. LCA results were also generated for food waste landfilling and WTE combustion as a reference for other regions and waste generators not subject to the waste ban. No cost data were compiled for the landfill and WTE disposal options.

While five treatment and disposal options are compared in this analysis, as of 2017 the selection process is not an either-or proposition. The Massachusetts Department of Environmental Protection (MassDEP) estimates that organic material comprises greater than 25 percent of the solid waste stream. The state's goal to divert 35 percent of food waste by 2020 indicates an annual food waste diversion rate of 350,000 tons per year (MassDEP 2017). Currently, the generation of food waste is expected to exceed the capacity of compost, AD and other food waste recycling facilities regionally (Layzer and Schulman 2014). Regardless of the theoretical surplus, existing facilities may experience supply shortages due to competition or insufficient food waste collection systems.

Analysis Scope

This section introduces the system boundaries of the food waste disposal comparison. The functional unit for this analysis was defined as treatment of one kg of disposed food waste (gate-to-grave). Table A-1 lists the scenarios included in the food waste disposal comparison. The baseline scenarios for the compost and AD systems are highlighted in bold.

Table A-1. Summary of Compost Comparison Scenarios

Disposal Method	System Performance	Transport Distance
Windrow	Improved Performance	Local
		Regional
	Base Performance	**Local**
		Regional
Aerated Static Pile	Improved Performance	Local
		Regional
	Base Performance	Local
		Regional
Anaerobic Digestion	Low Performance	**Actual**
	Base Performance	

Notes: Baseline scenario values highlighted in bold. The base performance scenario represents the average environmental impact of composting facility operation. The improved performance scenario represents a well-managed compost facility with reduced energy use and GHG emissions. Transport scenarios are introduced in Table A-5 and associated text. The local transport scenario was based on existing facilities in Eastern Massachusetts. The regional scenario is a hypothetical scenario that assumes local capacity is insufficient to meet compost capacity demands, requiring further transport.

Food waste is sourced from commercial and industrial sources. When destined for AD, the food waste is first processed into an engineered bioslurry that removes contamination and standardizes the material, allowing consistent performance of the digesters. The full capacity AD scenario processes 92,000 gallons of SSO per day, which corresponds to approximately 154,000 kg of food waste per day, or 0.42 kg of food waste (wet mass) per kg of SSO. Food waste was assumed to have a solids content of 31 percent (Sundberg et al. 2011).

Windrow composting is currently the most common composting method practiced in Massachusetts based on our assessment of facilities in the Eastern half of the state. The use of ASP compost systems is less common but is practiced by at least one facility that accepts diverted food waste (Cook 2017).

Compost performance scenarios encompass process GHG emissions and energy consumption estimates. The composting base performance scenarios correspond to average emission and energy consumption values found in the literature. The improved performance scenario corresponds to the 25th percentile of emission and energy consumption values. For the AD unit process, the performance scenarios correspond to the original low and base AD performance scenarios detailed in the main study report. AD system performance primarily affects biogas production, the corresponding mix of on-site combustion process use and avoided energy products.

Local and regional transport distance scenarios were analyzed for both compost methods. The local transport distance was calculated based on the location of the 20 composting facilities that are nearest to the Boston metro region (Cook 2017). The regional transport scenario assumes a hypothetical transport distance that is three times the value used in the local scenario and is included due to questions about the availability of sufficient local composting capacity. Regional transport assumptions are assessed in a sensitivity analysis.

Compost System Boundaries

Figure A-1 depicts system boundaries for both the windrow and ASP composting systems. Transportation of waste to the compost or WWTF varies among the three options and is included within the system boundaries.

Both compost management systems require active management to ensure adequate material degradation, pile temperatures and low to average process emissions. Energy use estimates required for facility operation were included in the LCI and are discussed in detail in the section on LCI development in this Appendix. Initial moisture content of the compost pile is typically established in a range of between 50 to 60 percent weight/weight. The initial carbon to nitrogen ratio (C:N) of material in the compost pile should also be kept within a standard range of between 20:1 and 45:1 (Christensen 2009; Brewer et al. 2013), with 30:1 being optimal (MDAR 2011). Table A-2 lists a typical material composition of food waste.

Due to the high nitrogen and moisture content of food waste, a considerable quantity of carbon rich organic material is required for successful composting. However, this LCI and the associated impacts were solely based on the material composition of the food waste, assuming the other organic materials will be readily available and would be destined for composting regardless of food waste EOL management decisions.

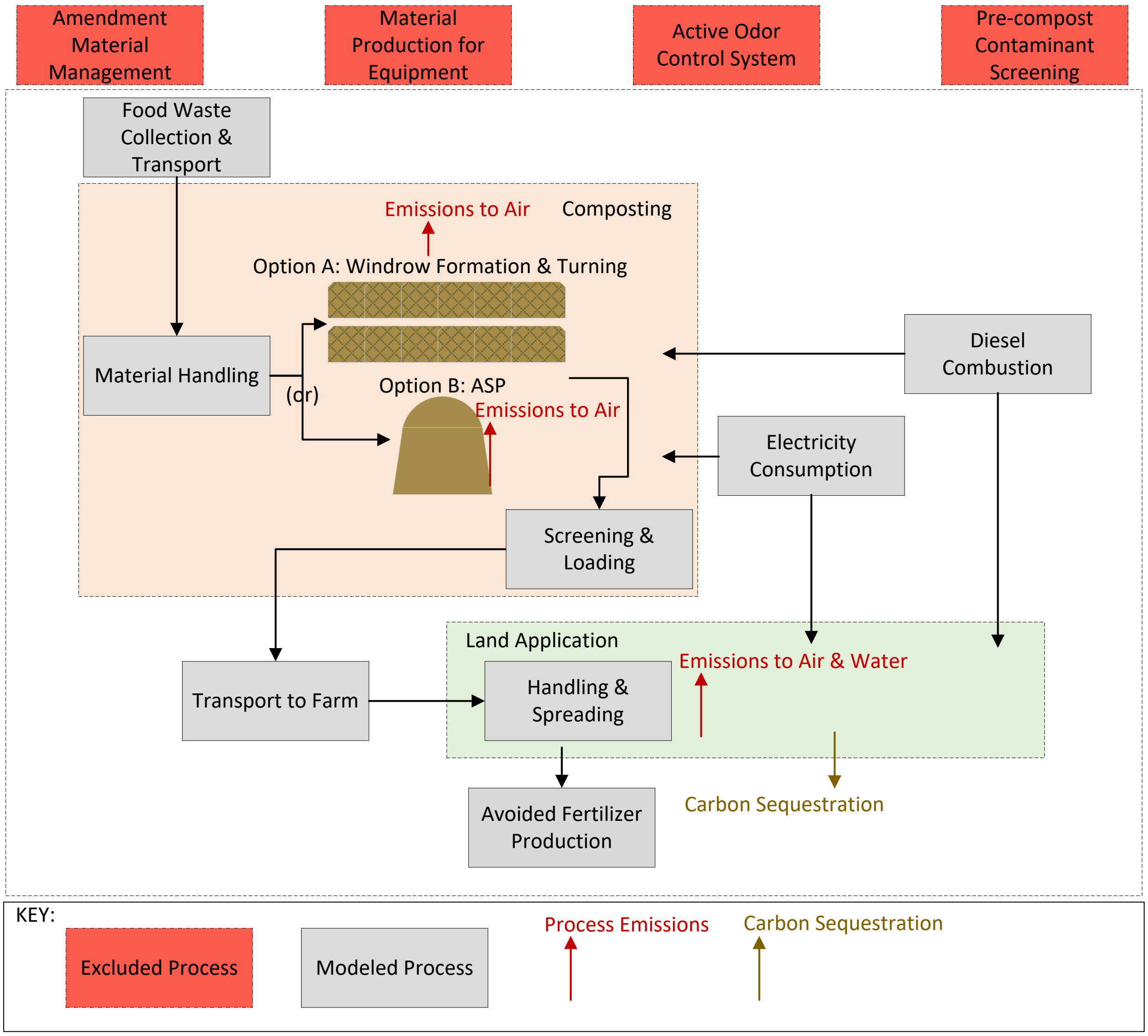


Figure A-1. System diagram of composting and land application processes.

Table A-2. Assumed Material Composition and Moisture Content of Collected Food Waste

Parameter	Units	Value	Source
Carbon Content	% dry mass	44%	(Boldrin et al. 2009; Richard 2014)
Nitrogen Content	% dry mass	2.5%	Calculated from (Richard 2014)
Phosphorus Content	% dry mass	0.90%	(ROU 2007)
C:N Ratio	unitless	18	Calculated
Moisture Content	% wet mass	69%	(Sundberg et al. 2011)
Dry Mass	kg dry/kg wet	31%	Calculated

Carbon (C), nitrogen (N) and phosphorus (P) present in the food waste can lead to pollutant emissions during the composting process and are a source of beneficial nutrients in the finished compost. Carbon-based compost process emissions of methane (CH_4) and carbon monoxide (CO) were included in the LCI. Carbon dioxide (CO_2) emissions are also emitted during composting but were excluded from the inventory as the carbon is biogenic in origin and will not contribute to net global warming potential. Compost methane emissions are also derived from biogenic carbon, but are included because they still contribute to GWP, having a greater GWP than CO_2 per unit carbon. Nitrous oxide (N_2O) and ammonia (NH_3) emitted from the compost pile were also estimated for the inventory as a function of food waste N content.

Diesel combustion and electricity consumption required for facility operation were included in the LCI. Sources of energy consumption within the compost facilities include material handling, windrow turning, screening, administrative space conditioning and blowers for the ASP process. Electricity consumption for shredding, prior to composting, was excluded from the inventory as it is not expected to be required for food waste.

Based on conversations with several local facilities, it does not appear that pre-compost screening or ventilated odor control strategies are standard in current regional practice. Given this, such processing steps have been excluded from the analysis. However, many facilities expressed reservations about accepting additional sources of food waste as residential and restaurant collection were perceived to be potentially high in contaminants. If this remains the case, and considerable additional compost processing capacity is pursued, additional contaminant removal steps may be required in the future.

Based on conversations with Boston-area compost facilities, it does not appear that installation of leachate management systems is common practice in this region. Alternatively, facility managers and regulators have indicated that use of grass buffer regions has proved sufficient to allow adequate infiltration, thereby preventing runoff from compost facilities. No leachate collection system materials, energy use, or emissions were included in the LCI. Other authors have noted that leachate production can be considered negligible at well managed facilities (Komilis and Ham 2004).

Material production and assembly for mechanical equipment (e.g., ASP piping and compost turner) were excluded from the analysis (ROU 2007; Saer et al. 2013). Mechanical equipment materials are expected to contribute little to the impact per unit of food waste processed over the equipment's expected lifespan. The same assumption was used for mechanical equipment within the WWTF. Infrastructure for the compost administration building is included in the compost LCIs, as was new infrastructure for the added AD capacity in the GLSD LCI.

Transportation of finished compost in the base performance scenario was estimated using the same distance assumption as that originally developed for trucking of pelletized biosolids to the site of land application, 121 km. Due to uncertainty regarding this assumption, a shorter transport distance of 60 km was assumed in the improved performance scenario. Compost is applied as an agricultural amendment, leading to field emissions and avoiding the production and use of chemical fertilizers. A carbon credit was applied for the estimated fraction of carbon in the compost that remains in the soil beyond 100 years.

Adaptation of GLSD Wastewater Treatment Facility System Boundaries

To directly compare compost and co-digestion food waste management options, the WWTF low and base AD LCI models from the main study report were adjusted to reflect only the portion of treatment plant impact that is attributable to SSO processing. Annual input and output quantities used to develop the original LCI were scaled and recalculated to be based on the updated functional unit, 1 kg of food waste treated, by dividing annual LCI and cost inputs and outputs by the annual quantity of food waste within the SSO accepted at the WWTF.

Not all treatment processes at the WWTF are considerably affected by the decision to accept SSO for co-digestion with municipal solids. Table A-3 summarizes the adjustments made to individual unit process LCIs throughout the GLSD WWTF. The influent pump station, preliminary and primary treatment processes, secondary clarification and plant water and disinfection were assumed not to incur additional operational input requirements as a result of accepting SSO. The influent pump station, bar screening and grit removal are bypassed altogether by the SSO material, which is received, stored temporarily and pumped directly into the AD tanks. The clarifiers, plant water and disinfection processes demand operational energy and chemical use primarily on a volume basis of wastewater treated, which is only marginally affected by the decision to accept SSO (less than 0.5 percent of influent water volume).

Table A-3. Adjustment of Unit Process LCI Data for Compost Comparison.

Treatment Group	Unit Process Name	Compost Comparison Adjustment
Influent pump station	Influent pump station	Excluded
Preliminary/primary	Screening and grit removal	Excluded
	Primary clarification	Excluded
Biological treatment	Pre-anoxic tank	Scaled[1]
	Aeration basins	Scaled[1]
	Secondary clarification	Excluded
Plant water and disinfection	Plant water and disinfection	Excluded
Sludge dewatering	Gravity belt thickener	Scaled[1]
	Gravity thickener	Scaled[1]
	Centrifuge	Scaled[1]
Anaerobic digestion and CHP	SSO transport and processing	Included
	Anaerobic digestion	Scaled[2] [Base AD factor – 78%] [Low AD factor – 69%]
	Combined heat and power	
Pellet drying	Biosolids drying and pelletization	Scaled[1]
Land application	Land application of biosolids pellets	Scaled[1]
Effluent release	Effluent release; to surface water	Scaled[1]
Building operation	Administration building utilities	Excluded

[1] Food Waste LCI value = (Full Capacity LCI value – Baseline LCI value)

[2] Food Waste LCI values affected by the installation of CHP are scaled based on food waste's fraction of biogas production, which are 78 percent and 69 percent in the base and low AD performance scenarios, respectively. Food Waste LCI value = (Full Capacity LCI value * ($Biogas_{FC}$-$Biogas_{base}$)/$Biogas_{FC}$)). $Biogas_{FC}$ = biogas production in the full capacity scenario, $Biogas_{base}$ = Biogas production in the baseline scenario.

Other unit processes, particularly the solids processing and AD units, are directly affected by food waste acceptance. Previously calculated LCI values for these unit processes were scaled to reflect the difference in solids acceptance and associated biogas production attributable to SSO co-digestion and the AD and CHP expansion project. Many of the food waste specific LCI values were calculated by subtracting baseline LCI quantities (without food waste) from corresponding full capacity LCI values and dividing by the new reference flow of total food waste treated. This approach is sufficient for input parameters that are not affected by the installation of CHP at the WWTF (e.g., AD and aeration electricity consumption, ferric chloride use and pellet drying heat demand).

The installation of a CHP system at the GLSD WWTF coincided with the decision to accept SSO waste. Changes to the LCI that result from CHP installation are therefore not wholly attributable to SSO acceptance, and another approach was required to accurately allocate the associated LCI values between the SSO and municipal sewage. Installation of CHP at the WWTF affects the relative fraction of biogas that is utilized in the various on-site combustion processes. The quantity of biogas produced is itself independent of CHP installation. Biogas combustion, and the associated avoided energy products, is therefore scaled by the fraction of biogas production attributable to SSO acceptance, which in the full capacity-base AD performance scenario is 78 percent. This means that 78 percent of avoided electricity production was attributed to the additional food waste processed at the GLSD WWTF. Infrastructure materials associated with the added AD capacity and SSO pre-processing and transport were allocated completely to SSO.

Finally, it is necessary to remove the avoided EOL burdens for WTE and landfilling from the AD unit process. In the results presented per kg of food waste, we are directly comparing EOL treatment options, and avoided disposal burdens can be excluded from the analysis scope, as they would not differ between the compared AD and composting options. The main analysis takes a more indirect approach to the comparison of EOL treatment options, instead focusing on net environmental impact per m^3 of treated wastewater.

Using the above approaches, the new inventory isolates the environmental benefits and burdens of accepting SSO for co-digestion at an existing WWTF, allowing a direct comparison with windrow and ASP composting that serve as alternative options for food waste EOL disposal.

Compost - Life Cycle Inventory Development

As of 2017, there were at least 30 composting facilities permitted to handle food waste in Massachusetts. Table A-4 lists 20 composting facilities that are nearest to the Boston metro region (Cook 2017), their distance from downtown and an estimate of potentially available capacity. These facilities were used to estimate the transport distance for the local transport scenario. Available capacity was estimated to be 30 percent of permitted capacity, based on conversations with contact persons from several local compost facilities. Total estimated capacity was based on contact with facility personnel when possible. In the absence of site specific information, farm-based compost operations were assumed to operate under the general permit, allowing them to accept 95 metric tons (Mg) of food waste (105 U.S. tons) per week (MassDEP 2012). For dedicated composting facilities operating on a solid waste permit, a value of 150 Mg/week was assumed as the estimated capacity. Transport distances were estimated using Google Maps and address information associated with individual compost facilities (Cook 2017). Table A-4 shows that using the above assumptions, 20 composting facilities are required to process the volume of food waste treated in the full capacity AD scenario. Available capacity for handling food waste via composting is speculative as the facilities contacted were concerned about the impact of additional contamination on facility operation and quality of the final compost. Several facilities indicated that if contamination cannot be controlled, they are not interested in accepting additional food material.

Table A-4. Estimated Capacity and Distance of Compost Facilities Nearest to Boston

Facility Number	Estimated Capacity (Mg/week)	Available Capacity	Transport Distance, km[1]
Facility 1[2]	95	30%	61
Facility 2	150	30%	55
Facility 3[2]	91	30%	49
Facility 4	95	30%	109
Facility 5	95	30%	71
Facility 6	95	30%	91
Facility 7	150	30%	78
Facility 8	95	30%	62
Facility 9	95	30%	115
Facility 10[2]	64	30%	71
Facility 11	95	30%	34
Facility 12[2]	872	30%	85
Facility 13[2]	30	0%	31
Facility 14	95	30%	69
Facility 15	95	30%	105
Facility 16	95	30%	78
Facility 17	95	30%	22
Facility 18[2]	0	30%	25
Facility 19	95	30%	78
Facility 20[2]	939	30%	39
Estimated Available Capacity[3]	1,020	Mg/week	
Required Available Capacity[4]	1,080	Mg/week	

[1] Transport distance was estimated from city center.

[2] Indicates a conversation with facility personnel.

[3] Estimated available capacity was estimated as the ∑(estimated capacity*available capacity) for the 20 local composting facilities. Estimated available capacity does not exactly match required capacity, as it is only a rough estimate and could in practice move considerably up or down.

[4] Required available capacity was based on the food waste quantity processed in the GLSD full capacity AD scenario.

Table A-5 lists distances associated with the two compost transport scenarios. An estimated collection route distance of 20 km was included for compost and WWTF disposal scenarios (included in Table A-5). Transport distance for the local transport scenario was estimated to be 61 km, based on a weighted average of the available capacity data presented in Table A-4. The regional transport scenario assumes a hypothetical transport distance that is three times the value used in the local scenario and is intended to represent out-of-state and/or regional transport.

Table A-5. Total Food Waste Transport Distances

Transport Scenario	Distance (km)
Compost – Local[1]	81
Compost – Regional	203

[1] Total transport distance is the sum of collection route distance (20 km) plus transport from end-of-route to the compost facility.

Food waste to be composted is received and immediately mixed with absorbent material to help control odors. Unlike yard waste, it is essential that food waste be mixed with absorbent, carbonaceous materials quickly (Christensen 2009). No shredding or grinding of source separated food waste is typically employed. Diesel use for material handling at receiving was included in the LCI (ROU 2007). Table A-6 presents a summary of calculated LCI values for the four compost LCA scenarios.

Additional diesel fuel use was included for windrow turning (Komilis and Ham 2004; ROU 2007; Saer et al. 2013) and loading of finished compost (ROU 2007). Inclusive electricity consumption factors from Boldrin et al. (2009) were used to estimate electricity use at the windrow and ASP compost facilities. Electricity consumption estimates include pre- and post-screening, administrative facility operation and aeration energy for ASP.

Methane emissions from windrow composting were estimated using a calculated average emission factor of 0.0082 kg CH_4-C/kg C entering the compost pile (Hellmann et al. 1997; Hellebrand 1998; Fukumoto et al. 2003; Pipatti et al. 2006; Amlinger et al. 2008; Boldrin et al. 2009; SYLVIS 2011; Maulini-Duran et al. 2013) or 0.82 percent of carbon in the compost feedstock. No methane emissions are expected from the ASP system due to the use of active aeration and biofilter venting to ensure oxidation of any methane that might form in anaerobic pockets within the compost pile (SYLVIS 2011). Carbon monoxide, nitrous oxide, ammonia and NMVOC emissions are not expected to be affected by the biofilter and were assumed to be the same for both composting methods. Sources used to develop process emission LCI values are presented in footnotes to Table A-6. The 25th percentile of values taken from the cited references was used to estimate values for the improved performance scenario. A mass loss of 58 percent was estimated during the compost process (Tiquia et al. 2002; Fukumoto et al. 2003; Razza et al. 2009; Saer et al. 2013), which affects the quantity of compost that is ultimately land applied.

A transport distance of 121 km was assumed from the compost facility to the land application site, the same as that used for transportation of pelletized biosolids to the site of land application. A shorter transport distance of 60 km was assumed in the improved performance scenario.

Diesel use was included for field application of compost. Compost application avoids the production of the chemical fertilizers urea and single superphosphate based on equivalent, available N and P content. A phosphorus fertilizer replacement value of 95 percent was assumed (Boldrin et al. 2009). A cumulative fertilizer replacement value of 55 percent was assumed for compost nitrogen content. The nitrogen fertilizer replacement value assumes that 40 percent of land applied nitrogen is plant available in year one (Smith and Durham 2002). In years two and three, an additional 10 percent and 5 percent of nitrogen content mineralize and become plant available (Rigby et al. 2016).

Table A-6. Compost and Land Application Life Cycle Inventory

Basic Input	Detailed Use	Windrow		ASP		Units
		Base Performance	*Improved Performance*	*Base Performance*	*Improved Performance*	
		Composting				*per kg wet feedstock*
Diesel use	Material receiving[1]	4.80E-4	4.80E-4	4.80E-4	4.80E-4	liters
	Windrow formation & turning[2]	4.99E-4	2.99E-4	-	-	liters
	Compost loading for transport[1]	3.00E-5	3.00E-5	3.00E-5	3.00E-5	liters
Electricity use	Total[3]	9.86E-3	4.94E-3	0.037	0.023	kWh
Process emissions	Ammonia[4]	4.06E-4	8.35E-5	4.06E-4	8.35E-5	kg NH_3
	Methane[5]	1.50E-3	3.10E-4	-	-	kg CH_4
	Nitrous oxide[6]	1.54E-4	3.14E-5	1.54E-04	3.14E-05	kg N_2O
	NMVOCs[7]	1.04E-4	6.85E-5	1.04E-4	6.85E-5	kg NMVOC
	Carbon monoxide[8]	1.27E-4	1.27E-4	1.27E-4	1.27E-4	kg CO
		Land Application				*per kg compost[9]*
Transport	To agricultural field	0.121	0.060	0.121	0.060	tkm
Diesel use	Compost application[1]	1.06E-3	7.07E-4	1.06E-3	7.07E-4	liters
Field Emissions	Ammonia, to air[10]	5.30E-4	3.54E-4	5.30E-4	3.54E-4	kg NH_3
	Nitrous oxide, to air[11]	1.91E-4	1.27E-4	1.91E-4	1.27E-4	kg N_2O
	NOx, to air[12]	8.39E-5	5.59E-5	8.39E-5	5.59E-5	kg NOx
	Nitrate, to water[11]	8.29E-3	5.53E-3	8.29E-3	5.53E-3	kg NO_3

Table A-6. Compost and Land Application Life Cycle Inventory

Basic Input	Detailed Use	Windrow		ASP		Units
		Base Performance	***Improved Performance***	***Base Performance***	***Improved Performance***	
	Phosphorous, to surfacewater[12]	3.94E-5	2.63E-5	3.94E-5	2.63E-5	kg P
	Phosphorous, to groundwater[12]	1.29E-6	8.62E-7	1.29E-6	8.62E-7	kg P
Avoided products	Urea[13]	7.63E-3	5.08E-3	7.63E-3	5.08E-3	kg (as N)
	Single superphosphate[14]	0.012	7.84E-3	0.012	7.84E-3	kg (as P_2O_5)
Carbon Sequestration	Storage beyond 100 years[15]	0.051	0.119	0.051	0.119	kg CO_2

[1] (ROU 2007)

[2] (Komilis and Ham 2004; ROU 2007; Saer et al. 2013)

[3] (Boldrin et al. 2009)

[4] (Hellebrand 1998; Fukumoto et al. 2003; Maulini-Duran et al. 2013)

[5] (Hellmann et al. 1997; Hellebrand 1998; Fukumoto et al. 2003; Pipatti et al. 2006; Amlinger et al. 2008; Boldrin et al. 2009; SYLVIS 2011; Maulini-Duran et al. 2013)

[6] (Hellmann et al. 1997; Hellebrand 1998; Fukumoto et al. 2003; Pipatti et al. 2006; Boldrin et al. 2009; Maulini-Duran et al. 2013)

[7] (Maulini-Duran et al. 2013)

[8] (Hellebrand 1998)

[9] Mass and carbon loss during composting is accounted for in land application LCI values.

[10] (Goedkoop et al. 2013)

[11] (De Klein et al. 2006)

[12] (Nemecek and Kägi 2007)

[13] (Smith and Durham 2002; Rigby et al. 2016)

[14] (Boldrin et al. 2009)

[15] The amount of land applied carbon remaining in soil after 100 years was estimated using sequestration factors from 3 references (ROU 2007; Favoino and Hogg 2008; Boldrin et al. 2009). Sequestration is estimated as Mg CO_2/Mg C in finished compost and therefore must account for carbon loss during composting. On average 58 percent of incoming wet mass is lost during composting (Tiquia et al. 2002; Fukumoto et al. 2003; Razza et al. 2009; Saer et al. 2013). A large fraction, 74 percent, of mass loss is due to a reduction in pile moisture content (calculated). The complementary fraction, 16 percent, is attributed to the loss of carbon as CO_2, CH_4 and CO. Losses of N and P were assumed to be negligible on a cumulative, wet mass basis.

Landfill and WTE Food Waste Disposal Options

Despite the landfill and incineration material ban on large, commercial producers of food waste in Massachusetts, a considerable fraction of food scraps in the U.S. are still disposed of in landfills and WTE facilities. Environmental result figures included in this Appendix include landfill and WTE disposal options to represent this fraction of food waste. Landfill and WTE LCI data were developed using the MSW DST (RTI International 2012) to model emissions to air and water as described in report Section 3.3.14. Modeled landfill gas management reflects current practice in Massachusetts, where 19 percent of gas is flared and 81 percent is used for energy recovery. Nationally, approximately 24 percent of landfill gas is flared, 68 percent is used for energy recovery, and 8 percent is vented to the atmosphere. Therefore, the results presented in this Appendix should be considered conservative from the perspective of global warming potential.

Life Cycle Cost Assessment

The life cycle costs of food waste disposal are compared per metric ton of food waste disposed over a 30-year time horizon using the LCCA methodology described in Section 4.2. Cost estimates were based on a typical (small) composting facility that operates under a Massachusetts general permit. This permit allows the facility to process 95 Mg (105 U.S. short tons) of food waste per week. Food waste can make up no more than 25 percent of the compost mixture by volume (MassDEP 2012). This corresponds to a total processing capacity of approximately 13,100 Mg/yr, which includes over 4,900 Mg of food waste. The cost analysis focuses only on the food waste being processed at the compost facility and excludes costs associated with yard waste and woody debris processing. Capital costs that apply to both food and yard waste were allocated to the two materials on a volume basis assuming that 25 percent of accepted volume is food waste.

In addition to the cost methodology described in Section 4.2, it was necessary to include several additional cost elements that do not apply in the case of the WWTF retrofit or were unnecessary due to basing WWTF costs on plant records. In particular, we include interest during construction and indirect costs associated with establishing a new compost facility. Table A-7 lists the indirect cost factors applicable to the windrow and ASP compost systems. Indirect cost factors were applied to the sum of year 1 capital costs.

Table A-7. Indirect Cost Factors for Composting Systems

Indirect Cost Elements	Indirect Cost Factor (%)
Miscellaneous Costs	5%
Legal Costs	2%
Engineering Design Fee	15%
Inspection Costs	2%
Contingency	20%
Technical	2%

Sources: (Hydromantis 2014; AACEI 2016)

Interest during construction was assessed using Equation A-1 and a conservative 5 percent interest rate (Komilis and Ham 2004). A two-year construction period was assumed.

$$\text{Interest During Construction} = (\text{Installed Equipment Cost} + \text{Indirect Costs}) \times \text{Construction Period} \times \frac{\text{Interest Rate During Construction}}{2}$$

Equation A-1

The ASP and windrow compost facilities were assumed to process material outdoors without employing advanced odor and leachate processing systems. These assumptions are intended to represent existing facilities in Central and Eastern Massachusetts, but they will not apply in all contexts. For example, a report titled *Odor in Commercial Scale Compost: Literature Review and Critical Analysis* indicates that most larger municipal compost facilities in

Washington State include indoor handling of the initial composting phase, leachate collection and advanced odor control (Ma et al. 2013). These facilities are considerably costlier to operate and are likely to lend themselves to greater process control. Reasons that contribute to these differences in approach include climate conditions, proximity to urban areas, local and state regulations, and public vs. private ownership.

The GLSD LCCA input values were adjusted to reflect the updated system boundaries described earlier in Table A-3.

LCCA results are presented as NPV in dollars per Mg of food waste disposed (2016 $). All system costs were tabulated on an annual basis. Total system NPV (in 2016 $) was divided by the quantity of food waste processed over a 30-year period, allowing comparison between the three food waste management options. The quantity of food waste processed annually is held constant over the 30-year period. Cost input parameters correspond to the base and low cost scenario parameters listed in Table 4-2. Table A-8 lists several additional cost parameters specific to the compost treatment options. Like the cost scenarios defined in the main report, the low cost scenario refers to the combination of cost parameters that lead to lower system NPV. The base cost scenario provides a more conservative estimate of life cycle cost. These cost parameter values are described in detail in the subsequent sections.

Table A-8. Compost Low and Base Cost Parameters

Cost Parameters	Low Cost	Base Cost	Units
Tipping fee, food waste	0.044	0.033	$/kg food waste
Compost value	0.019	0.015	$/kg compost sold
Construction interest rate	3%	5%	of capital cost

An LCI and cost assessment by Komilis and Ham (2004) was the primary source of composting cost data used in the analysis. Cost estimates in that document originally pertained to 1999 and have been adjusted into current (2016) dollars.

Costs Common to Both Compost Methods

Each of the two hypothetical composting facilities was modeled to handle an identical quantity of food and yard waste, leading to several life cycle costs that remain constant across the two systems. Table A-9 summarizes the life cycle costs that apply to both the windrow and ASP composting systems. Both facilities process approximately 4,900 Mg of food waste annually, with typical tipping fees ranging from $20 to $40 per Mg of material accepted. The base and low cost scenarios assume tipping fees of $30 and $40/Mg, respectively. The base cost tipping fee corresponds to an annual revenue of $164,000.

Each composting facility requires one frontend loader, tub grinder and trommel (rotary) screen. The capital cost of the tub grinder was excluded from the analysis as it was assumed not to be required for the food waste, being used to grind woody yard waste. Annual maintenance costs for the frontend loader and trommel screen were estimated per piece of equipment. A 15-year service life was applied to mechanical equipment. Each compost facility was assumed to require a 186 m^2 (2,000 ft^2) administration building at a cost of $519 per m^2. An annual building maintenance factor of 3 percent of capital cost was applied. Capital and maintenance costs were allocated to the food waste processed using food wastes' share of the total facility material volume processed, which is 25 percent.

Labor costs were estimated based on labor estimates from Komilis and Ham (2004), which works out to a labor requirement of 0.57 hours per metric ton of material processed. Processing 4,900 Mg of food waste per year therefore requires 2,800 hours of labor. The estimated labor requirement was divided equally between a supervisor and laborer/machine operator. The supervisor's labor rate is $28.57/hour. Laborers/equipment operators are paid a rate of $21.16/hour. A 40 percent overhead factor was applied to all labor costs (Komilis and Ham 2004). Estimated labor rates represent national averages for "first-line supervisors of transportation and material-moving machine and vehicle operators" and "excavating and loading machine and dragline operators" for NAICS code 325300 representing the pesticide, fertilizer and other agricultural chemical manufacturing industry (U.S. DOL 2016).

Each kg of material processed at the composting facility yields between 0.42 and 0.46 kg of finished compost. The base and low cost scenarios assume values of finished compost of $15 and $19 per metric ton, which corresponds to a cost of between $12 and $16 per cubic yard. These values are broadly representative of compost produced in the New England region. A residual production rate of 5 percent was assumed for all incoming food waste, and is disposed of in a sanitary landfill at a cost of $54 per metric ton.

The base cost construction interest rate of 5 percent was suggested by Komilis and Ham (2004), while the 3 percent interest rate represents a conservative rate for a State Revolving Fund (SRF) loan. Current loan interest rates for the Massachusetts State Revolving Fund, administered by the Massachusetts Department of Environmental Protection, are 2 percent (MassDEP 2015).

Table A-9. Life Cycle Costs Common to both Composting Systems[1]

Cost Element	Cost	Cost Frequency
Labor	107,350	annual
Tipping Fee	(163,457)	annual
Compost Sales	(31,522)	annual
Administrative Building	28,775	year 1
Administrative Building, maintenance	863	annual
Residuals Landfilling	13,480	annual
Loader	54,023	year 1
Loader, maintenance	360	annual
Screen	36,015	year 1
Screen, maintenance	180	annual

[1] All costs are scaled to represent only food wastes share of capital and annual costs and revenues.

Windrow Composting Costs

Table A-10 summarizes life cycle costs specific to the windrow composting system. The windrow composting system requires a specialized compost turner with a capital cost of $259,000 (scaled to represent food wastes share). The machine has an expected useful lifespan of 15 years. Maintenance cost for the windrow turner was estimated assuming a cost factor of 2 percent of capital costs. Land area required for a windrow facility was estimated using aerial photos of four windrow facilities in Eastern Massachusetts. The average land area requirement across the four facilities was 3.2 m^2/Mg/yr or a total land requirement of 1.6 hectares for food waste processing. Land cost was estimated using the CAPDETWorks™ default value adjusted to 2016 dollars, or $50,104/hectare ($20,276/acre). Annual property tax was estimated using an average 2016 Massachusetts commercial property tax rate of $18.59 per thousand dollars of assessed value (MA DLS 2019). The cost of site grading was applied to the entire facility area at a unit cost of $18,000 per hectare. Electricity and diesel cost was estimated using the developed LCI value and assuming electricity and diesel unit costs of 14.3 cents/kWh and 0.63 $/liter (2.38 $2016/gallon) (US EIA 2019). Energy costs were escalated using the energy escalation factors included in Table C-1.

Table A-10. Windrow Composting Life Cycle Costs

Cost Element[1]	Base Cost	Low Cost	Cost Frequency
Windrow Turner	64,828		Year 1
Windrow Turner, maintenance	1,297		annual
Land cost	78,245		Year 1
Property taxes	1,455		annual
Site grading	28,122		Year 1
Indirect costs	105,882		Year 1
Electricity	6,993	3,505	annual
Diesel	3,142	2,518	annual
Loan interest	15,882	9,529	Year 1

[1] All costs are scaled to represent only food wastes share of capital and annual costs and revenues.

Aerated Static Pile Composting Costs

Table A-11 summarizes life cycle costs specific to the ASP compost system. The system layout was based on the configuration of a 153 m^3 (200 cubic yard) pilot scale system operated in Walla Walla, WA (O2 Compost 2015). The system consists of perforated PVC pipe manifolds lain on top of the ground and connected to a 1.5 HP blower for aeration control. The blowers are run on a pulse schedule where they typically operate for between one and four minutes in every 20 minutes. The pile will not be able to maintain sufficient temperatures if the blowers are run continuously. A 150 mm (6 in) pipe is used as a manifold to connect the blower with four 100 mm (4 in) lateral lines each 18 meters in length. The manifold is 7.3 meters (24 ft) in length. Pile height is approximately 2.4 meters. The pipes are made of SDR 35 PVC, which is commonly used for sewer mains and is stronger than regular schedule 40 PVC. Pipe cost was estimated using 2016 cost factors from the RSMeans database (RSMeans 2016). A 30 percent installation cost factor was applied to bare material cost assuming that facility staff would assemble the manifolds. Unit cost for the 150 and 100 mm pipe was $23.66 and $17.45 per meter of pipe, respectively (including fittings).

Each static pile contains 153 m^3 of material when the composting process begins, corresponding to a pile mass of approximately 110 Mg. The ASP system requires approximately 30 days for the active composting phase and 30 days of curing time (O2 Compost 2015). The blowers are only required during the active phase. Using these assumptions 5 pipe manifolds were required to process the incoming food waste. When a pile finishes the active phase, the blower is moved to a newly formed pile. Manifolds remain in place during the curing phase, to avoid the additional material handling. One extra blower was specified in the event that one is down for maintenance. The capital cost per blower is $1400. A 30 percent installation cost factor and 2% annual maintenance cost factor was applied to the blowers. A total of 10 pipe manifolds and 6 blowers comprise the capital equipment required for operation of the ASP composting system. This system configuration is easily scalable. The useful lifespan of piping and blowers was assumed to be 3 and 5 years, respectively. Electricity and diesel cost were estimated using the developed LCI values and the same cost assumptions described for windrow composting.

The land area requirement for the ASP composting facility was based on aerial photos of a facility in Central Massachusetts. The land area requirement was estimated to be 0.59 Mg/m^2/year or 0.3 hectare in total to process 4,900 Mg of material. The decreased land area requirement of ASP composting is corroborated by the pilot study in Walla Walla, Washington, which concluded that ASP would allow a fourfold increase in the throughput of their existing (windrow) facility. Land cost, property taxes and site grading we estimated using the developed land area estimate and cost factors described in the section on windrow composting.

Table A-11. ASP Composting Life Cycle Costs

Cost Element[1]	Base Cost	Low Cost	Cost Frequency
ASP piping	20,708		Year 1
ASP blowers	11,726		Year 1
Blower maintenance	164		annual
Land cost	14,590		Year 1
Property taxes	271		annual
Site grading	5,244		Year 1
Indirect costs	78,246		Year 1
Electricity	26,237	16,310	annual
Diesel	1,588		annual
Loan interest	11,737	7,042	Year 1

[1] All costs are scaled to represent only food wastes share of capital and annual costs and revenues.

GLSD LCCA Cost Adjustments

All GLSD annual and capital costs common to both the baseline and full capacity scenario were zeroed out for the food waste disposal LCCA comparison. No food waste is processed in the baseline scenario, so it follows that costs common to both feedstock scenarios are not attributable to the food waste being processed. Additionally, all cost inputs associated with unit processes marked as "Excluded" in Table A-3 were zeroed out. Remaining process costs were assumed to partially reflect the additional system costs and revenues associated with SSO acceptance. Cost inputs that are independent of the decision to install CHP capacity were adjusted to reflect the cost of food waste processing by subtracting baseline life cycle cost inputs from the corresponding input value for the full capacity feedstock scenario. Cost input values that are influenced by the decision to install a CHP system were allocated to food waste based on the fraction of biogas production contributed by food waste. Food waste contributes approximately 69 and 78 percent of biogas production in the low and base AD performance scenarios, respectively.

As described in Section 4.3, the majority of system costs associated with large maintenance and equipment replacement projects were estimated using plant-provided data on debt service payments. A portion of debt service payments was allocated to food waste processing based on the volume fraction of SSO as compared to municipal sewage, which is approximately 0.4 percent. Maintenance costs associated with the CHP system were allocated using the food waste biogas production fraction, while maintenance costs for the fourth digester tank were allocated solely to food waste processing.

Table C-4 includes detailed cost input data for the food waste comparison, allowing comparison with cost input data associated with LCCA results in the main report.

Food Waste Disposal – Comparative Results

This Appendix provides a comparative analysis of food waste management options including: AD, windrow and ASP composting, landfilling and WTE combustion. Results are presented for eight environmental impact categories as well as for life cycle costs for the AD and two compost treatment options. All AD results correspond to the full capacity scenario, which assumes that AD infrastructure is fully utilized. LCA results are presented in the order they are introduced in the main report.

Base performance results, which are representative of estimated average performance, are presented for AD and compost treatment options. A low performance scenario was evaluated in the main report to test the sensitivity of LCA and LCCA results to worse than expected performance of AD treatment units. This scenario has been carried forward into this Appendix. An improved performance scenario has been evaluated for the compost options, based on the judgement that a well-managed compost facility should be able to achieve reduced equipment use and GHG emissions through efficient management. The following model parameters are varied within the performance scenarios:

- AD
    - Volatile solids reduction, biogas yield and rate of on-site biogas utilization (i.e., fraction flared)
- Compost
    - Equipment energy consumption, process GHG emissions, transport distance to land application, quantity of sequestered carbon and amount of avoided fertilizer

Summary Results

Table A-12 presents impact assessment results per kg of food waste disposed for each of the five treatment options. Cost results are presented per metric ton. Cost was not assessed for the landfill and WTE treatment options. Landfill and WTE options are shown as historical reference points for the environmental results, but these options are no longer available to commercial food waste generators in Massachusetts given the ban on disposal of commercial organic food waste. It should also be noted that landfilling and WTE combustion of food waste remove material from the nutrient cycle; whereas, AD and composting allow continued beneficial use of the nutrient material. Benefits of long-term nutrient recovery are not fully captured in the impact categories covered in this LCA.

Figure A-2 presents impact assessment results in a format that allows relative comparison of the treatment options as a percentage of maximum impact within each environmental or cost category. Treatment options for which relative net impacts are greater than zero correspond to environmental impacts and/or economic costs. Treatment options that have relative net impacts that are less than zero correspond to environmental benefits or revenue. Environmental benefits indicate that the positive environmental effect of avoided products (e.g., electricity, natural gas, fertilizer) is greater than the environmental impact of inputs and process emissions associated with an individual treatment option for that impact category. In both Table and Figure A-2, lower values indicate treatment options with lower environmental impact.

Figure A-2 indicates that the base performance AD scenario has the lowest environmental impact or the greatest environmental benefit in six of eight impact categories, and also yields the lowest NPV per unit of food waste processed. The FDP and CED impact categories, that are directly related to energy use and production, demonstrate the best relative performance of food waste anaerobic co-digestion due to biogas energy recovery. The use of a split axis in Figure A-2 visually minimizes the relative FDP and CED benefits of food waste managed via AD, but still clearly demonstrates its superior performance. Figure A-7 confirms that avoided grid electricity and natural gas consumption are responsible for the large relative benefits of food waste co-digestion. WTE combustion is the second best performer in these two impact categories. The ASP compost option demonstrates the highest FDP and CED impact, followed closely by windrow composting. WTE combustion, AD and landfilling all capture at least a small fraction of the energy content present in food waste. However, composting is a net energy consumer, and the relative energy demand of electricity consumption for ASP composting is greater than that of diesel use to fuel the windrow turner.

The base performance AD scenario is the only EOL treatment option that generates net benefits for PMFP, SFP and AP. These three impact categories are strongly linked to combustion emissions, and only with the higher biogas yield of the base performance scenario do the benefits of avoided energy products outweigh the impacts associated with on-site combustion and transportation of heavy food waste and pelletized biosolids. Biogas combustion does produce pollutant emissions that contribute to these three impact categories. Windrow and ASP compost systems have the largest environmental impact in these three categories in the base performance scenario, due to process emissions that occur during composting or land application. Food waste landfilling also leads to relatively high PMFP and SFP impacts, similar in magnitude to compost options within the improved performance scenario.

Anaerobic digestion of food waste also leads to an environmental benefit in the GWP impact category, again due to avoided energy products. Food waste landfilling has a considerably higher carbon footprint than all other food waste EOL disposal options. Modeled landfill gas management reflects current practice in Massachusetts, where 19 percent of gas is flared and 81 percent is used for energy recovery. As a reference point, nationally approximately 24 percent of landfill gas is flared, 68 percent is used for energy recovery and 8 percent is vented to the atmosphere. See report Section 3.3.14 for more detail. The GWP impact of composting is associated with methane and nitrous oxide emissions in the base performance scenario. All other food waste EOL treatment scenarios lead to a GWP benefit due to avoided energy products, fertilizer production and carbon sequestration for the fraction of land applied carbon that remains in the soil after 100 years.

It is rare to find products, technologies or processes in any comparative environmental analysis that outperform all other options across all of the included indicators. These variations in environmental performance force communities, plant personnel and policy makers to grapple with challenging environmental and cost trade-offs, that challenge the notion of a "best" available option. An increase in EP associated with food waste AD is the largest environmental impact of co-digestion. A fraction of nutrient content in the food waste is returned to the primary and secondary treatment processes, and is ultimately released with the treated effluent. The base and low AD performance scenarios assume that 55 percent and 80 percent of food waste nutrients are solubilized during digestion and return to plants headworks. The 55 percent estimate used in the base performance scenario was based on the result of GPS-X™ model runs, while the 80% value used in the low performance scenario assumes that VS destruction correlates with nutrient solubility. Approximately 70 percent of nitrogen and phosphorus returned to the headworks are released with the effluent, based on GPS-X™ estimates. The two compost options have the next highest EP, due to emissions associated with land application. Both landfilling and WTE combustion exhibit negligible EP impact. Water use is also greatest for the food waste co-digestion due to the water that is used to reduce the solids content of incoming food waste during the bioslurry production process.

Life cycle cost is presented per metric ton of food waste processed for AD and compost treatment options. The base performance AD scenario demonstrates the best economic performance, with revenue of approximately $7.60 per metric ton over the thirty year time horizon. Dollars are expressed as NPV. The low performance AD scenario has the highest NPV per metric ton of food waste primarily due to reduced production of electricity from the CHP system because a larger fraction of overall biogas heat content is required for the pellet drying process, which bypasses the CHP engine. All compost scenarios lead to net revenue per metric ton of food waste accepted, which ranges between $1.70 and $4.80 across the base and improved compost performance scenarios.

Table A-12. Summary LCA Results Comparing Food Waste EOL Management Options - per kg of food waste treated

	Performance Scenario	*Base*	*Low*	*Base*	*Base*	*Improved*	*Improved*	*n.a.*	*n.a.*
Impact Category	**Units**	**AD**	**AD**	**Windrow**	**ASP**	**Windrow**	**ASP**	**Landfill**	**WTE**
Acidification Potential	kg SO_2 eq	-1.1E-4	2.1E-4	1.2E-3	1.2E-3	5.0E-4	4.9E-4	1.4E-4	8.1E-5
Cumulative Energy Demand	MJ	-7.2	-3.2	0.29	0.54	0.22	0.39	-0.20	-0.96
Eutrophication Potential	kg N eq	2.4E-3	3.1E-3	9.5E-4	9.5E-4	6.7E-4	6.7E-4	8.6E-6	6.2E-6
Fossil Depletion Potential	kg oil eq	-0.12	-0.06	7.1E-3	9.1E-3	5.7E-3	7.1E-3	-1.1E-3	-9.8E-3
Global Warming Potential	kg CO_2 eq	-0.14	-0.03	0.10	0.07	-0.01	-0.01	0.32	-0.02
Particulate Matter Formation Potential	kg $PM_{2.5}$ eq	-2.5E-5	4.0E-7	2.8E-5	2.8E-5	7.4E-6	7.4E-6	7.5E-6	2.9E-6
Smog Formation Potential	kg O_3 eq	-3.8E-3	3.0E-3	6.4E-3	6.4E-3	5.1E-3	5.2E-3	4.8E-3	2.0E-3
Water Use	m^3 H_2O	8.0E-4	1.1E-3	-5.1E-4	-4.7E-4	-3.7E-4	-3.4E-4	-3.4E-5	-1.2E-4
Cost[1]	$/ Mg	-7.6	10	-3.8	-1.7	-4.8	-3.6	n.a.[2]	n.a.[2]

[1] All cost results presented in this table were developed using the base cost assumptions defined in this Appendix and report Section 4.2.6.
[2] Cost per ton for landfill and WTE combustion were not evaluated.

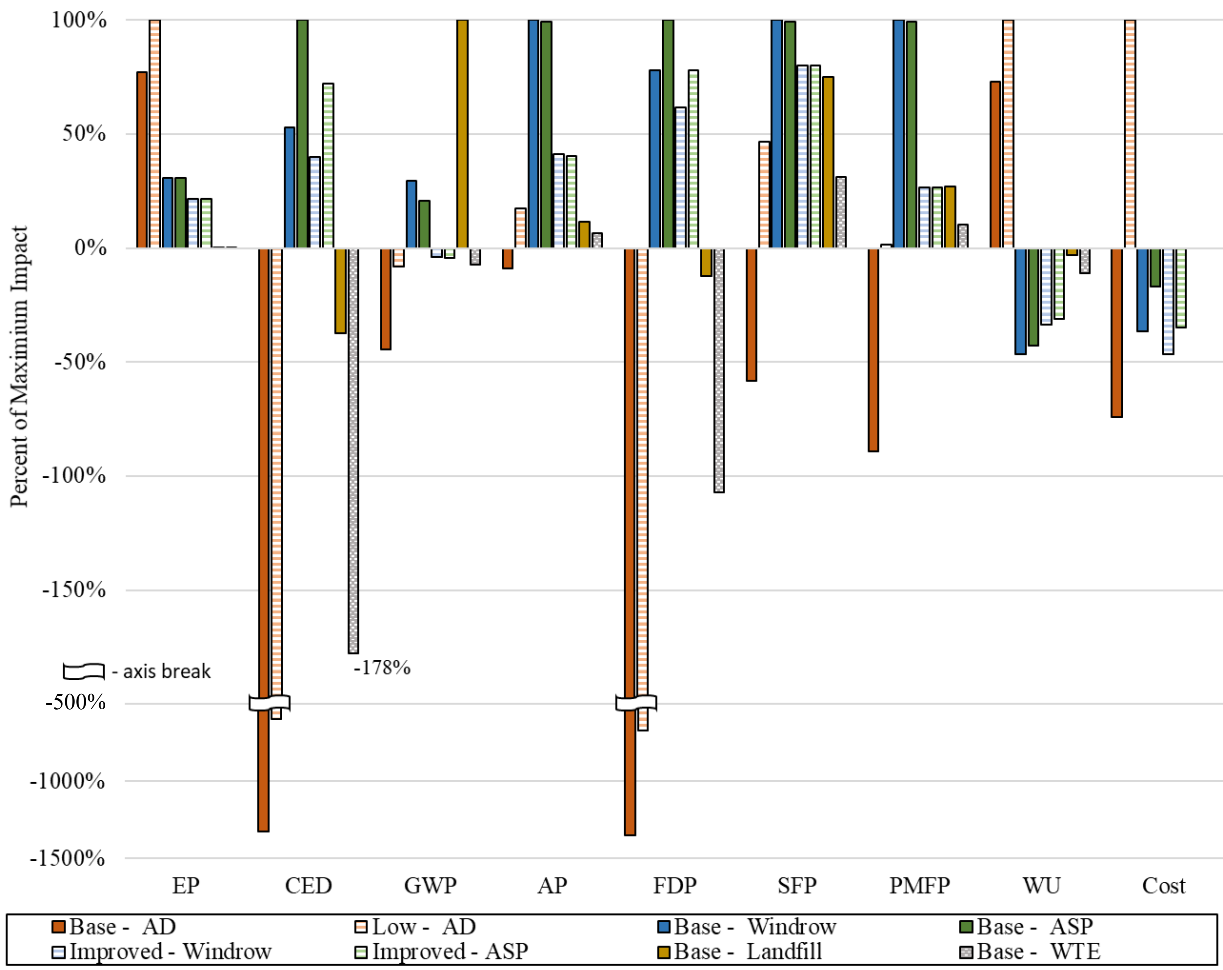
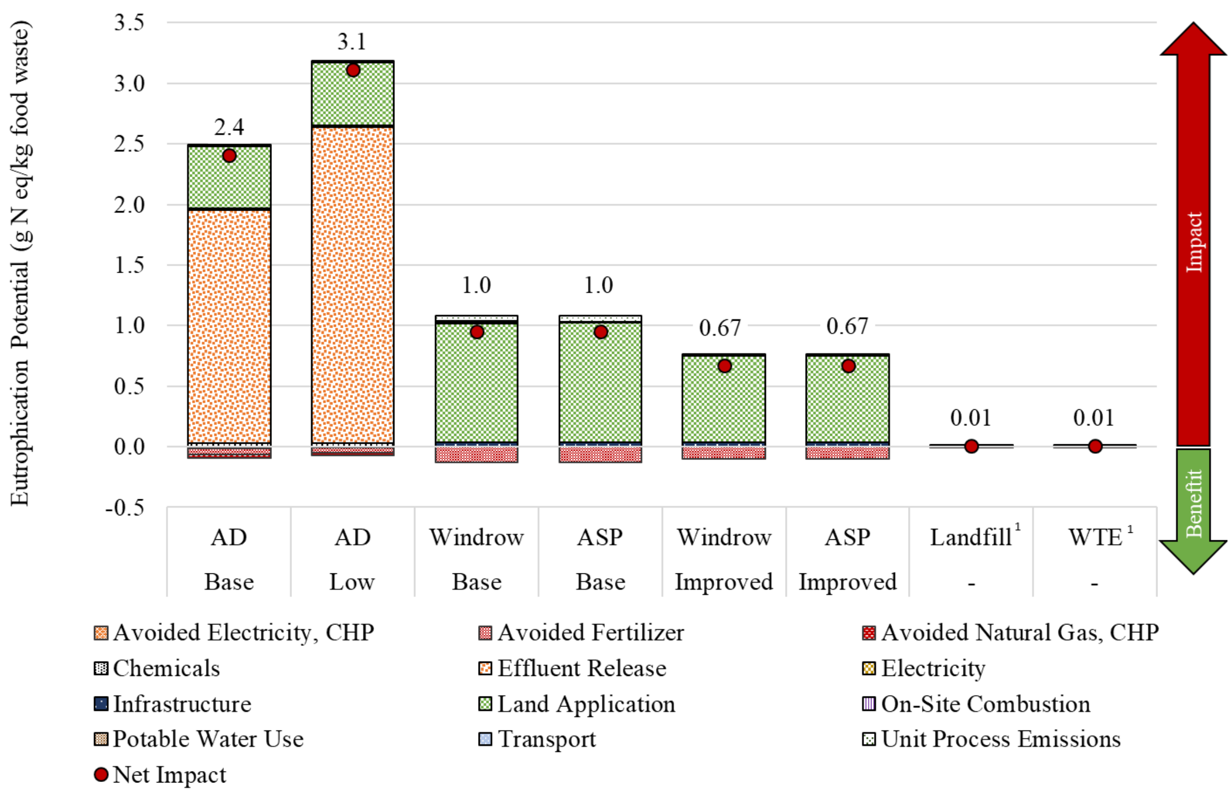


Figure A-2. Comparative LCA results for food waste end-of-life options per mass of food waste treated. Figure acronyms: AD – Anaerobic Digestion, AP – Acidification Potential, ASP – Aerated Static Pile, CED – Cumulative Energy Demand, EP – Eutrophication Potential, FDP – Fossil fuel Depletion Potential, GWP – Global Warming Potential, PMFP – Particulate Matter Formation Potential, SFP – Smog Formation Potential, WTE – Waste-to-Energy, WU – Water Use.

Eutrophication Potential Results

Figure A-3 presents EP impact assessment results for each of the five food waste treatment options according to the underlying drivers that contribute to impact. Food waste co-digestion leads to the highest overall EP across both performance scenarios, with effluent release contributing between 77 percent and 82 percent of gross positive impact. Land application of pelletized biosolids and compost contribute considerably to EP impact, especially for the compost treatment options, where it dominates impact assessment results. Avoided fertilizer production provides modest reductions in net EP impact for the windrow and ASP compost systems in both performance scenarios. The benefits of avoided fertilizer production are minor for the AD treatment options. Both landfilling and WTE combustion have negligible relative EP impact.

The actual quantity of food waste nitrogen and phosphorus that is returned to the plant headworks and ultimately contributes to effluent concentrations has not been well studied and is a source of uncertainty in the current results. Preliminary water quality monitoring is ongoing to determine what effect, if any, the addition of SSO material may have on final effluent nutrient concentrations (further discussed in the Appendix B Nutrient Supplement Section).



[1] Landfilling and combustion of commercial food waste are prohibited in the State of Massachusetts per regulation 310 CMR 19.000.

Figure A-3. Eutrophication potential results by process category for food waste end-of-life treatment.

Cumulative Energy Demand Results

Figure A-4 presents CED inventory results for each of the five treatment options according to the underlying drivers that contribute to energy demand. Positive contributions to CED are dominated by electricity consumption for the AD and ASP treatment options. Transportation of food waste, SSO, pelletized biosolids and finished compost also contribute visibly to CED. The two AD treatment scenarios lead to net reductions in energy demand due to their avoided energy products. Biogas combustion is not considered to contribute to energy demand because it enters EOL treatment facilities as a waste product. Avoided electricity production also leads to net reductions in energy demand when considering landfilling and WTE combustion of food waste. The heat fraction of energy associated with biogas combustion at landfills and WTE plants was assumed not to contribute avoided product benefits. Specific facilities that cooperate with local industrial partners, or otherwise find beneficial uses for waste heat would be eligible to receive additional avoided product benefits. The landfill and WTE treatment options consider disposal in facilities relatively close, 73 km total transit distance, to the point of waste generation. Increased transport distances would lead to increases in energy demand for these options.

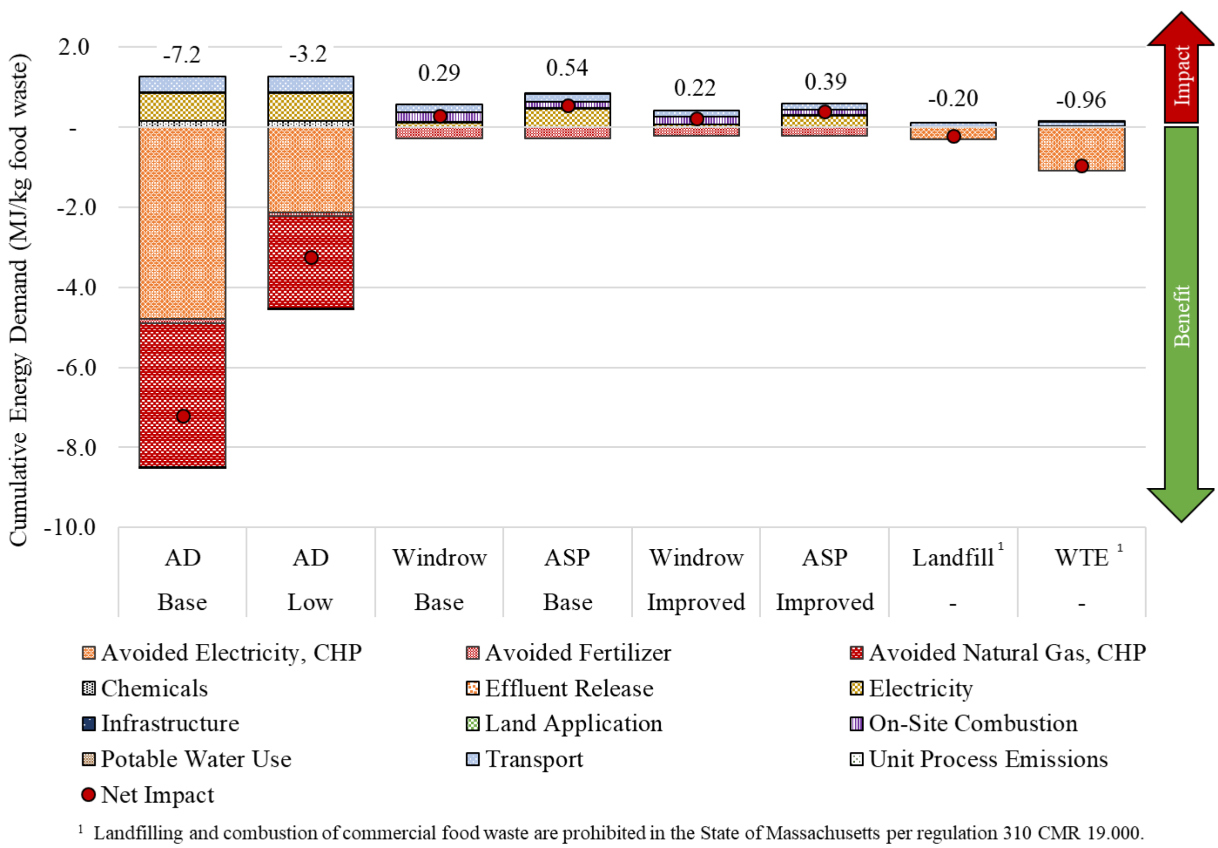
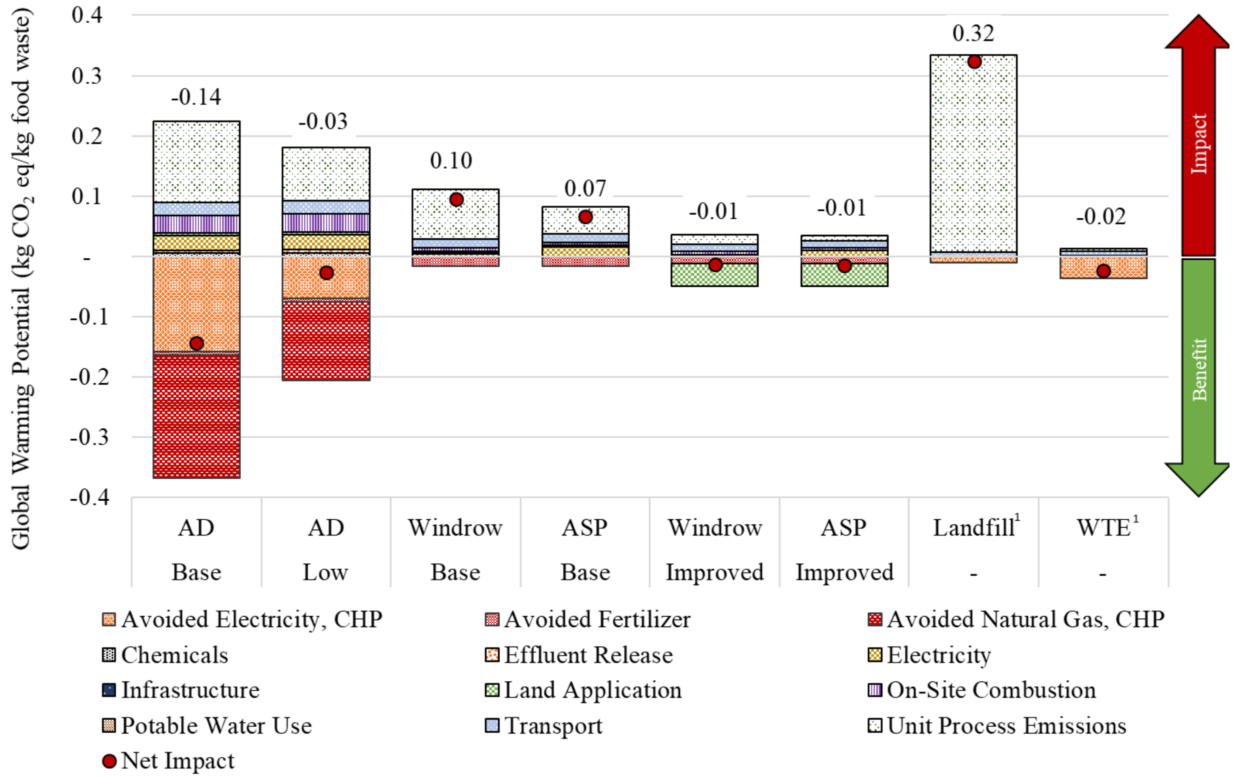


Figure A-4. Cumulative energy demand results by process category for food waste end-of-life treatment.

Global Warming Potential Results

Figure A-5 presents GWP impact assessment results for each of the five treatment options according to the underlying drivers that contribute to impact. Process emissions of GHGs are the predominant contributor to GWP impact, especially for food waste landfilling, which has the highest GWP impact. Process emissions also contribute considerably to the GWP of food waste co-digestion and both composting options within the base performance scenario. Fugitive emissions from the AD tank were estimated assuming a 5 percent leakage rate (UNFCCC 2012). Methane emissions in the base performance windrow scenario are approximately 0.8 percent of carbon entering the compost pile. No methane emissions are assumed in the ASP system. Nitrous oxide emissions are approximately 1.3 percent of nitrogen entering the compost pile for both the ASP and windrow composting methods. On-site combustion of biogas and transportation of food waste contribute additional visible increases in GWP for the AD treatment route.

Avoided products serve to reduce the net GWP of all five treatment options, to varying degrees. Avoided energy products are responsible for the net environmental benefit associated with food waste co-digestion and WTE combustion, and are therefore dependent on biogas replacing natural gas combustion and grid based electricity consumption. The New England ISO grid is being replaced in this analysis. Over 80 percent of electricity demand in the 2016 grid mix was supplied by natural gas and nuclear power plants (Table 2-2). Replacement of dirtier or cleaner electrical grid mixes will directly affect the realized avoided product benefits. Carbon sequestration and avoided fertilizer production associated with compost land application are responsible for the net GWP benefit associated with windrow and ASP compost options in the improved performance scenario. Land application of the pelletized biosolids yields a negligible sequestration credit when compared against other processes in the AD life cycle. Higher GHG emissions and a more conservative assumption regarding the carbon sequestration potential of compost use lead to net GWP impacts in the base performance compost scenarios. In the base performance scenario, approximately 8 percent of land applied carbon is sequestered beyond 100 years. This value increases to 19 percent in the improved performance scenario.



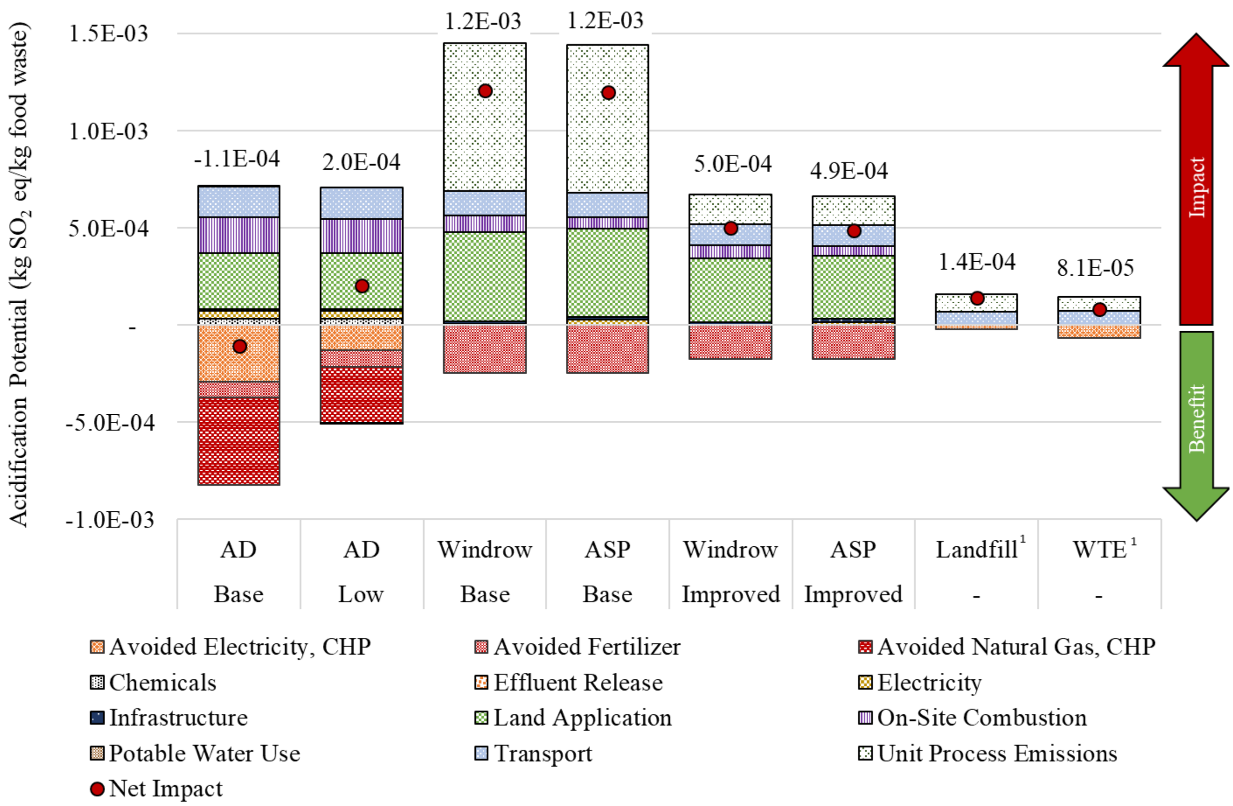
[1] Landfilling and combustion of commercial food waste are prohibited in the State of Massachusetts per regulation 310 CMR 19.000.

Figure A-5. Global warming potential results by process category for food waste end-of-life treatment.

Acidification Potential Results

Figure A-6 presents AP impact assessment results for each of the five treatment options according to the underlying drivers that contribute to impact. A number of sources contribute emissions that lead to AP impact including process emissions, waste transport, emissions associated with land application, and on-site combustion of biogas. The base performance compost scenarios lead to the highest AP impact due to a combination of these process categories. Process based ammonia emissions are the single largest contributor to composting AP impact. Avoided fertilizer production reduces composting net AP by between 15 percent and 25 percent across all included scenarios.

The base performance AD scenario is the only EOL treatment option that leads to a net reduction in AP, due primarily to avoided energy product credits. Landfilling, WTE combustion, and the low performance AD scenarios all have relatively low AP impacts per kg of food waste disposed.



[1] Landfilling and combustion of commercial food waste are prohibited in the State of Massachusetts per regulation 310 CMR 19.000.

Figure A-6. Acidification potential results by process category for food waste end-of-life treatment.

Fossil Fuel Depletion Potential Results

Figure A-7 presents FDP inventory results for each of the five treatment options according to the underlying drivers that contribute to impact. The low and base performance AD treatment options lead to the largest reductions in FDP across the five treatment options. Reduced fossil fuel consumption stems primarily from the replacement of fossil energy sources with the heat and power recovered from biogas combustion. WTE combustion and landfilling also lead to modest reductions in FDP due to energy recovery at these respective facilities. The windrow and ASP compost systems have similar, low consumption of fossil fuel resources attributable primarily to diesel consumption during food waste and compost transport and for operation of processing equipment.

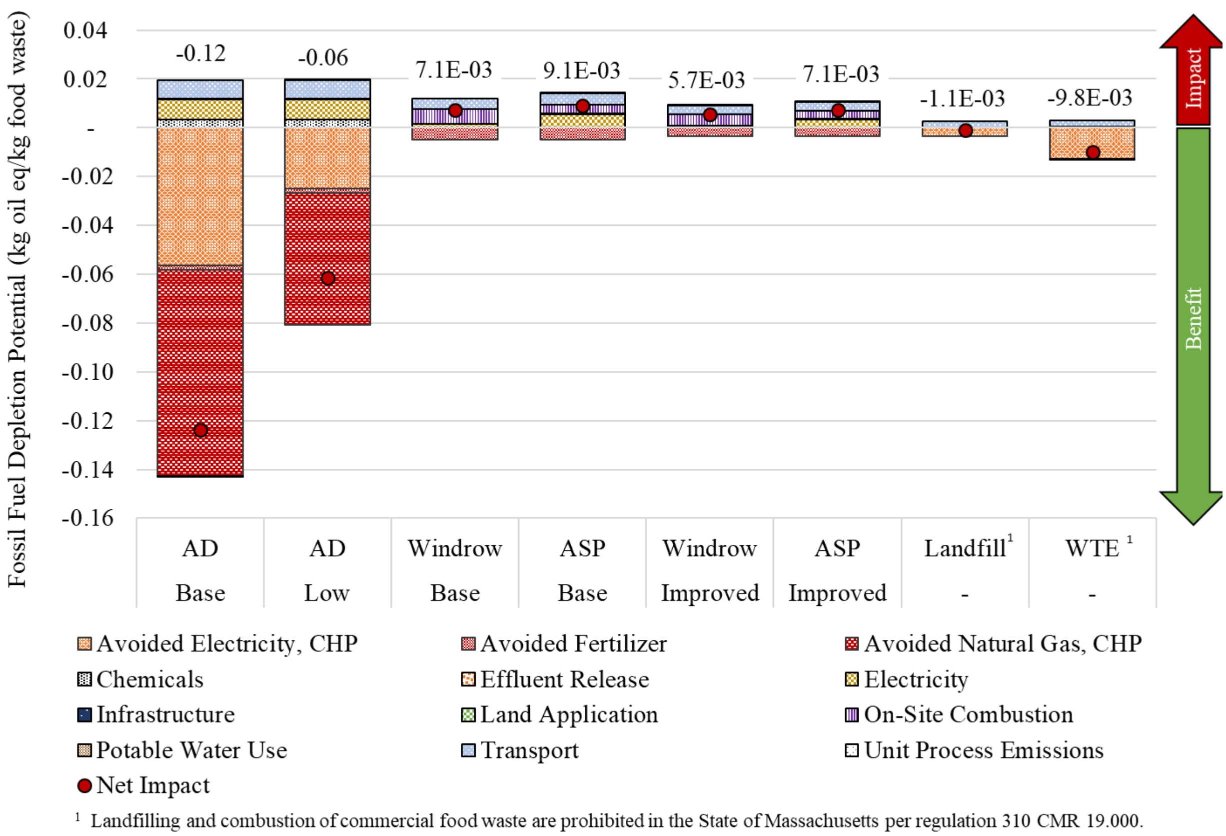
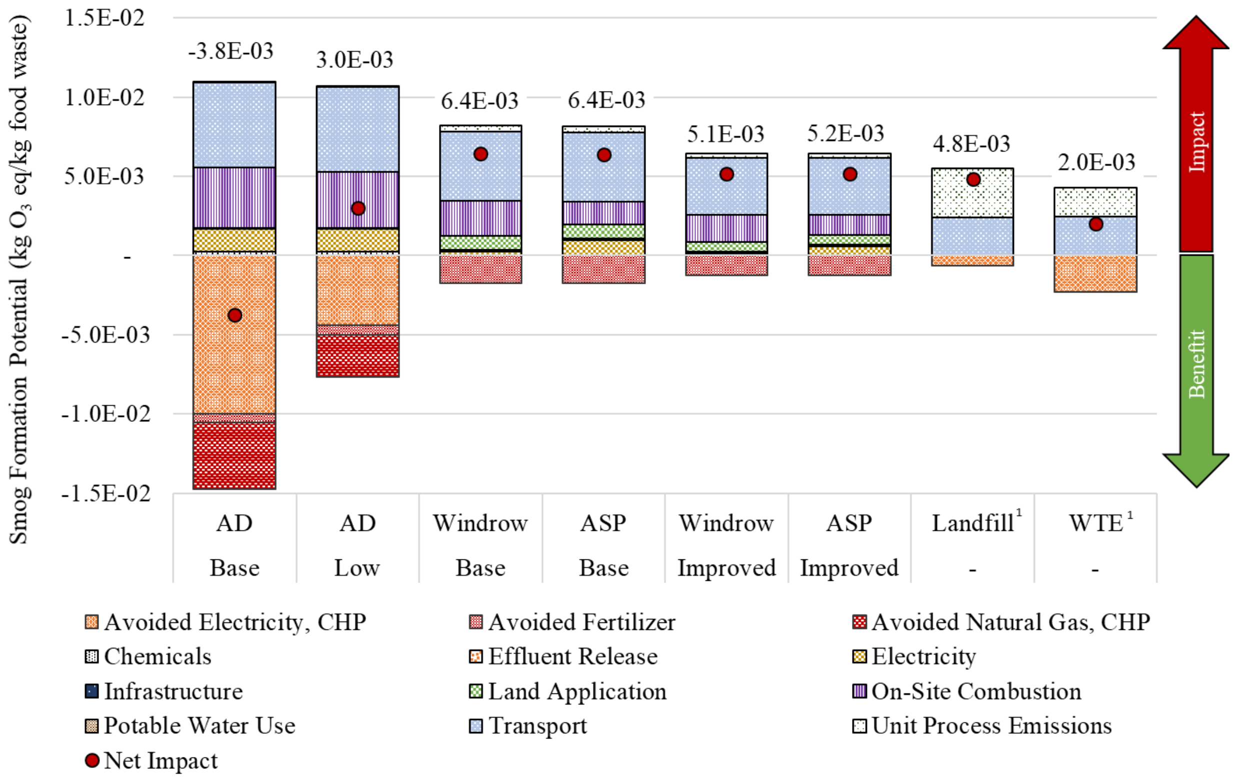


Figure A-7. Fossil fuel depletion potential results by process category for food waste end-of-life treatment.

Smog Formation Potential Results

Figure A-8 presents SFP impact assessment results for each of the five treatment options according to the underlying drivers that contribute to impact. Emission of nitrogen oxides during transportation of food waste, compost and pelletized biosolids is a primary contributor to SFP impact for all of the EOL treatment options. On-site biogas combustion in the CHP engine and pellet drying facility also contribute to SFP impact. The base performance AD scenario is the only EOL treatment option to generate a net SFP benefit, attributable to the avoided energy products. WTE combustion has the lowest net SFP impact among the remaining treatment options. Windrow and ASP composting systems have the highest SFP due to a combination of high transportation related impact and minimal avoided product benefits.



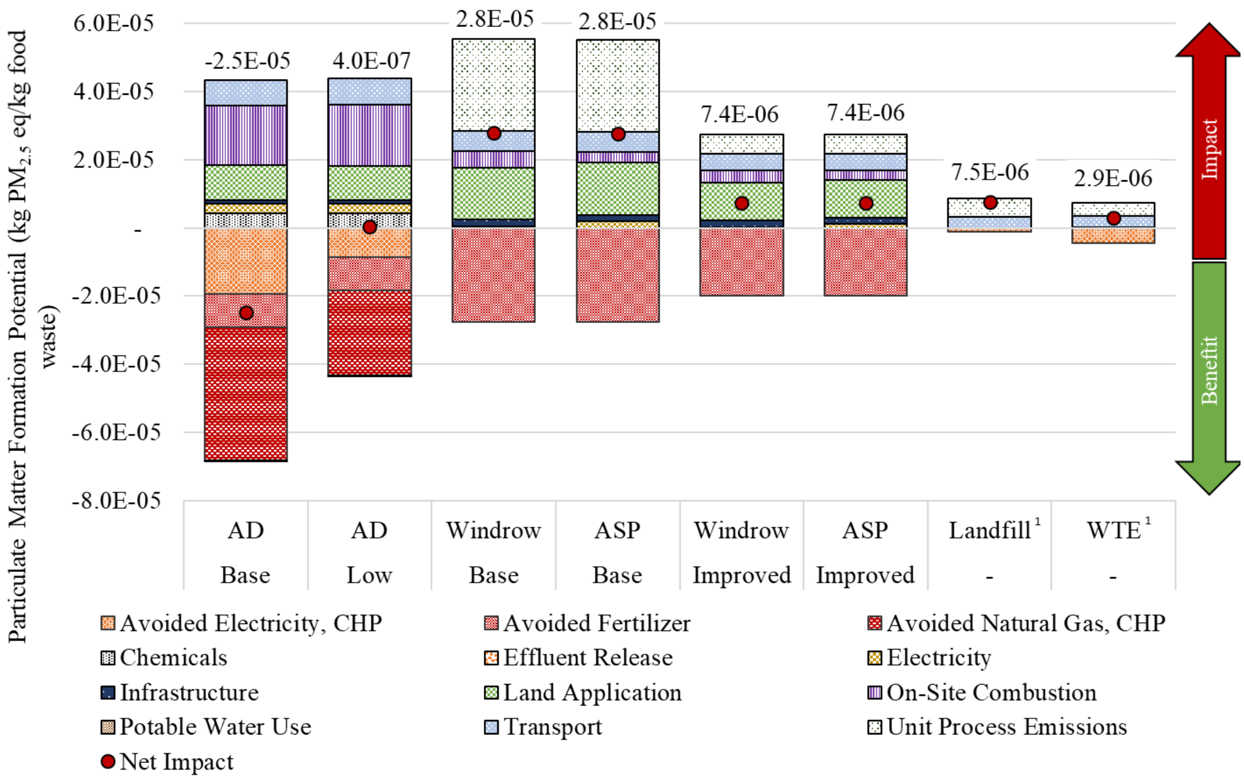
[1] Landfilling and combustion of commercial food waste are prohibited in the State of Massachusetts per regulation 310 CMR 19.000.

Figure A-8. Smog formation potential results by process category for food waste end-of-life treatment.

Particulate Matter Formation Potential Results

Figure A-9 presents PMFP impact assessment results for each of the five treatment options according to the underlying drivers that contribute to impact. A number of sources contribute emissions that lead to PMFP impact including process emissions, waste transport, emissions associated with land application and on-site combustion of biogas. The base performance compost scenarios lead to the highest PMFP impact due to a combination of these process categories. Process based ammonia emissions are the single largest contributor to compost PMFP impact. Avoiding production of the chemical fertilizers urea and single superphosphate helps reduce the net environmental burden of both compost and AD treatment options.

The base performance AD scenario leads to an overall net reduction of PMFP impact due to the combined benefits of avoided fertilizer production and energy products. On-site combustion of biogas is the largest contributor to AD PMFP impact, followed by land application of pelletized biosolids. All of the other treatment options, including the low performance AD scenario and the improved performance compost scenarios yield low, net positive PMFP impact per kg of food waste treated.



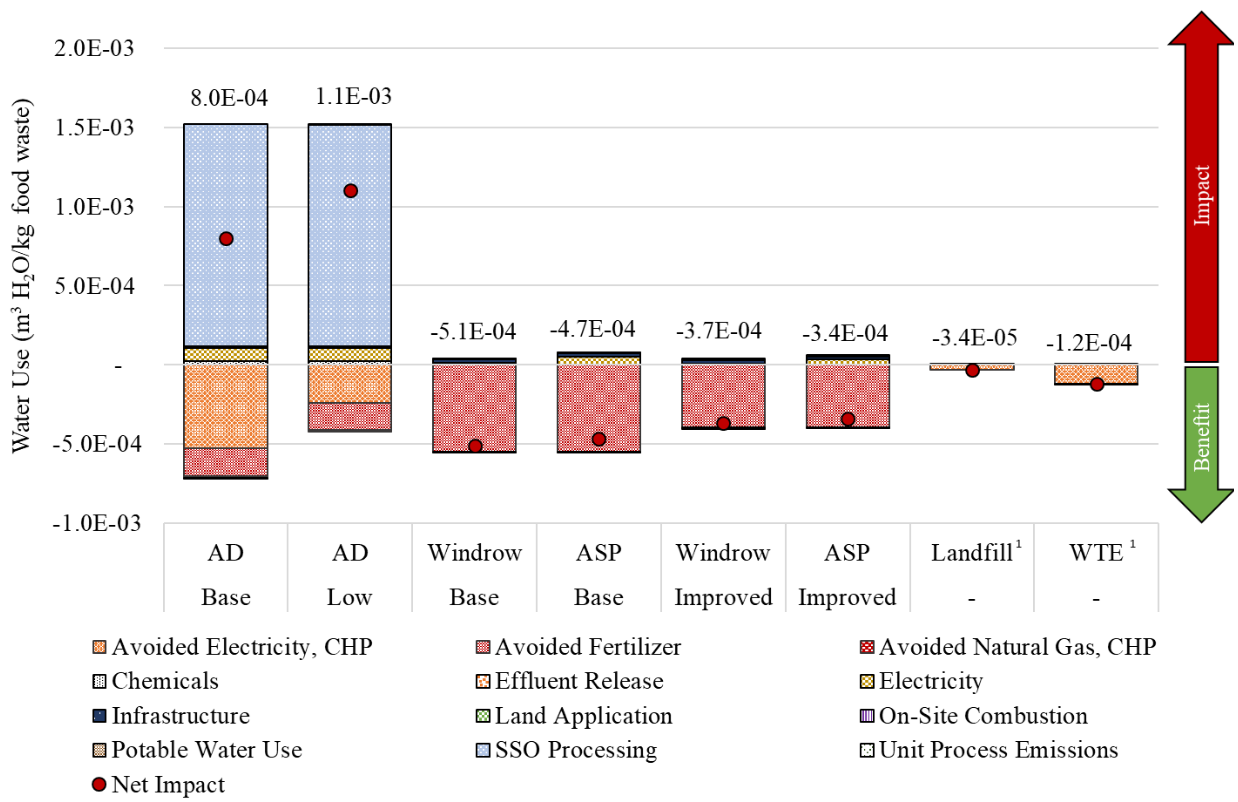
[1] Landfilling and combustion of commercial food waste are prohibited in the State of Massachusetts per regulation 310 CMR 19.000.

Figure A-9. Particulate matter formation potential results by process category for food waste end-of-life treatment.

Water Use Results

Figure A-10 presents WU inventory results for each of the five treatment options according to the underlying drivers that contribute to water demand. Water use required to produce the SSO slurry for co-digestion is the largest contributor to water use across the five treatment option, and leads to the highest water demand being associated with the low and base performance AD scenarios. Total water use necessary to process the SSO is approximately 3 percent of plant water use. Water use associated with SSO production is a conservative estimate. Some or all of the necessary moisture may be sourced from complementary liquid wastes, leading to direct reductions in estimated water use. Avoided fertilizer production provides a water use credit for the AD and compost treatment options. Water use during fertilizer production is primarily associated with sulfuric acid production and electricity generation.

The high moisture content of food waste relative to the desired moisture content of compost feedstock was assumed to eliminate compost water use for the food waste fraction of pile feedstock.



[1] Landfilling and combustion of commercial food waste are prohibited in the State of Massachusetts per regulation 310 CMR 19.000.

Figure A-10. Water use results by process category for food waste end-of-life treatment.

Life Cycle Cost Assessment Results

Table A-13 presents life cycle costs per metric ton of food waste processed at each facility type. Cost estimates are provided for all performance scenarios considered in the LCA results. For information of payback period of the AD and CHP installation refer to Section 6.5. Overall the base AD performance scenario realizes the most revenue per metric ton of food waste processed within both the base and low cost scenarios. The low performance AD scenario assumes a more conservative estimate of biogas production, which considerably lowers revenue associated with avoided energy products. The low AD performance scenario leads to a cost of $10 per metric ton of food waste processed in the base cost scenario, and drops to approximately $0.50 per ton in the low cost scenario. All of the eight composting scenarios lead to revenue that ranges between $2.50 and $10 per metric ton of food waste treated.

Figure A-11 summarizes life cycle costs for each treatment option according to underlying cost categories. Negative values correspond to net revenue, over a 30-year period, for the relevant cost category. The AD system has much higher overall costs but also results in greater cost savings. Costs and revenue for the composting systems are over an order of magnitude lower compared to the AD system.

Although anaerobic digestion is more capital intensive, it leads to increased revenue potential from the sale of renewable and alternative energy credits or by avoiding electricity and natural gas costs. It is this revenue potential, particularly from the renewable and alternative energy credits, that leads to the lowest life cycle costs per metric ton of food waste processed in the base AD performance scenario. Capital costs are fixed however, and when the digesters produce less biogas in the low AD performance scenario the balance of expenditure to revenue shifts considerably, which leads to an economic loss. Tipping fees are categorized as an operational cost, which produce a small amount of net revenue in the low cost scenario, negating other operational costs.

In Figure A-12, results are presented relative to gross positive expenditures to allow composting and AD cost contribution analysis results to be viewed more clearly on the same axis scale. This figure shows that revenue is a smaller fraction of total expenditures for both of the AD scenarios as compared to composting. Still, the AD option leads to the highest revenue per metric ton of food waste processed, in the case of the base performance scenario as indicated by the X marks in the figure. Labor cost is included in the annual operation cost category and is offset by tipping fee revenue and the sale of finished compost. The sale of RECs and AECs leads to net revenue in the energy cost category for the WWTF.

Table A-13. Life Cycle Cost or Revenue per Metric Ton of Food Waste Treated

Treatment System	Performance Scenario	Life Cycle Cost (2016 $/Mg)	
		Base Cost	Low Cost
AD	Base	-7.6	-16
	Low	10	0.55
Windrow	Base	-4.5	-9.9
	Improved	-5.4	-11
ASP	Base	-2.4	-8.5
	Improved	-4.3	-10

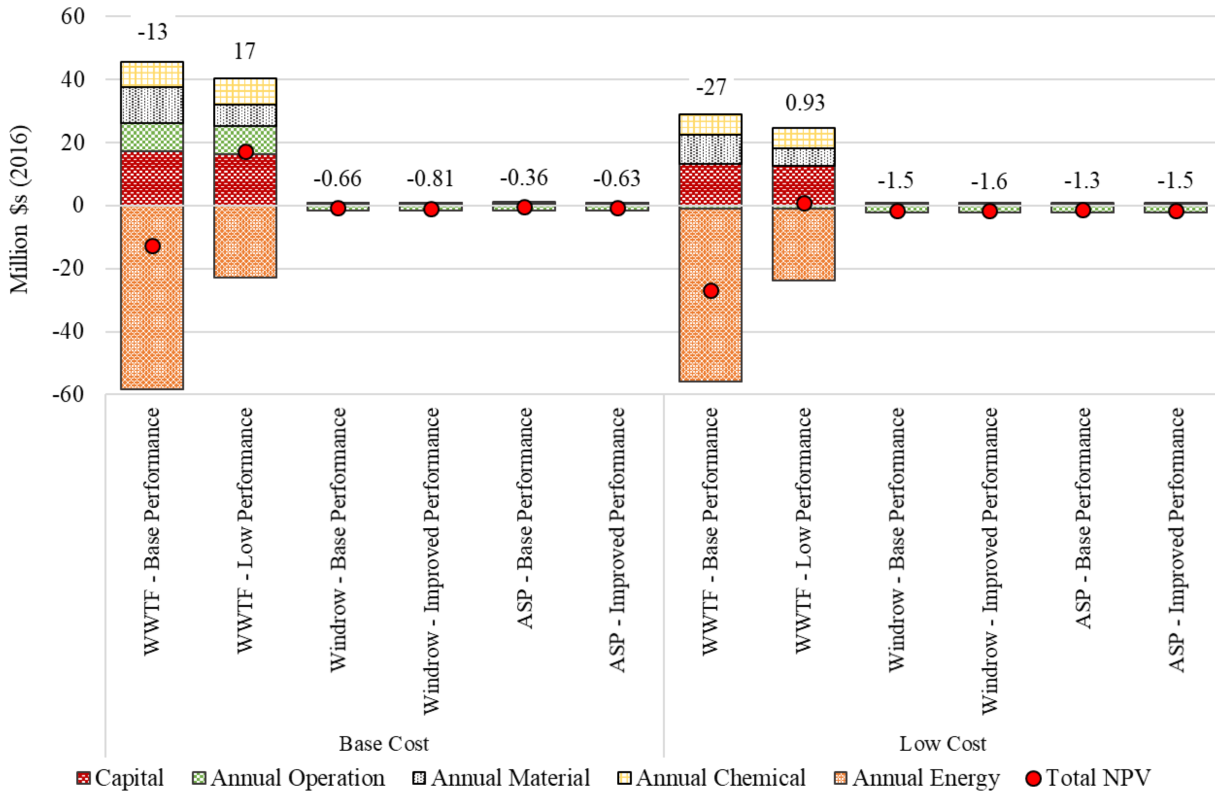


Figure A-11. Net present value life cycle costs by cost category.

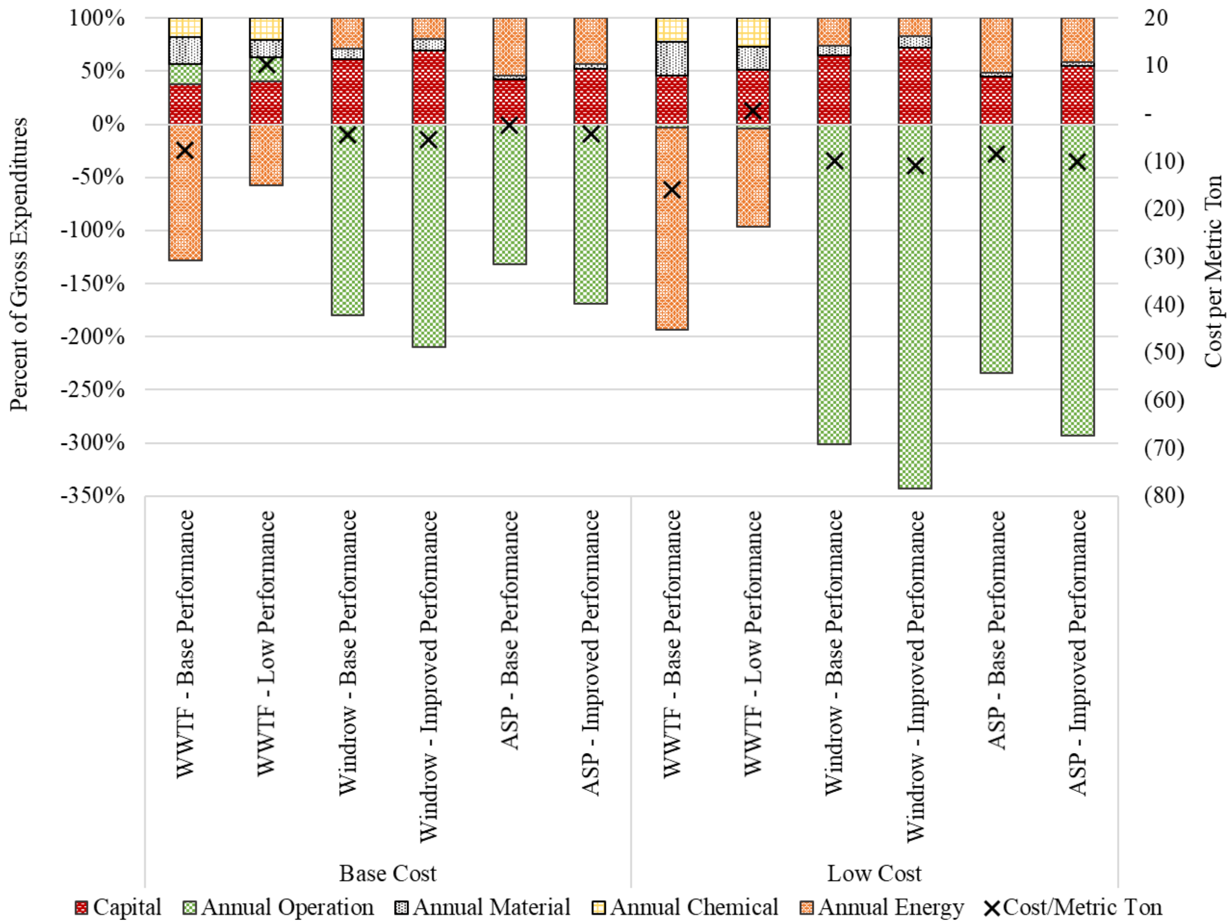


Figure A-12. Relative life cycle costs by cost category. Net cost per metric ton of food waste processed is marked with an X and values correspond to the secondary y-axis.

Compost LCA Results – Transport Distance Sensitivity

The availability of sufficient composting capacity in Eastern Massachusetts is not certain given the large quantity of organic material being considered. A regional transportation scenario was analyzed to determine the sensitivity of LCA results to longer transport distances, should local composting capacity prove insufficient for the considered waste volumes. The regional transport scenario assumes a hypothetical transport distance of food waste to the composting facility that is three times the calculated local transport distance, 203 km (125 miles).

Figure A-13 depicts relative LCA results for the windrow and ASP compost systems for both performance and transport distance scenarios. All windrow composting results are displayed in shades of blue with fill patterns that vary according to scenario assumptions. ASP compost system results are displayed in shades of green. Each pair of bars is labeled with values that represent the percent increase in impact associated with the regional transportation scenario, relative to the local transport scenario. Larger increases in LCA results indicate greater sensitivity to the underlying transport assumptions used in the analysis.

CED, FDP and SFP impact assessment results are most strongly affected by increased transportation distances, with relative increases in impact that range from 32 percent to 81 percent of impact potential when shifting from the local to regional transport scenario. The WU and EP impact results are negligibly affected by transport assumptions, less than 1 percent. Relative increases in impact potential are greater for the improved performance scenario due to the lower magnitude of impact potential, and the correspondingly greater influence of increased trucking.

While the impact assessment results are sensitive to transport distance assumptions in several impact categories, the realized shifts in impact do not have a material effect on the relative environmental performance of the five EOL treatment options discussed previously.

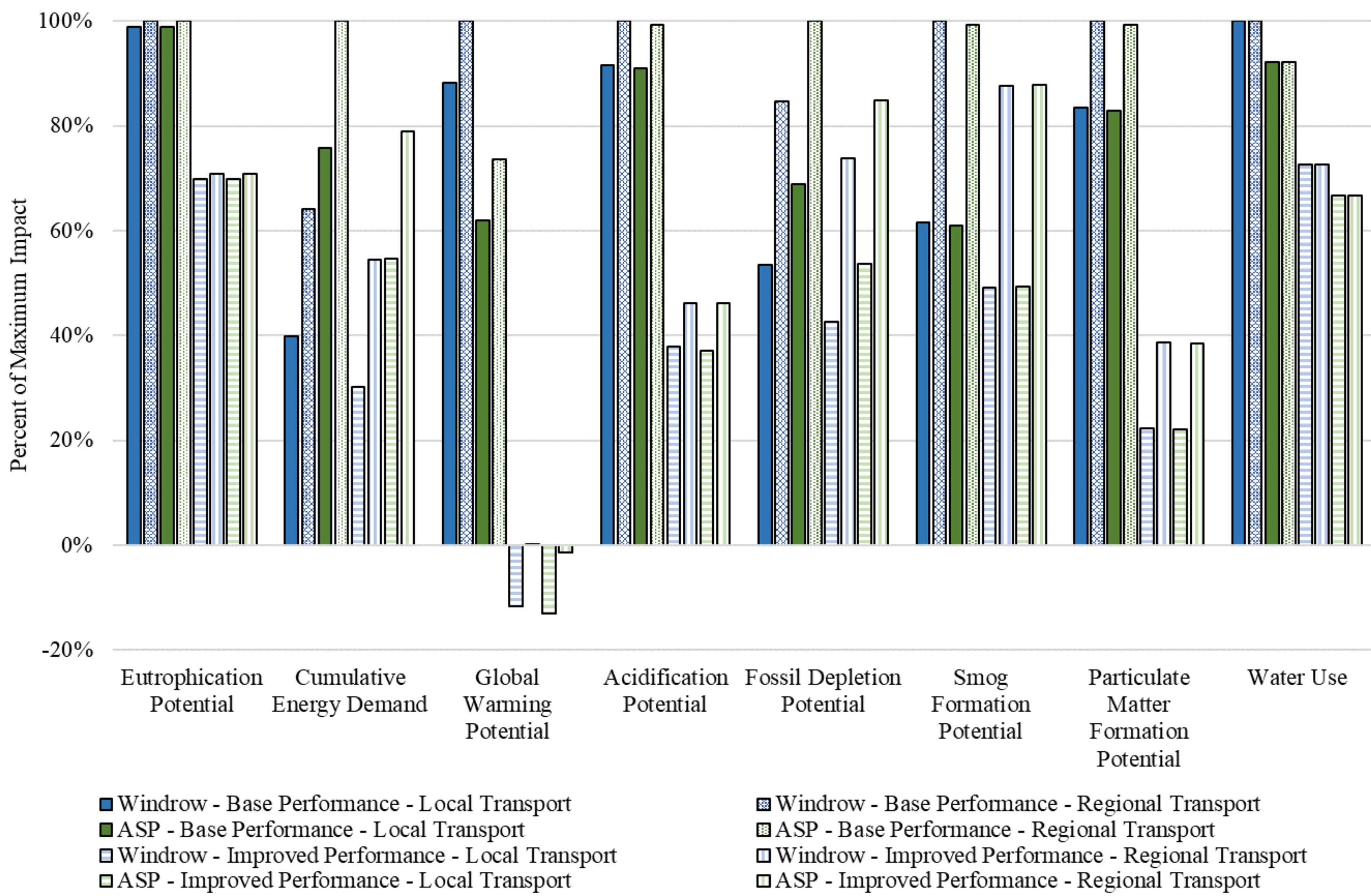


Figure A-13. Sensitivity of compost LCA results to food waste transportation distance.

Conclusions

This Appendix presents comparative LCA and LCCA results for five food waste EOL treatment and disposal options including anerobic digestion, windrow composting, aerated static pile composting, landfill disposal and WTE combustion. LCA results indicate that food waste treatment via AD produces considerable environmental benefits in six of eight impact categories assuming base AD performance. These benefits are primarily attributable to replacing grid electricity and natural gas with power and heat from biogas combustion. Composting treatment options generate larger environmental impacts in categories strongly dependent on energy production and consumption such as CED, AP, SFP and PMFP because all other treatment and disposal options capture at least a small fraction of the energy contained in food waste. Notable results include the high GWP of food waste disposal in landfills, and the low EP of landfill and WTE disposal options. WTE combustion performs reasonably well in all impact categories. An increase in EP is the largest possible tradeoff associated with co-digestion of food waste. Additional treatment options are available to address this issue.

The results indicate three unique approaches to food waste treatment. Anaerobic digestion recognizes the energy potential value of food waste, but requires a considerable capital investment to realize these benefits. The low AD performance scenario results demonstrate the importance of sound digester management if an overall economic benefit and maximum environmental benefits or reductions in environmental impact are to be achieved. Compost LCCA results depict a different strategy for food waste treatment with a much lower capital cost, that does not capture the energy potential and associated environmental benefit of food waste energy recovery. Both strategies recover nitrogen and phosphorus contained in the original food waste and put it to beneficial use as an agricultural amendment. The sale of compost to end users, is an important revenue stream for composting facilities, while the production and distribution of pelletized biosolids remains a net cost for the WWTF. Landfills and WTE disposal represent a third approach that is in line with the traditional approach to waste disposal where materials are effectively taken out of active circulation, albeit with energy recovery.

The scenarios and sensitivities presented in this Appendix highlight the importance of careful management of all systems and site specific consideration of important underlying model parameters where possible. The transportation sensitivity for example indicates strong sensitivity of several LCA impact categories to underlying assumptions about the distance the food waste or compost is assumed to travel. Other examples of key parameters that are expected to vary nationally include realized AD performance, fugitive methane emissions from digesters and landfills, GHG emissions from compost piles, and long-term carbon sequestration of land applied soil amendments. Appropriate interpretation of the reported results should consider such factors when drawing their own conclusions.

Appendix B:

Detailed LCI Calculations and Background Information

Appendix B
Detailed LCI Calculations
and Background Information

Process Emission Calculations

Process GHG emissions were calculated for biological treatment, anaerobic digestion and effluent release. Carbon dioxide releases from the WWTF were assumed to be biogenic in origin, do not contribute to global warming potential impact and were therefore excluded from the analysis. The following sections describe calculation procedures used to estimate process GHG emissions.

Nitrous Oxide Emissions from Biological Treatment

The methodology for calculating N_2O emissions associated with the biological wastewater treatment unit was based on IPCC guidelines for national inventories (IPCC 2006). The average N_2O emission factor of two MLE treatment systems, 0.16 percent influent TKN emitted as N_2O (EF%), was used to estimate N_2O emissions from biological treatment (Chandran 2012).

$$N_2O \text{ process emissions} = TKN\ (mg/L) \times Flow\ (gpd) \times 3.785\ L/gal \times 365.25\ days/yr \times 1x10\text{-}6\ kg/mg \times EF_{\%} \times 44/28$$

Equation B-1

Where:

N_2O process emissions = 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 (gpd)
$EF_{\%}$ = average measured percentage of TKN emitted as N_2O
44/28 = molecular weight conversion of N to N_2O

Methane Emissions from Biological Treatment

The methodology for calculating methane emissions associated with the biological wastewater treatment unit was based on IPCC guidelines for national inventories (IPCC 2006). Methane emissions were estimated using the amount of organic material (i.e., BOD) entering the unit operations that may exhibit anaerobic activity, an estimate of the theoretical maximum amount of methane that can be generated from the organic material (Bo), and a methane correction factor (MCF) that reflects the degree to which theoretical maximum methane generation rates are realized. In general, the IPCC does not estimate methane emissions from well managed centralized aerobic treatment systems. However, there is acknowledgement that some methane can be emitted from pockets of anaerobic activity and the treatment process evaluated has an anoxic zone preceding the aeration basin. An MCF of 0.05 was used to estimate CH_4 process emissions based on emission measurements from Daelman et al. (2013).

Daelman et al. (2013) reports measured emissions data from a WWTF in the Netherlands. The Netherlands biological treatment process includes an anoxic zone preceding the aerated zone. Unlike the Lawrence WWTF the Netherlands treatment process utilizes an internal recycle between the aerated and anoxic zones. The average reported methane emission factor is 11 g CH_4 per kg of influent COD, which converts to an MCF of approximately 0.044 using a B_O of 0.25 kg CH_4/kg COD (IPCC 2006).

$$\text{Methane process emissions} = \text{BOD (mg/L)} \times \text{Flow (gpd)} \times 3.785\ \text{L/gal} \times 365.25\ \text{days/yr} \times 1\text{x}10\text{-}6\ \text{kg/mg} \times \text{Bo} \times \text{MCF}$$

Equation B-2

Where:

Methane process emissions = Methane 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 (gpd)

Bo = maximum methane producing capacity, 0.6 kg CH_4/kg BOD (IPCC 2006)

MCF = methane correction factor (fraction)

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 (IPCC 2006). 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.

$$N_2O_{EFFLUENT} = N_{EFFLUENT} \times \text{Flow} \times 3.785\ \text{L/gal} \times 365.25\ \text{days/yr} \times 1\text{x}10\text{-}6\ \text{kg/mg} \times EF_3 \times 44/28$$

Equation B-3

Where:

$N_2O_{EFFLUENT}$ = N_2O emissions from wastewater effluent discharged to aquatic environments (kg N_2O/yr)

$N_{EFFLUENT}$ = Nitrogen 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

Avoided End-Of-Life Disposal Life Cycle Inventory Data

Table B-1 and Table B-2 list LCI flow information for the avoided landfill and WTE disposal processes. Results were generated using the Municipal Solid Waste Decision Support Tool (MSW DST) (RTI International 2012).

Table B-1. Massachusetts and National Average Landfill LCI, including Waste Collection

Parameter	Compartment	National Average Landfill	Massachusetts Landfill	Units
Energy, diesel	input	2.92E-7	2.92E-7	MJ/kg SSO

Table B-1. Massachusetts and National Average Landfill LCI, including Waste Collection

Parameter	Compartment	National Average Landfill	Massachusetts Landfill	Units
Electricity	output	0.025	0.021	kWh/kg SSO
Total Particulate Matter	air emission	1.85E-5	1.65E-5	kg/kg SSO
Nitrogen Oxides	air emission	1.15E-4	1.03E-4	kg/kg SSO
Hydrocarbons (non CH_4)	air emission	7.00E-6	7.00E-6	kg/kg SSO
Sulfur Oxides	air emission	6.06E-6	5.97E-6	kg/kg SSO
Carbon Monoxide	air emission	3.43E-5	3.37E-5	kg/kg SSO
Carbon Dioxide Biogenic	air emission	0.149	0.144	kg/kg SSO
Carbon Dioxide Fossil	air emission	2.01E-3	2.01E-3	kg/kg SSO
Ammonia (Air)	air emission	2.89E-9	2.89E-9	kg/kg SSO
Lead (Air)	air emission	1.26E-11	1.26E-11	kg/kg SSO
Methane (CH_4)	air emission	0.013	0.015	kg/kg SSO
Hydrochloric Acid	air emission	4.14E-6	3.83E-6	kg/kg SSO
Dissolved Solids	water discharge	1.22E-5	1.22E-5	kg/kg SSO
Suspended Solids	water discharge	3.10E-6	3.10E-6	kg/kg SSO
BOD	water discharge	1.45E-7	1.45E-7	kg/kg SSO
COD	water discharge	2.77E-8	2.77E-8	kg/kg SSO
Oil	water discharge	2.10E-7	2.10E-7	kg/kg SSO
Sulfuric Acid	water discharge	4.20E-5	4.20E-5	kg/kg SSO
Iron	water discharge	6.17E-10	6.17E-10	kg/kg SSO
Ammonia (Water)	water discharge	1.74E-9	1.74E-9	kg/kg SSO
Copper	water discharge	3.55E-9	3.55E-9	kg/kg SSO
Cadmium	water discharge	2.69E-14	2.69E-14	kg/kg SSO
Arsenic	water discharge	1.16E-10	1.16E-10	kg/kg SSO
Mercury (Water)	water discharge	1.05E-14	1.05E-14	kg/kg SSO
Phosphate	water discharge	8.76E-15	8.76E-15	kg/kg SSO
Selenium	water discharge	3.19E-10	3.19E-10	kg/kg SSO
Chromium	water discharge	2.74E-14	2.74E-14	kg/kg SSO
Lead (Water)	water discharge	1.16E-10	1.16E-10	kg/kg SSO
Zinc	water discharge	1.35E-12	1.35E-12	kg/kg SSO

Table B-2. Massachusetts and National Average WTE Combustion LCI, including Waste Collection

Parameter	Compartment	National Average WTE Combustion	Massachusetts WTE Combustion	Units
Energy, Diesel	input	5.32E-4	5.32E-4	gal/kg SSO
Natural Gas Use	input	0.020	0.020	MJ/kg SSO
Electricity Production	output	0.087	0.093	kWh/kg SSO
Total Particulate Matter	air emission	8.65E-6	1.16E-5	kg/kg SSO
Nitrogen Oxides	air emission	7.40E-5	1.67E-4	kg/kg SSO
Hydrocarbons (non CH_4)	air emission	1.86E-6	1.86E-6	kg/kg SSO
Sulfur Oxides	air emission	1.83E-5	3.14E-5	kg/kg SSO
Carbon Monoxide	air emission	1.75E-5	4.08E-5	kg/kg SSO
Carbon Dioxide Biogenic	air emission	0.212	0.212	kg/kg SSO
Carbon Dioxide Fossil	air emission	4.04E-3	4.04E-3	kg/kg SSO
Ammonia (Air)	air emission	1.66E-6	1.66E-6	kg/kg SSO
Lead (Air)	air emission	3.24E-9	3.24E-9	kg/kg SSO
Methane (CH_4)	air emission	3.52E-6	3.52E-6	kg/kg SSO
Hydrochloric Acid	air emission	1.27E-5	1.27E-5	kg/kg SSO
Dissolved Solids	water discharge	3.86E-6	3.86E-6	kg/kg SSO
Suspended Solids	water discharge	1.42E-7	1.42E-7	kg/kg SSO
BOD	water discharge	5.92E-9	5.92E-9	kg/kg SSO
COD	water discharge	2.45E-7	2.45E-7	kg/kg SSO
Oil	water discharge	4.37E-7	4.37E-7	kg/kg SSO
Sulfuric Acid	water discharge	1.16E-8	1.16E-8	kg/kg SSO
Iron	water discharge	6.26E-8	6.26E-8	kg/kg SSO
Ammonia (Water)	water discharge	4.32E-8	4.32E-8	kg/kg SSO
Copper	water discharge	2.83E-14	2.83E-14	kg/kg SSO
Cadmium	water discharge	1.76E-10	1.76E-10	kg/kg SSO
Arsenic	water discharge	7.87E-14	7.87E-14	kg/kg SSO
Mercury (Water)	water discharge	1.35E-14	1.35E-14	kg/kg SSO
Phosphate	water discharge	5.80E-9	5.80E-9	kg/kg SSO
Selenium	water discharge	1.69E-13	1.69E-13	kg/kg SSO
Chromium	water discharge	1.71E-10	1.71E-10	kg/kg SSO
Lead (Water)	water discharge	1.66E-12	1.66E-12	kg/kg SSO
Zinc	water discharge	6.29E-11	6.29E-11	kg/kg SSO

Nutrient Supplement

In order to assess whether the increased SSO loadings, commenced in February 2018, had any measurable effect on plant nutrient effluent concentrations, ERG conducted a preliminary analysis of historical water quality data. To try and isolate any effects of the process change, data for one year prior to the change were grouped (February 2017 through January 2018) and plotted alongside data after the process change, which at the time of data acquisition extended through June of 2018. Available effluent data for nitrogen and phosphorus are shown in Figure B-1 through Figure B-3, with the delineation in each figure corresponding to February 1, 2018.

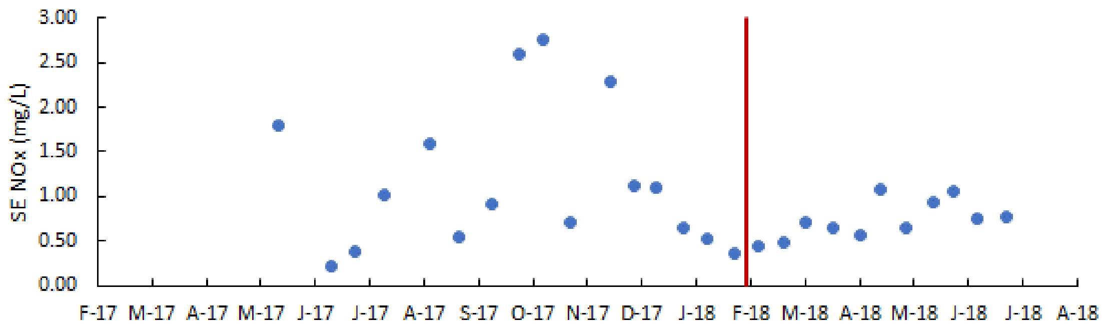


Figure B-1. Secondary effluent nitrate+nitrite, February 2017 through June 2018.

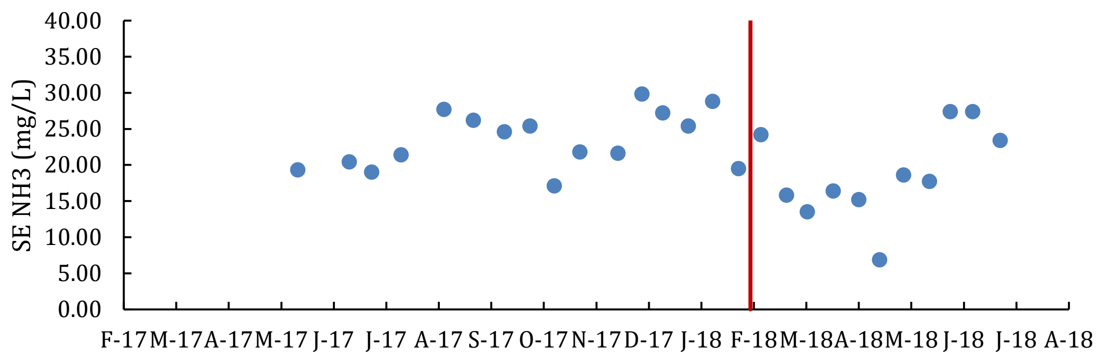


Figure B-2. Secondary effluent ammonia, February 2017 through June 2018.

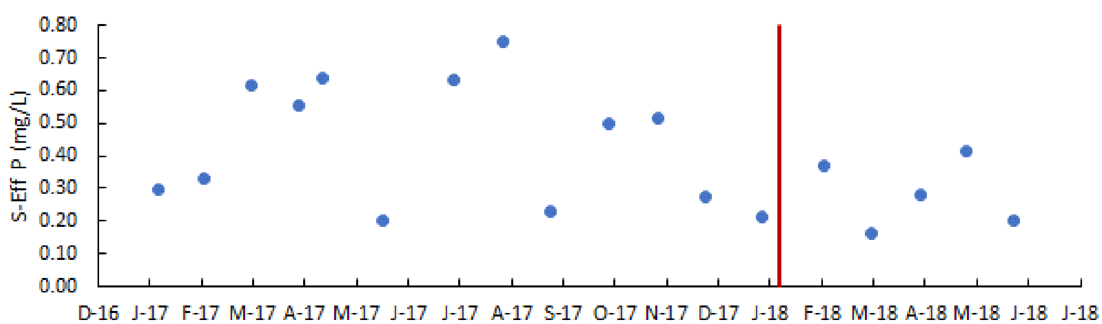


Figure B-3. Secondary effluent total phosphorus, February 2017 through June 2018.

Graphically, effluent nutrient levels appear to have decreased following the February 2018 process change, however all data sets have a considerable degree of variability. Moreover, when looking at long-term influent data, a seasonal pattern is apparent in the strength of wastewater received, with the lowest strength water appearing roughly February through April. This is best illustrated in the BOD and TSS datasets (Figure B-4 and Figure B-5) due to the greater frequency with which these parameters are measured.

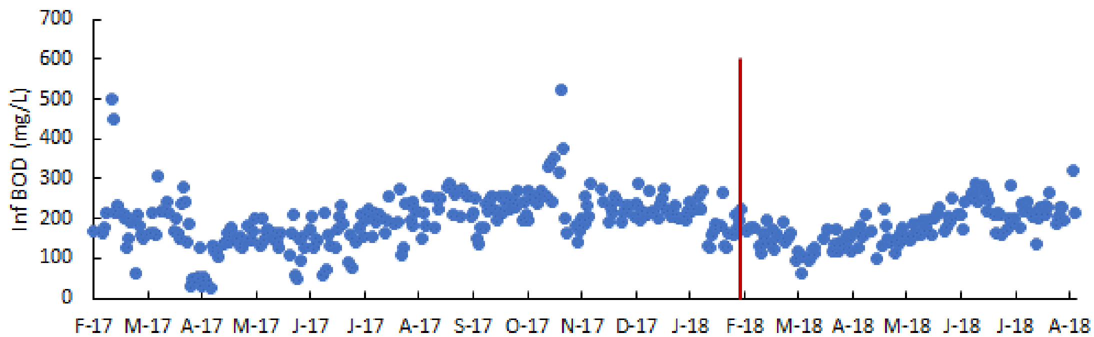


Figure B-4. Influent BOD data, February, 2017 through August, 2018.

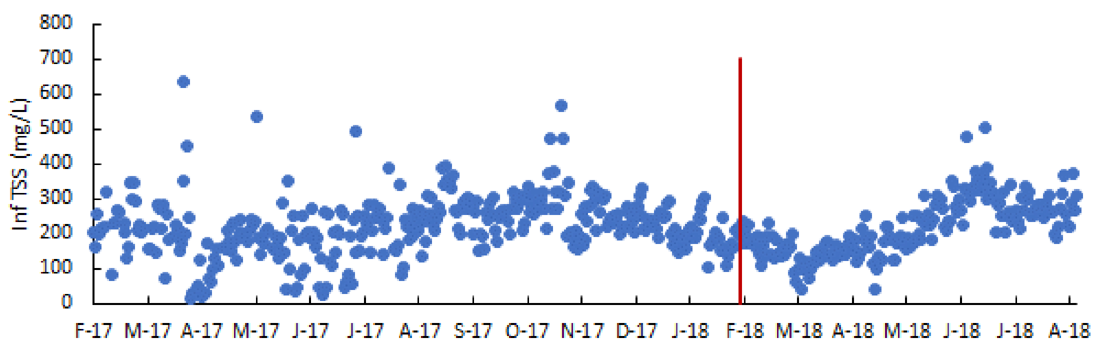


Figure B-5. Influent TSS data, February, 2017 through August, 2018.

Given these dataset limitations, which for effluent nutrient concentrations include sparse availability, a high degree of variability and incomplete seasonal coverage, t-tests were performed to test for statistical differences in like datasets. For each parameter above, groupings were made for pre- and post- process change data with equal seasonal coverage and tested for equal means. Equal seasonal coverage was established to remove any seasonal effect, though this also reduced the total sample sizes for some parameters. Seasonal groupings were made where there were approximately equivalent coverages in 2017 and 2018. Table B-3 summarizes these groupings and results. For the test that was used (t-test assuming unequal variances in Excel), the p-value is a measure of the statistical significance of the null hypothesis, which states that the sample means are equal. In other words, a low p-value would suggest that the sample means are not statistically equal.

Table B-3. Sample t-test Results, Assuming Unequal Variances

Parameter (mg/L)		Months	2017 Mean[1]	2018 Mean[1]	Change	P-value
Influent	BOD	Feb-Aug	168 (129)	180 (125)	7%	0.08
Influent	TSS	Feb-Aug	198 (176)	215 (192)	9%	0.07
Secondary Effluent	NOx	May-Jun	0.795 (3)	0.872 (4)	10%	0.89
Secondary Effluent	NH_3	May-Jun	19.6 (3)	24.0 (4)	23%	0.16
Secondary Effluent	TP	Feb-Jun	0.469 (5)	0.285 (5)	-39%	0.11

[1] value in parentheses refer to number of samples

Table B-3 indicates that none of the sample means are statistically different at the 95% confidence level (p-value ≤ 0.05). There is however suggestion that BOD and TSS influent concentrations increased (>90% confidence), ammonia effluent concentrations increased (>80% confidence) and total phosphorus effluent concentrations decreased (>85% confidence)., though effluent average concentrations are based on few observations.

The results do not therefore indicate a clear effect of the increased SSO acceptance on effluent nutrient concentrations. Although ammonia effluent concentrations did appear to increase, the change is not statistically significant and the change occurred over a time where the strength of the wastewater influent also increased. Moreover, the observed decrease in total phosphorus effluent concentrations is contradictory, indicating that the relationship between influent concentration, SSO load and effluent concentrations is not easily deduced at least from the current dataset. Additional data collection and comparison of a full year of pre- and post-process change effluent data may show a stronger relationship.

Appendix C:

LCCA Supporting Information and Detailed Results

Appendix C
LCCA Supporting Information and Detailed Results

Table C-1 shows the diesel, natural gas and electricity escalation factors that are used in the LCCA analysis. The escalation factors exclude general inflation and are specific to the Northeastern United States. Detailed LCCA results are presented in Table C-3 and Table C-4.

Table C-1. Energy Cost Escalation Factors

Year	Distillate Fuel Oil Escalation Factor	Natural Gas Escalation Factor[1]	Electricity Escalation Factor[1]
2016	1.00	1.00	1.00
2017	1.00	1.00	1.00
2018	1.12	1.02	0.980
2019	1.19	1.08	0.990
2020	1.22	1.18	1.01
2021	1.23	1.23	1.01
2022	1.25	1.26	1.03
2023	1.27	1.28	1.04
2024	1.29	1.30	1.05
2025	1.32	1.30	1.07
2026	1.34	1.29	1.09
2027	1.36	1.29	1.10
2028	1.37	1.31	1.11
2029	1.38	1.33	1.13
2030	1.41	1.35	1.14
2031	1.44	1.35	1.14
2032	1.47	1.36	1.14
2033	1.47	1.36	1.14
2034	1.49	1.38	1.13
2035	1.50	1.42	1.14
2036	1.53	1.45	1.15
2037	1.54	1.47	1.15
2038	1.55	1.48	1.15
2039	1.56	1.50	1.15
2040	1.58	1.49	1.15
2041	1.58	1.49	1.14
2042	1.58	1.50	1.14
2043	1.58	1.51	1.15
2044	1.58	1.53	1.15
2045	1.59	1.56	1.15

[1] (Lavappa et al. 2017)

Table C-2. Annual Estimates of Debt Service Expenditure.

Analysis Year	Year	Debt Service ($ 2016) - Plant Records			Debt Service ($ 2016) - Analysis Values	
		Baseline	CHP-AD Project	Partial and Full Capacity	Baseline	Partial and Full Capacity
year 1	2016	$ 3,316,494	$ -	$3,316,494	$ 3,316,494	$3,316,494
year 2	2017	$ 3,376,809	$ -	$3,376,809	$ 3,376,809	$3,376,809
year 3	2018	$ 3,255,369	$ -	$3,255,369	$ 3,255,369	$3,255,369
year 4	2019	$ 3,133,929	$ -	$3,133,929	$ 3,133,929	$3,133,929
year 5	2020	$ 3,137,225	$ -	$3,137,225	$ 3,137,225	$3,137,225
year 6	2021	$ 2,651,634	$1,427,317	$4,078,951	$ 2,651,634	$4,078,951
year 7	2022	$ 2,630,064	$1,409,541	$4,039,605	$ 2,630,064	$4,039,605
year 8	2023	$ 2,630,652	$1,411,210	$4,041,862	$ 2,630,652	$4,041,862
year 9	2024	$ 2,583,593	$1,412,916	$3,996,508	$ 2,583,593	$3,996,508
year 10	2025	$ 2,580,475	$1,414,657	$3,995,132	$ 2,580,475	$3,995,132
year 11	2026	$ 2,577,294	$1,416,437	$3,993,730	$ 2,929,625	$4,346,061
year 12	2027	$ 1,302,075	$1,418,256	$2,720,331	$ 2,929,625	$4,347,881
year 13	2028	$ 1,300,708	$1,420,114	$2,720,822	$ 2,929,625	$4,349,739
year 14	2029	$ 1,299,311	$1,422,013	$2,721,324	$ 2,929,625	$4,351,637
year 15	2030	$ 1,297,883	$1,423,952	$2,721,835	$ 2,929,625	$4,353,577
year 16	2031	$ 1,296,425	$1,425,934	$2,722,359	$ 2,929,625	$4,355,559
year 17	2032	$ 1,294,934	$1,427,960	$2,722,893	$ 2,929,625	$4,357,584
year 18	2033	$ 1,293,412	$1,430,028	$2,723,440	$ 2,929,625	$4,359,653
year 19	2034	$ 712,567	$1,432,143	$2,144,709	$ 2,929,625	$4,361,767
year 20	2035	$ 710,842	$1,434,302	$2,145,144	$ 2,929,625	$4,363,927
year 21	2036	$ 553,055	$1,436,509	$1,989,565	$ 2,929,625	$4,366,134
year 22	2037	$ 551,218	$1,438,764	$1,989,982	$ 2,929,625	$4,368,389
year 23	2038	$ 549,341	$1,441,068	$1,990,409	$ 2,929,625	$4,370,693
year 24	2039	$ 547,424	$1,443,422	$1,990,846	$ 2,929,625	$4,373,047
year 25	2040	$ 545,464	$1,445,828	$1,991,292	$ 2,929,625	$4,375,452
year 26	2041	$ 1,805,128	$ -	$2,946,423	$ 2,929,625	$2,929,625
year 27	2042	$ 1,805,128	$ -	$2,946,423	$ 2,929,625	$2,929,625
year 28	2043	$ 1,805,128	$ -	$2,946,423	$ 2,929,625	$2,929,625
year 29	2044	$ 1,805,128	$ -	$2,946,423	$ 2,929,625	$2,929,625
year 30	2045	$ 1,805,128	$ -	$2,946,423	$ 2,929,625	$2,929,625

Table C-3. Summary of Life Cycle Costs

Cost Scenario	Scenario (Feedstock, AD performance)	Capital	Annual Operation	Annual Material	Annual Chemical	Annual Energy	Total NPV
Base Cost	Baseline	96	106	37	14	61	314
	Partial Capacity, Low AD	115	111	44	18	41	329
	Partial Capacity, Base AD	115	111	47	18	10	301
	Full Capacity, Low AD	115	115	46	23	19	317
	Full Capacity, Base AD	115	115	52	23	-21	282
Low Cost	Baseline	77	85	30	11	49	251
	Partial Capacity, Low AD	91	85	35	15	29	255
	Partial Capacity, Base AD	91	85	38	15	2	230
	Full Capacity, Low AD	91	84	37	18	9	239
	Full Capacity, Base AD	91	84	41	18	-28	207

Table C-4. Detailed Life Cycle Costs – WWTF[1]

AD Scenario	Feed Stock Scenario[2]	General Cost Category	Detailed Cost Category	Process	Description	Wastewater Value[3]	Food Waste Value[4,5,6]	Unit
All	All	Chemical	Chemicals	AD & CHP	Defoamant	20,000	-	$/yr
All	All	Maintenance	General	AD & CHP	Digester Cleaning	500,000	166,667	$/replacement
All	All	Operation	General	AD & CHP	Draft Tube Leak	20,000	-	$
All	All Future Scenarios	Operation	Labor	AD & CHP	Additional Staffing	104,000	104,000	$/yr
All	All Future Scenarios	Maintenance	General	AD & CHP	Maintenance of AD and biogas processing	175,600	136,835	$/yr
All	Baseline	Energy	Natural Gas	AD & CHP	Utility Bills	37,214	n.a.	$/yr
All	Baseline	Chemical	Chemicals	AD & CHP	Ferric Chloride	31,797	n.a.	$/yr
All	Baseline	Energy	Electricity	AD & CHP	Utility Bills	235,205	n.a.	$/yr
All	Full Capacity	Chemical	Chemicals	AD & CHP	Ferric Chloride	39,746	7,949	$/yr
All	Full Capacity	Operation	Fee Revenue	AD & CHP	SSO	-167,900	-167,900	$/yr
All	Full Capacity	Energy	Electricity	AD & CHP	Utility Bills	300,539	65,335	$/yr
All	Partial Capacity	Chemical	Chemicals	AD & CHP	Ferric Chloride	35,772	n.a.	$/yr
All	Partial Capacity	Operation	Fee Revenue	AD & CHP	SSO	-83,950	n.a.	$/yr
All	Partial Capacity	Energy	Electricity	AD & CHP	Utility Bills	300,539	n.a.	$/yr
Baseline	Full Capacity	Energy	Electricity	AD & CHP	Electricity Sale	-3,380,142	-2,633,960	$/yr
Baseline	Full Capacity	Energy	Renewable Energy Credit	AD & CHP	Electricity Sale	-301,143	-234,665	$/yr
Baseline	Full Capacity	Maintenance	General	AD & CHP	CHP Maintenance	524,061	408,372	$/yr
Baseline	Full Capacity	Energy	Alternative Energy Credit	AD & CHP	Electricity Sale	-385,802	-300,634	$/yr
Baseline	Partial Capacity	Energy	Electricity	AD & CHP	Electricity Sale	-1,955,772	n.a.	$/yr
Baseline	Partial Capacity	Energy	Renewable Energy Credit	AD & CHP	Electricity Sale	-162,180	n.a.	$/yr
Baseline	Partial Capacity	Maintenance	General	AD & CHP	CHP Maintenance	303,225	n.a.	$/yr
Baseline	Partial Capacity	Energy	Alternative Energy Credit	AD & CHP	Electricity Sale	-292,182	n.a.	$/yr

Table C-4. Detailed Life Cycle Costs – WWTF[1]

AD Scenario	Feed Stock Scenario[2]	General Cost Category	Detailed Cost Category	Process	Description	Wastewater Value[3]	Food Waste Value[4,5,6]	Unit
Low	Full Capacity	Energy	Electricity	AD & CHP	Electricity Sale	-1,688,895	-1,169,866	$/yr
Low	Full Capacity	Energy	Renewable Energy Credit	AD & CHP	Electricity Sale	-136,144	-94,304	$/yr
Low	Full Capacity	Energy	Alternative Energy Credit	AD & CHP	Electricity Sale	-385,802	-267,238	$/yr
Low	Full Capacity	Maintenance	General	AD & CHP	CHP Maintenance	261,848	181,377	$/yr
Low	Partial Capacity	Energy	Electricity	AD & CHP	Electricity Sale	-901,215	n.a.	$/yr
Low	Partial Capacity	Energy	Renewable Energy Credit	AD & CHP	Electricity Sale	-59,297	n.a.	$/yr
Low	Partial Capacity	Energy	Alternative Energy Credit	AD & CHP	Electricity Sale	-221,853	n.a.	$/yr
Low	Partial Capacity	Maintenance	General	AD & CHP	CHP Maintenance	139,725	n.a.	$/yr
Low	Partial Capacity	Energy	Natural Gas	AD & CHP	Purchase	40,794	n.a.	$/yr
All	Baseline	Energy	Electricity	Biological Treatment	Utility Bills	621,612	n.a.	$/yr
All	Full Capacity	Energy	Electricity	Biological Treatment	Utility Bills	644,981	23,369	$/yr
All	Partial Capacity	Energy	Electricity	Biological Treatment	Utility Bills	632,518	n.a.	$/yr
All	All	Operation	Labor	Full Plant	Administration Salaries	620,572	-	$/yr
All	All	Operation	Labor	Full Plant	Monitoring Salaries	332,969	-	$/yr
All	All	Maintenance	Labor	Full Plant	Maintenance Salaries	760,210	-	$/yr
All	All	Operation	Labor	Full Plant	Operations Salaries	1,439,598	-	$/yr
All	All	Operation	General	Full Plant	Administrative Costs	737,213	-	$/yr
All	All	Operation	General	Full Plant	Monitoring	113,530	-	$/yr
All	All	Maintenance	General	Full Plant	Maintenance	2,000	-	$/yr
All	All	Operation	General	Full Plant	Operations	102,150	-	$/yr
All	All	Operation	Labor	Full plant	Fringe Benefits	943,621	-	$/yr
All	All	Maintenance	Labor	Full plant	Fringe Benefits	299,753	-	$/yr
All	All	Operation	General	Full Plant	Contingency	230,000	-	$/yr
All	All	Maintenance	Labor	Full Plant	Hired Maintenance Labor	312,765	-	$/yr

Table C-4. Detailed Life Cycle Costs – WWTF[1]

AD Scenario	Feed Stock Scenario[2]	General Cost Category	Detailed Cost Category	Process	Description	Wastewater Value[3]	Food Waste Value[4,5,6]	Unit
All	All	Maintenance	Materials	Full Plant	Mechanical and Electrical Supplies	418,483	-	$/yr
All	All	Operation	Diesel	Full plant	Gasoline for vehicles	19,000	-	$/yr
All	All	Operation	Water	Full plant	Utility Bills	17,236	-	$/yr
All	All	Chemical	Chemicals	Full Plant	Other Chemicals	2,000	-	$/yr
All	All	Energy	Renewable Energy Credit	Full Plant	Solar Electricity Plant	-15,000	-	$/yr
All	All	Operation	Fee Revenue	Full Plant	Industrial Surcharge	-110,000	-	$/yr
All	All	Operation	Fee Revenue	Full Plant	Industrial Cost Recovery	-3,000	-	$/yr
All	All	Operation	Fee Revenue	Full Plant	Other revenue	-7,200	-	$/yr
All	All	Operation	General	Full Plant	Waste Disposal, Utility	12,000	-	$/yr
All	All	Capital	Capital	Full Plant	Capital Projects	1,800,000	7,004	$/yr
All	Baseline	Energy	Natural Gas	Full plant	Utility Bills	121,793	n.a.	$/yr
All	Baseline	Energy	Electricity	Full plant	Utility Bills	33,601	n.a.	$/yr
All	Full Capacity	Energy	Electricity	Full plant	Utility Bills	35,281	1,680	$/yr
All	Partial Capacity	Energy	Electricity	Full plant	Utility Bills	35,281	n.a.	$/yr
Baseline	Full Capacity	Energy	Natural Gas	Full Plant	Purchase	-	-	$/yr
Baseline	Partial Capacity	Energy	Natural Gas	Full Plant	Purchase	-	n.a.	$/yr
Low	Full Capacity	Energy	Natural Gas	Full Plant	Purchase	-	-	$/yr
Low	Partial Capacity	Energy	Natural Gas	Full Plant	Purchase	121,793	n.a.	$/yr
All	All	Operation	General	Pelletization	Capacity Charge	2,293,445	-	$/yr
All	Baseline	Energy	Natural Gas	Pelletization	Utility Bills	6,766	n.a.	$/yr
All	Baseline	Operation	General	Pelletization	Processing Charge	66,462	n.a.	$/yr
All	Baseline	Energy	Electricity	Pelletization	Utility Bills	293,162	n.a.	$/yr
All	Full Capacity	Operation	General	Pelletization	Processing Charge	575,785	509,323	$/yr
All	Full Capacity	Energy	Electricity	Pelletization	Utility Bills	557,033	263,870	$/yr
All	Partial Capacity	Operation	General	Pelletization	Processing Charge	300,619	n.a.	$/yr

Table C-4. Detailed Life Cycle Costs – WWTF[1]

AD Scenario	Feed Stock Scenario[2]	General Cost Category	Detailed Cost Category	Process	Description	Wastewater Value[3]	Food Waste Value[4,5,6]	Unit
All	Partial Capacity	Energy	Electricity	Pelletization	Utility Bills	414,474	n.a.	$/yr
Low	Partial Capacity	Energy	Natural Gas	Pelletization	Utility Bills	6,766	n.a.	$/yr
All	All	Chemical	Chemicals	Plant Water & Disinfection	Sodium Hypochlorite	100,000	-	$/yr
All	All	Chemical	Chemicals	Plant Water & Disinfection	Sodium Bisulfite	100,000	-	$/yr
All	All	Operation	Fee Revenue	Plant Water & Disinfection	Effluent Sale	-72,000	-	$/yr
All	Baseline	Energy	Electricity	Plant Water & Disinfection	Utility Bills	134,403	n.a.	$/yr
All	Full Capacity	Energy	Electricity	Plant Water & Disinfection	Utility Bills	134,403	-	$/yr
All	Partial Capacity	Energy	Electricity	Plant Water & Disinfection	Utility Bills	134,403	n.a.	$/yr
All	All	Chemical	Chemicals	Preliminary and Primary Treatment	Potassium Perm. - Odor Control	11,000	-	$/yr
All	All	Operation	General	Preliminary and Primary Treatment	Grit Disposal	47,500	-	$/yr
All	All	Operation	Fee Revenue	Preliminary and Primary Treatment	Septage Receiving Fees	-1,500,000	-	$/yr
All	All	Operation	Fee Revenue	Preliminary and Primary Treatment	Outside Sludge	-60,000	-	$/yr
All	All	Operation	Materials	Preliminary and Primary Treatment	Activated Carbon, Grit	12,681	-	$/yr
All	All Future Scenarios	Maintenance	General	Preliminary and Primary Treatment	Additional Receiving Station	7,600	7,600	$/yr
All	Baseline	Energy	Electricity	Preliminary and Primary Treatment	Utility Bills	935,931	n.a.	$/yr
All	Full Capacity	Energy	Electricity	Preliminary and Primary Treatment	Utility Bills	935,931	-	$/yr
All	Partial Capacity	Energy	Electricity	Preliminary and Primary Treatment	Utility Bills	935,931	n.a.	$/yr
All	Baseline	Energy	Electricity	Secondary Clarification	Utility Bills	151,203	n.a.	$/yr
All	Full Capacity	Energy	Electricity	Secondary Clarification	Utility Bills	151,203	-	$/yr
All	Partial Capacity	Energy	Electricity	Secondary Clarification	Utility Bills	151,203	n.a.	$/yr

Table C-4. Detailed Life Cycle Costs – WWTF[1]

AD Scenario	Feed Stock Scenario[2]	General Cost Category	Detailed Cost Category	Process	Description	Wastewater Value[3]	Food Waste Value[4,5,6]	Unit
All	Baseline	Chemical	Chemicals	Thickening & Dewatering	Polymer	447,149	n.a.	$/yr
All	Baseline	Energy	Electricity	Thickening & Dewatering	Utility Bills	201,604	n.a.	$/yr
All	Full Capacity	Chemical	Chemicals	Thickening & Dewatering	Polymer	843,865	396,716	$/yr
All	Full Capacity	Energy	Electricity	Thickening & Dewatering	Utility Bills	300,162	98,558	$/yr
All	Partial Capacity	Chemical	Chemicals	Thickening & Dewatering	Polymer	647,377	n.a.	$/yr
All	Partial Capacity	Energy	Electricity	Thickening & Dewatering	Utility Bills	251,643	n.a.	$/yr

[1] Costs presented in this table are annual or year one costs.

[2] All Future Scenarios includes both the partial and full capacity feedstock scenarios.

[3] Cost data in this column corresponds to LCCA results present in report Sections 5.10 and 6.5.

[4] Cost data in this column corresponds to LCCA results presented in report Appendix A.

[5] n.a. – not applicable. The baseline and partial capacity scenarios were not evaluated as part of the food waste EOL treatment analysis in Appendix A.

[6] Values of zero indicate no change in life cycle cost due to the addition of food waste co-digestion.

Appendix D:
LCIA Process Results

Appendix D
LCIA Process Results

The tables in this section include detailed LCIA results by treatment group for all feedstock, AD performance and avoided EOL disposal process scenarios.

Table D-1. Process LCIA Results for the MA Disposal Mix Avoided SSO Disposal Scenario

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
Global Warming Potential - kg CO_2 eq	WWTF, Total	0.36	6.6E-3	0.19	-0.28	-0.05
	Land Application	-3.7E-3	-5.4E-3	-5.4E-3	-7.3E-3	-7.3E-3
	Preliminary/Primary	0.03	0.03	0.03	0.03	0.03
	Pellet Drying	0.03	0.04	0.04	0.05	0.05
	Influent Pump Station	0.07	0.07	0.07	0.07	0.07
	Biological Treatment	0.18	0.18	0.18	0.18	0.18
	Sludge Dewatering	0.03	0.04	0.04	0.05	0.05
	Plant Water and Disinfection	-0.02	-0.02	-0.02	-0.02	-0.02
	Building Operation	0.03	3.3E-3	0.03	3.3E-3	3.3E-3
	Secondary Clarification	0.01	0.01	0.01	0.01	0.01
	Effluent Release	0.05	0.05	0.05	0.06	0.06
	Anaerobic Digestion and CHP	-0.05	-0.40	-0.24	-0.71	-0.48
Eutrophication Potential - kg N eq	WWTF, Total	0.02	0.03	0.03	0.03	0.03
	Land Application	9.0E-4	1.3E-3	1.3E-3	1.7E-3	1.7E-3
	Preliminary/Primary	2.8E-5	2.8E-5	2.8E-5	2.8E-5	2.8E-5
	Pellet Drying	6.3E-6	9.0E-6	9.2E-6	1.2E-5	1.2E-5
	Influent Pump Station	7.4E-6	7.4E-6	7.4E-6	7.4E-6	7.4E-6
	Biological Treatment	5.6E-6	5.7E-6	5.7E-6	5.8E-6	5.8E-6
	Sludge Dewatering	5.9E-5	8.6E-5	8.6E-5	1.1E-4	1.1E-4
	Plant Water and Disinfection	-2.9E-5	-2.9E-5	-2.9E-5	-2.9E-5	-2.9E-5
	Building Operation	4.7E-6	5.6E-7	4.7E-6	5.6E-7	5.6E-7

Table D-1. Process LCIA Results for the MA Disposal Mix Avoided SSO Disposal Scenario

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
	Secondary Clarification	1.4E-6	1.4E-6	1.4E-6	1.4E-6	1.4E-6
	Effluent Release	0.02	0.02	0.02	0.03	0.03
	Anaerobic Digestion and CHP	-1.3E-5	-1.9E-5	4.9E-6	-5.0E-5	-1.5E-5
Cumulative Energy Demand - MJ	WWTF, Total	5.0	-1.7	3.7	-6.4	1.2
	Land Application	-0.23	-0.32	-0.32	-0.43	-0.43
	Preliminary/Primary	1.1	1.1	1.1	1.1	1.1
	Pellet Drying	0.83	1.1	1.1	1.5	1.5
	Influent Pump Station	2.2	2.2	2.2	2.2	2.2
	Biological Treatment	1.7	1.7	1.7	1.7	1.7
	Sludge Dewatering	0.83	1.1	1.1	1.4	1.4
	Plant Water and Disinfection	-0.62	-0.62	-0.62	-0.62	-0.62
	Building Operation	0.58	0.10	0.59	0.10	0.10
	Secondary Clarification	0.41	0.41	0.41	0.41	0.41
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.8	-8.5	-3.6	-14	-6.2
Fossil Depletion Potential - kg oil eq	WWTF, Total	0.05	-0.07	0.02	-0.15	-0.04
	Land Application	-4.1E-3	-5.9E-3	-5.9E-3	-7.9E-3	-7.9E-3
	Preliminary/Primary	0.02	0.02	0.02	0.02	0.02
	Pellet Drying	0.01	0.01	0.01	0.02	0.02
	Influent Pump Station	0.03	0.03	0.03	0.03	0.03
	Biological Treatment	0.02	0.02	0.02	0.02	0.02
	Sludge Dewatering	0.01	0.02	0.02	0.02	0.02
	Plant Water and Disinfection	-7.5E-3	-7.5E-3	-7.5E-3	-7.5E-3	-7.5E-3
	Building Operation	0.01	1.2E-3	0.01	1.2E-3	1.2E-3
	Secondary Clarification	4.9E-3	4.9E-3	4.9E-3	4.9E-3	4.9E-3
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-0.05	-0.16	-0.08	-0.25	-0.14

Table D-1. Process LCIA Results for the MA Disposal Mix Avoided SSO Disposal Scenario

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
Particulate Matter Formation Potential - kg $PM_{2.5}$ eq	WWTF, Total	5.4E-5	1.8E-5	5.6E-5	-4.5E-6	4.4E-5
	Land Application	1.7E-6	2.3E-6	2.3E-6	3.2E-6	3.2E-6
	Preliminary/Primary	1.6E-5	1.6E-5	1.6E-5	1.6E-5	1.6E-5
	Pellet Drying	1.8E-5	2.7E-5	2.8E-5	3.7E-5	3.7E-5
	Influent Pump Station	9.1E-6	9.1E-6	9.1E-6	9.1E-6	9.1E-6
	Biological Treatment	6.8E-6	6.9E-6	6.9E-6	7.0E-6	7.0E-6
	Sludge Dewatering	1.1E-5	1.5E-5	1.5E-5	1.9E-5	1.9E-5
	Plant Water and Disinfection	7.1E-8	7.1E-8	7.1E-8	7.1E-8	7.1E-8
	Building Operation	5.7E-6	4.0E-7	5.7E-6	4.0E-7	4.0E-7
	Secondary Clarification	1.7E-6	1.7E-6	1.7E-6	1.7E-6	1.7E-6
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.6E-5	-6.1E-5	-2.9E-5	-9.8E-5	-5.0E-5
Acidification Potential - kg SO_2 eq	WWTF, Total	1.0E-3	6.6E-4	1.1E-3	5.4E-4	1.1E-3
	Land Application	4.1E-4	5.8E-4	5.8E-4	7.8E-4	7.8E-4
	Preliminary/Primary	1.8E-4	1.8E-4	1.8E-4	1.8E-4	1.8E-4
	Pellet Drying	1.9E-4	2.8E-4	2.8E-4	3.7E-4	3.7E-4
	Influent Pump Station	1.3E-4	1.3E-4	1.3E-4	1.3E-4	1.3E-4
	Biological Treatment	1.0E-4	1.0E-4	1.0E-4	1.0E-4	1.0E-4
	Sludge Dewatering	9.6E-5	1.3E-4	1.3E-4	1.7E-4	1.7E-4
	Plant Water and Disinfection	-6.3E-6	-6.3E-6	-6.3E-6	-6.3E-6	-6.3E-6
	Building Operation	6.7E-5	6.0E-6	6.7E-5	6.0E-6	6.0E-6
	Secondary Clarification	2.5E-5	2.5E-5	2.5E-5	2.5E-5	2.5E-5
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.8E-4	-7.6E-4	-3.6E-4	-1.2E-3	-6.2E-4
Smog Formation	WWTF, Total	0.02	8.3E-3	0.02	3.7E-3	0.02
	Land Application	-3.0E-4	-4.3E-4	-4.3E-4	-5.5E-4	-5.5E-4
	Preliminary/Primary	3.6E-3	3.6E-3	3.6E-3	3.6E-3	3.6E-3

Table D-1. Process LCIA Results for the MA Disposal Mix Avoided SSO Disposal Scenario

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
Potential - kg O_3 eq	Pellet Drying	3.6E-3	5.3E-3	5.4E-3	7.2E-3	7.2E-3
	Influent Pump Station	4.6E-3	4.6E-3	4.6E-3	4.6E-3	4.6E-3
	Biological Treatment	3.6E-3	3.6E-3	3.6E-3	3.7E-3	3.7E-3
	Sludge Dewatering	1.6E-3	2.1E-3	2.1E-3	2.5E-3	2.5E-3
	Plant Water and Disinfection	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3
	Building Operation	7.6E-4	2.1E-4	7.7E-4	2.1E-4	2.1E-4
	Secondary Clarification	8.6E-4	8.6E-4	8.6E-4	8.6E-4	8.6E-4
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-3.0E-4	-0.01	-1.7E-3	-0.02	-3.8E-3
Water Use - m^3 H_2O	WWTF, Total	-0.13	-0.12	-0.12	-0.12	-0.12
	Land Application	-3.4E-4	-4.7E-4	-4.7E-4	-6.4E-4	-6.4E-4
	Preliminary/Primary	8.4E-5	8.4E-5	8.4E-5	8.4E-5	8.4E-5
	Pellet Drying	8.8E-5	1.2E-4	1.2E-4	1.7E-4	1.7E-4
	Influent Pump Station	2.5E-4	2.5E-4	2.5E-4	2.5E-4	2.5E-4
	Biological Treatment	1.9E-4	1.9E-4	1.9E-4	1.9E-4	1.9E-4
	Sludge Dewatering	1.1E-4	1.4E-4	1.4E-4	1.8E-4	1.8E-4
	Plant Water and Disinfection	-0.13	-0.13	-0.13	-0.13	-0.13
	Building Operation	4.7E-4	4.6E-4	4.7E-4	4.6E-4	4.6E-4
	Secondary Clarification	4.6E-5	4.6E-5	4.6E-5	4.6E-5	4.6E-5
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	7.0E-5	8.3E-4	1.2E-3	1.7E-3	2.3E-3

Table Acronyms: AD – anaerobic digestion, CHP – combined heat and power, LCIA – life cycle impact assessment, MA – Massachusetts, SSO – source separated organics, WWTF – wastewater treatment facility

Table D-2. Process LCIA Results for the National Disposal Mix Avoided SSO Disposal Scenario

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
Global Warming Potential - kg CO_2 eq	WWTF, Total	0.36	-0.42	-0.23	-1.1	-0.90
	Land Application	-3.7E-3	-5.4E-3	-5.4E-3	-7.3E-3	-7.3E-3
	Preliminary/Primary	0.03	0.03	0.03	0.03	0.03
	Pellet Drying	0.03	0.04	0.04	0.05	0.05
	Influent Pump Station	0.07	0.07	0.07	0.07	0.07
	Biological Treatment	0.18	0.18	0.18	0.18	0.18
	Sludge Dewatering	0.03	0.04	0.04	0.05	0.05
	Plant Water and Disinfection	-0.02	-0.02	-0.02	-0.02	-0.02
	Building Operation	0.03	3.3E-3	0.03	3.3E-3	3.3E-3
	Secondary Clarification	0.01	0.01	0.01	0.01	0.01
	Effluent Release	0.05	0.05	0.05	0.06	0.06
	Anaerobic Digestion and CHP	-0.05	-0.82	-0.67	-1.6	-1.3
Eutrophication Potential - kg N eq	WWTF, Total	0.02	0.03	0.03	0.03	0.03
	Land Application	9.0E-4	1.3E-3	1.3E-3	1.7E-3	1.7E-3
	Preliminary/Primary	2.8E-5	2.8E-5	2.8E-5	2.8E-5	2.8E-5
	Pellet Drying	6.3E-6	9.0E-6	9.2E-6	1.2E-5	1.2E-5
	Influent Pump Station	7.4E-6	7.4E-6	7.4E-6	7.4E-6	7.4E-6
	Biological Treatment	5.6E-6	5.7E-6	5.7E-6	5.8E-6	5.8E-6
	Sludge Dewatering	5.9E-5	8.6E-5	8.6E-5	1.1E-4	1.1E-4
	Plant Water and Disinfection	-2.9E-5	-2.9E-5	-2.9E-5	-2.9E-5	-2.9E-5
	Building Operation	4.7E-6	5.6E-7	4.7E-6	5.6E-7	5.6E-7
	Secondary Clarification	1.4E-6	1.4E-6	1.4E-6	1.4E-6	1.4E-6
	Effluent Release	0.02	0.02	0.02	0.03	0.03
	Anaerobic Digestion and CHP	-1.3E-5	-2.2E-5	1.7E-6	-5.7E-5	-2.1E-5
Cumulative Energy Demand - MJ	WWTF, Total	5.0	-2.5	2.9	-8.0	-0.47
	Land Application	-0.23	-0.32	-0.32	-0.43	-0.43
	Preliminary/Primary	1.1	1.1	1.1	1.1	1.1
	Pellet Drying	0.83	1.1	1.1	1.5	1.5

Table D-2. Process LCIA Results for the National Disposal Mix Avoided SSO Disposal Scenario

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
	Influent Pump Station	2.2	2.2	2.2	2.2	2.2
	Biological Treatment	1.7	1.7	1.7	1.7	1.7
	Sludge Dewatering	0.83	1.1	1.1	1.4	1.4
	Plant Water and Disinfection	-0.62	-0.62	-0.62	-0.62	-0.62
	Building Operation	0.58	0.10	0.59	0.10	0.10
	Secondary Clarification	0.41	0.41	0.41	0.41	0.41
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.8	-9.3	-4.4	-15	-7.8
Fossil Depletion Potential - kg oil eq	WWTF, Total	0.05	-0.08	9.0E-3	-0.17	-0.06
	Land Application	-4.1E-3	-5.9E-3	-5.9E-3	-7.9E-3	-7.9E-3
	Preliminary/Primary	0.02	0.02	0.02	0.02	0.02
	Pellet Drying	0.01	0.01	0.01	0.02	0.02
	Influent Pump Station	0.03	0.03	0.03	0.03	0.03
	Biological Treatment	0.02	0.02	0.02	0.02	0.02
	Sludge Dewatering	0.01	0.02	0.02	0.02	0.02
	Plant Water and Disinfection	-7.5E-3	-7.5E-3	-7.5E-3	-7.5E-3	-7.5E-3
	Building Operation	0.01	1.2E-3	0.01	1.2E-3	1.2E-3
	Secondary Clarification	4.9E-3	4.9E-3	4.9E-3	4.9E-3	4.9E-3
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-0.05	-0.17	-0.09	-0.27	-0.16
Particulate Matter Formation Potential - kg $PM_{2.5}$ eq	WWTF, Total	5.4E-5	1.3E-5	5.1E-5	-1.4E-5	3.4E-5
	Land Application	1.7E-6	2.3E-6	2.3E-6	3.2E-6	3.2E-6
	Preliminary/Primary	1.6E-5	1.6E-5	1.6E-5	1.6E-5	1.6E-5
	Pellet Drying	1.8E-5	2.7E-5	2.8E-5	3.7E-5	3.7E-5
	Influent Pump Station	9.1E-6	9.1E-6	9.1E-6	9.1E-6	9.1E-6
	Biological Treatment	6.8E-6	6.9E-6	6.9E-6	7.0E-6	7.0E-6
	Sludge Dewatering	1.1E-5	1.5E-5	1.5E-5	1.9E-5	1.9E-5
	Plant Water and Disinfection	7.1E-8	7.1E-8	7.1E-8	7.1E-8	7.1E-8

Table D-2. Process LCIA Results for the National Disposal Mix Avoided SSO Disposal Scenario

	AD Scenario	Base	Base	Low	Base	Low
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
	Building Operation	5.7E-6	4.0E-7	5.7E-6	4.0E-7	4.0E-7
	Secondary Clarification	1.7E-6	1.7E-6	1.7E-6	1.7E-6	1.7E-6
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.6E-5	-6.6E-5	-3.4E-5	-1.1E-4	-6.0E-5
Acidification Potential - kg SO_2 eq	WWTF, Total	1.0E-3	5.9E-4	1.1E-3	3.8E-4	9.8E-4
	Land Application	4.1E-4	5.8E-4	5.8E-4	7.8E-4	7.8E-4
	Preliminary/Primary	1.8E-4	1.8E-4	1.8E-4	1.8E-4	1.8E-4
	Pellet Drying	1.9E-4	2.8E-4	2.8E-4	3.7E-4	3.7E-4
	Influent Pump Station	1.3E-4	1.3E-4	1.3E-4	1.3E-4	1.3E-4
	Biological Treatment	1.0E-4	1.0E-4	1.0E-4	1.0E-4	1.0E-4
	Sludge Dewatering	9.6E-5	1.3E-4	1.3E-4	1.7E-4	1.7E-4
	Plant Water and Disinfection	-6.3E-6	-6.3E-6	-6.3E-6	-6.3E-6	-6.3E-6
	Building Operation	6.7E-5	6.0E-6	6.7E-5	6.0E-6	6.0E-6
	Secondary Clarification	2.5E-5	2.5E-5	2.5E-5	2.5E-5	2.5E-5
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.8E-4	-8.4E-4	-4.4E-4	-1.4E-3	-7.8E-4
Smog Formation Potential - kg O_3 eq	WWTF, Total	0.02	4.9E-3	0.01	-3.1E-3	0.01
	Land Application	-3.0E-4	-4.3E-4	-4.3E-4	-5.5E-4	-5.5E-4
	Preliminary/Primary	3.6E-3	3.6E-3	3.6E-3	3.6E-3	3.6E-3
	Pellet Drying	3.6E-3	5.3E-3	5.4E-3	7.2E-3	7.2E-3
	Influent Pump Station	4.6E-3	4.6E-3	4.6E-3	4.6E-3	4.6E-3
	Biological Treatment	3.6E-3	3.6E-3	3.6E-3	3.7E-3	3.7E-3
	Sludge Dewatering	1.6E-3	2.1E-3	2.1E-3	2.5E-3	2.5E-3
	Plant Water and Disinfection	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3
	Building Operation	7.6E-4	2.1E-4	7.7E-4	2.1E-4	2.1E-4
	Secondary Clarification	8.6E-4	8.6E-4	8.6E-4	8.6E-4	8.6E-4
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-3.0E-4	-0.01	-5.1E-3	-0.02	-0.01

Table D-2. Process LCIA Results for the National Disposal Mix Avoided SSO Disposal Scenario

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
Water Use - m^3 H_2O	WWTF, Total	-0.13	-0.12	-0.12	-0.12	-0.12
	Land Application	-3.4E-4	-4.7E-4	-4.7E-4	-6.4E-4	-6.4E-4
	Preliminary/Primary	8.4E-5	8.4E-5	8.4E-5	8.4E-5	8.4E-5
	Pellet Drying	8.8E-5	1.2E-4	1.2E-4	1.7E-4	1.7E-4
	Influent Pump Station	2.5E-4	2.5E-4	2.5E-4	2.5E-4	2.5E-4
	Biological Treatment	1.9E-4	1.9E-4	1.9E-4	1.9E-4	1.9E-4
	Sludge Dewatering	1.1E-4	1.4E-4	1.4E-4	1.8E-4	1.8E-4
	Plant Water and Disinfection	-0.13	-0.13	-0.13	-0.13	-0.13
	Building Operation	4.7E-4	4.6E-4	4.7E-4	4.6E-4	4.6E-4
	Secondary Clarification	4.6E-5	4.6E-5	4.6E-5	4.6E-5	4.6E-5
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	7.0E-5	7.3E-4	1.1E-3	1.5E-3	2.1E-3

Table Acronyms: AD – anaerobic digestion, CHP – combined heat and power, LCIA – life cycle impact assessment, SSO – source separated organics, WWTF – wastewater treatment facility

Table D-3. Process LCIA Results Excluding Avoided SSO Disposal

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
Global Warming Potential - kg CO_2 eq	WWTF, Total	0.36	0.17	0.36	0.06	0.28
	Land Application	-3.7E-3	-5.4E-3	-5.4E-3	-7.3E-3	-7.3E-3
	Preliminary/Primary	0.03	0.03	0.03	0.03	0.03
	Pellet Drying	0.03	0.04	0.04	0.05	0.05
	Influent Pump Station	0.07	0.07	0.07	0.07	0.07
	Biological Treatment	0.18	0.18	0.18	0.18	0.18
	Sludge Dewatering	0.03	0.04	0.04	0.05	0.05
	Plant Water and Disinfection	-0.02	-0.02	-0.02	-0.02	-0.02
	Building Operation	0.03	3.3E-3	0.03	3.3E-3	3.3E-3
	Secondary Clarification	0.01	0.01	0.01	0.01	0.01
	Effluent Release	0.05	0.05	0.05	0.06	0.06
	Anaerobic Digestion and CHP	-0.05	-0.23	-0.08	-0.38	-0.15
Eutrophication Potential - kg N eq	WWTF, Total	0.02	0.03	0.03	0.03	0.03
	Land Application	9.0E-4	1.3E-3	1.3E-3	1.7E-3	1.7E-3
	Preliminary/Primary	2.8E-5	2.8E-5	2.8E-5	2.8E-5	2.8E-5
	Pellet Drying	6.3E-6	9.0E-6	9.2E-6	1.2E-5	1.2E-5
	Influent Pump Station	7.4E-6	7.4E-6	7.4E-6	7.4E-6	7.4E-6
	Biological Treatment	5.6E-6	5.7E-6	5.7E-6	5.8E-6	5.8E-6
	Sludge Dewatering	5.9E-5	8.6E-5	8.6E-5	1.1E-4	1.1E-4
	Plant Water and Disinfection	-2.9E-5	-2.9E-5	-2.9E-5	-2.9E-5	-2.9E-5
	Building Operation	4.7E-6	5.6E-7	4.7E-6	5.6E-7	5.6E-7
	Secondary Clarification	1.4E-6	1.4E-6	1.4E-6	1.4E-6	1.4E-6
	Effluent Release	0.02	0.02	0.02	0.03	0.03
	Anaerobic Digestion and CHP	-1.3E-5	-1.3E-5	1.0E-5	-4.0E-5	-4.3E-6
Cumulative Energy Demand - MJ	WWTF, Total	5.0	-3.4	2.0	-9.8	-2.2
	Land Application	-0.23	-0.32	-0.32	-0.43	-0.43
	Preliminary/Primary	1.1	1.1	1.1	1.1	1.1
	Pellet Drying	0.83	1.1	1.1	1.5	1.5

Table D-3. Process LCIA Results Excluding Avoided SSO Disposal

	AD Scenario	Base	Base	Low	Base	Low
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
	Influent Pump Station	2.2	2.2	2.2	2.2	2.2
	Biological Treatment	1.7	1.7	1.7	1.7	1.7
	Sludge Dewatering	0.83	1.1	1.1	1.4	1.4
	Plant Water and Disinfection	-0.62	-0.62	-0.62	-0.62	-0.62
	Building Operation	0.58	0.10	0.59	0.10	0.10
	Secondary Clarification	0.41	0.41	0.41	0.41	0.41
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.8	-10	-5.3	-17	-9.6
Fossil Depletion Potential - kg oil eq	WWTF, Total	0.05	-0.09	-1.1E-3	-0.19	-0.08
	Land Application	-4.1E-3	-5.9E-3	-5.9E-3	-7.9E-3	-7.9E-3
	Preliminary/Primary	0.02	0.02	0.02	0.02	0.02
	Pellet Drying	0.01	0.01	0.01	0.02	0.02
	Influent Pump Station	0.03	0.03	0.03	0.03	0.03
	Biological Treatment	0.02	0.02	0.02	0.02	0.02
	Sludge Dewatering	0.01	0.02	0.02	0.02	0.02
	Plant Water and Disinfection	-7.5E-3	-7.5E-3	-7.5E-3	-7.5E-3	-7.5E-3
	Building Operation	0.01	1.2E-3	0.01	1.2E-3	1.2E-3
	Secondary Clarification	4.9E-3	4.9E-3	4.9E-3	4.9E-3	4.9E-3
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-0.05	-0.18	-0.10	-0.29	-0.18
Particulate Matter Formation Potential - kg $PM_{2.5}$ eq	WWTF, Total	5.4E-5	2.0E-5	5.8E-5	-9.0E-8	4.8E-5
	Land Application	1.7E-6	2.3E-6	2.3E-6	3.2E-6	3.2E-6
	Preliminary/Primary	1.6E-5	1.6E-5	1.6E-5	1.6E-5	1.6E-5
	Pellet Drying	1.8E-5	2.7E-5	2.8E-5	3.7E-5	3.7E-5
	Influent Pump Station	9.1E-6	9.1E-6	9.1E-6	9.1E-6	9.1E-6
	Biological Treatment	6.8E-6	6.9E-6	6.9E-6	7.0E-6	7.0E-6
	Sludge Dewatering	1.1E-5	1.5E-5	1.5E-5	1.9E-5	1.9E-5
	Plant Water and Disinfection	7.1E-8	7.1E-8	7.1E-8	7.1E-8	7.1E-8
	Building Operation	5.7E-6	4.0E-7	5.7E-6	4.0E-7	4.0E-7

Table D-3. Process LCIA Results Excluding Avoided SSO Disposal

	AD Scenario	Base	Base	Low	Base	Low
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
	Secondary Clarification	1.7E-6	1.7E-6	1.7E-6	1.7E-6	1.7E-6
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.6E-5	-5.9E-5	-2.7E-5	-9.4E-5	-4.6E-5
Acidification Potential - kg SO_2 eq	WWTF, Total	1.0E-3	7.2E-4	1.2E-3	6.6E-4	1.3E-3
	Land Application	4.1E-4	5.8E-4	5.8E-4	7.8E-4	7.8E-4
	Preliminary/Primary	1.8E-4	1.8E-4	1.8E-4	1.8E-4	1.8E-4
	Pellet Drying	1.9E-4	2.8E-4	2.8E-4	3.7E-4	3.7E-4
	Influent Pump Station	1.3E-4	1.3E-4	1.3E-4	1.3E-4	1.3E-4
	Biological Treatment	1.0E-4	1.0E-4	1.0E-4	1.0E-4	1.0E-4
	Sludge Dewatering	9.6E-5	1.3E-4	1.3E-4	1.7E-4	1.7E-4
	Plant Water and Disinfection	-6.3E-6	-6.3E-6	-6.3E-6	-6.3E-6	-6.3E-6
	Building Operation	6.7E-5	6.0E-6	6.7E-5	6.0E-6	6.0E-6
	Secondary Clarification	2.5E-5	2.5E-5	2.5E-5	2.5E-5	2.5E-5
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.8E-4	-7.0E-4	-3.0E-4	-1.1E-3	-5.0E-4
Smog Formation Potential - kg O_3 eq	WWTF, Total	0.02	9.3E-3	0.02	5.7E-3	0.02
	Land Application	-3.0E-4	-4.3E-4	-4.3E-4	-5.5E-4	-5.5E-4
	Preliminary/Primary	3.6E-3	3.6E-3	3.6E-3	3.6E-3	3.6E-3
	Pellet Drying	3.6E-3	5.3E-3	5.4E-3	7.2E-3	7.2E-3
	Influent Pump Station	4.6E-3	4.6E-3	4.6E-3	4.6E-3	4.6E-3
	Biological Treatment	3.6E-3	3.6E-3	3.6E-3	3.7E-3	3.7E-3
	Sludge Dewatering	1.6E-3	2.1E-3	2.1E-3	2.5E-3	2.5E-3
	Plant Water and Disinfection	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3
	Building Operation	7.6E-4	2.1E-4	7.7E-4	2.1E-4	2.1E-4
	Secondary Clarification	8.6E-4	8.6E-4	8.6E-4	8.6E-4	8.6E-4
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-3.0E-4	-9.4E-3	-7.0E-4	-0.02	-1.7E-3

Table D-3. Process LCIA Results Excluding Avoided SSO Disposal

	AD Scenario	Base	Base	Low	Base	Low
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
Water Use - m^3 H_2O	WWTF, Total	-0.13	-0.12	-0.12	-0.12	-0.12
	Land Application	-3.4E-4	-4.7E-4	-4.7E-4	-6.4E-4	-6.4E-4
	Preliminary/Primary	8.4E-5	8.4E-5	8.4E-5	8.4E-5	8.4E-5
	Pellet Drying	8.8E-5	1.2E-4	1.2E-4	1.7E-4	1.7E-4
	Influent Pump Station	2.5E-4	2.5E-4	2.5E-4	2.5E-4	2.5E-4
	Biological Treatment	1.9E-4	1.9E-4	1.9E-4	1.9E-4	1.9E-4
	Sludge Dewatering	1.1E-4	1.4E-4	1.4E-4	1.8E-4	1.8E-4
	Plant Water and Disinfection	-0.13	-0.13	-0.13	-0.13	-0.13
	Building Operation	4.7E-4	4.6E-4	4.7E-4	4.6E-4	4.6E-4
	Secondary Clarification	4.6E-5	4.6E-5	4.6E-5	4.6E-5	4.6E-5
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	7.0E-5	6.4E-4	1.0E-3	1.4E-3	2.0E-3

Table Acronyms: AD – anaerobic digestion, CHP – combined heat and power, LCIA – life cycle impact assessment, SSO – source separated organics, WWTF – wastewater treatment facility

Table D-4. Process LCIA Results for 100% Landfill Avoided SSO Disposal Scenario

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
Global Warming Potential - kg CO_2 eq	WWTF, Total	0.36	-0.48	-0.29	-1.2	-1.0
	Land Application	-3.7E-3	-5.4E-3	-5.4E-3	-7.3E-3	-7.3E-3
	Preliminary/Primary	0.03	0.03	0.03	0.03	0.03
	Pellet Drying	0.03	0.04	0.04	0.05	0.05
	Influent Pump Station	0.07	0.07	0.07	0.07	0.07
	Biological Treatment	0.18	0.18	0.18	0.18	0.18
	Sludge Dewatering	0.03	0.04	0.04	0.05	0.05
	Plant Water and Disinfection	-0.02	-0.02	-0.02	-0.02	-0.02
	Building Operation	0.03	3.3E-3	0.03	3.3E-3	3.3E-3
	Secondary Clarification	0.01	0.01	0.01	0.01	0.01
	Effluent Release	0.05	0.05	0.05	0.06	0.06
	Anaerobic Digestion and CHP	-0.05	-0.88	-0.73	-1.7	-1.5
Eutrophication Potential - kg N eq	WWTF, Total	0.02	0.03	0.03	0.03	0.03
	Land Application	9.0E-4	1.3E-3	1.3E-3	1.7E-3	1.7E-3
	Preliminary/Primary	2.8E-5	2.8E-5	2.8E-5	2.8E-5	2.8E-5
	Pellet Drying	6.3E-6	9.0E-6	9.2E-6	1.2E-5	1.2E-5
	Influent Pump Station	7.4E-6	7.4E-6	7.4E-6	7.4E-6	7.4E-6
	Biological Treatment	5.6E-6	5.7E-6	5.7E-6	5.8E-6	5.8E-6
	Sludge Dewatering	5.9E-5	8.6E-5	8.6E-5	1.1E-4	1.1E-4
	Plant Water and Disinfection	-2.9E-5	-2.9E-5	-2.9E-5	-2.9E-5	-2.9E-5
	Building Operation	4.7E-6	5.6E-7	4.7E-6	5.6E-7	5.6E-7
	Secondary Clarification	1.4E-6	1.4E-6	1.4E-6	1.4E-6	1.4E-6
	Effluent Release	0.02	0.02	0.02	0.03	0.03
	Anaerobic Digestion and CHP	-1.3E-5	-2.2E-5	1.5E-6	-5.7E-5	-2.2E-5
Cumulative Energy Demand - MJ	WWTF, Total	5.0	-2.8	2.6	-8.5	-0.93
	Land Application	-0.23	-0.32	-0.32	-0.43	-0.43
	Preliminary/Primary	1.1	1.1	1.1	1.1	1.1
	Pellet Drying	0.83	1.1	1.1	1.5	1.5

Table D-4. Process LCIA Results for 100% Landfill Avoided SSO Disposal Scenario

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
	Influent Pump Station	2.2	2.2	2.2	2.2	2.2
	Biological Treatment	1.7	1.7	1.7	1.7	1.7
	Sludge Dewatering	0.83	1.1	1.1	1.4	1.4
	Plant Water and Disinfection	-0.62	-0.62	-0.62	-0.62	-0.62
	Building Operation	0.58	0.10	0.59	0.10	0.10
	Secondary Clarification	0.41	0.41	0.41	0.41	0.41
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.8	-9.6	-4.7	-16	-8.3
Fossil Depletion Potential - kg oil eq	WWTF, Total	0.05	-0.08	6.4E-3	-0.18	-0.06
	Land Application	-4.1E-3	-5.9E-3	-5.9E-3	-7.9E-3	-7.9E-3
	Preliminary/Primary	0.02	0.02	0.02	0.02	0.02
	Pellet Drying	0.01	0.01	0.01	0.02	0.02
	Influent Pump Station	0.03	0.03	0.03	0.03	0.03
	Biological Treatment	0.02	0.02	0.02	0.02	0.02
	Sludge Dewatering	0.01	0.02	0.02	0.02	0.02
	Plant Water and Disinfection	-7.5E-3	-7.5E-3	-7.5E-3	-7.5E-3	-7.5E-3
	Building Operation	0.01	1.2E-3	0.01	1.2E-3	1.2E-3
	Secondary Clarification	4.9E-3	4.9E-3	4.9E-3	4.9E-3	4.9E-3
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-0.05	-0.17	-0.10	-0.28	-0.16
Particulate Matter Formation Potential - kg $PM_{2.5}$ eq	WWTF, Total	5.4E-5	1.1E-5	4.9E-5	-1.7E-5	3.1E-5
	Land Application	1.7E-6	2.3E-6	2.3E-6	3.2E-6	3.2E-6
	Preliminary/Primary	1.6E-5	1.6E-5	1.6E-5	1.6E-5	1.6E-5
	Pellet Drying	1.8E-5	2.7E-5	2.8E-5	3.7E-5	3.7E-5
	Influent Pump Station	9.1E-6	9.1E-6	9.1E-6	9.1E-6	9.1E-6
	Biological Treatment	6.8E-6	6.9E-6	6.9E-6	7.0E-6	7.0E-6
	Sludge Dewatering	1.1E-5	1.5E-5	1.5E-5	1.9E-5	1.9E-5
	Plant Water and Disinfection	7.1E-8	7.1E-8	7.1E-8	7.1E-8	7.1E-8
	Building Operation	5.7E-6	4.0E-7	5.7E-6	4.0E-7	4.0E-7

Table D-4. Process LCIA Results for 100% Landfill Avoided SSO Disposal Scenario

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
	Secondary Clarification	1.7E-6	1.7E-6	1.7E-6	1.7E-6	1.7E-6
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.6E-5	-6.7E-5	-3.5E-5	-1.1E-4	-6.3E-5
Acidification Potential - kg SO_2 eq	WWTF, Total	1.0E-3	5.8E-4	1.1E-3	3.7E-4	9.8E-4
	Land Application	4.1E-4	5.8E-4	5.8E-4	7.8E-4	7.8E-4
	Preliminary/Primary	1.8E-4	1.8E-4	1.8E-4	1.8E-4	1.8E-4
	Pellet Drying	1.9E-4	2.8E-4	2.8E-4	3.7E-4	3.7E-4
	Influent Pump Station	1.3E-4	1.3E-4	1.3E-4	1.3E-4	1.3E-4
	Biological Treatment	1.0E-4	1.0E-4	1.0E-4	1.0E-4	1.0E-4
	Sludge Dewatering	9.6E-5	1.3E-4	1.3E-4	1.7E-4	1.7E-4
	Plant Water and Disinfection	-6.3E-6	-6.3E-6	-6.3E-6	-6.3E-6	-6.3E-6
	Building Operation	6.7E-5	6.0E-6	6.7E-5	6.0E-6	6.0E-6
	Secondary Clarification	2.5E-5	2.5E-5	2.5E-5	2.5E-5	2.5E-5
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.8E-4	-8.4E-4	-4.4E-4	-1.4E-3	-7.8E-4
Smog Formation Potential - kg O_3 eq	WWTF, Total	0.02	4.4E-3	0.01	-4.2E-3	9.3E-3
	Land Application	-3.0E-4	-4.3E-4	-4.3E-4	-5.5E-4	-5.5E-4
	Preliminary/Primary	3.6E-3	3.6E-3	3.6E-3	3.6E-3	3.6E-3
	Pellet Drying	3.6E-3	5.3E-3	5.4E-3	7.2E-3	7.2E-3
	Influent Pump Station	4.6E-3	4.6E-3	4.6E-3	4.6E-3	4.6E-3
	Biological Treatment	3.6E-3	3.6E-3	3.6E-3	3.7E-3	3.7E-3
	Sludge Dewatering	1.6E-3	2.1E-3	2.1E-3	2.5E-3	2.5E-3
	Plant Water and Disinfection	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3
	Building Operation	7.6E-4	2.1E-4	7.7E-4	2.1E-4	2.1E-4
	Secondary Clarification	8.6E-4	8.6E-4	8.6E-4	8.6E-4	8.6E-4
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-3.0E-4	-0.01	-5.7E-3	-0.03	-0.01
Water Use - m^3 H_2O	WWTF, Total	-0.13	-0.12	-0.12	-0.12	-0.12
	Land Application	-3.4E-4	-4.7E-4	-4.7E-4	-6.4E-4	-6.4E-4

Table D-4. Process LCIA Results for 100% Landfill Avoided SSO Disposal Scenario

	AD Scenario	Base	Base	Low	Base	Low
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
	Preliminary/Primary	8.4E-5	8.4E-5	8.4E-5	8.4E-5	8.4E-5
	Pellet Drying	8.8E-5	1.2E-4	1.2E-4	1.7E-4	1.7E-4
	Influent Pump Station	2.5E-4	2.5E-4	2.5E-4	2.5E-4	2.5E-4
	Biological Treatment	1.9E-4	1.9E-4	1.9E-4	1.9E-4	1.9E-4
	Sludge Dewatering	1.1E-4	1.4E-4	1.4E-4	1.8E-4	1.8E-4
	Plant Water and Disinfection	-0.13	-0.13	-0.13	-0.13	-0.13
	Building Operation	4.7E-4	4.6E-4	4.7E-4	4.6E-4	4.6E-4
	Secondary Clarification	4.6E-5	4.6E-5	4.6E-5	4.6E-5	4.6E-5
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	7.0E-5	7.1E-4	1.1E-3	1.5E-3	2.1E-3

Table Acronyms: AD – anaerobic digestion, CHP – combined heat and power, LCIA – life cycle impact assessment, SSO – source separated organics, WWTF – wastewater treatment facility

Table D-5. Process LCIA Results for 100% WTE Avoided SSO Disposal Scenario

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
Global Warming Potential - kg CO_2 eq	WWTF, Total	0.36	0.23	0.42	0.18	0.41
	Land Application	-3.7E-3	-5.4E-3	-5.4E-3	-7.3E-3	-7.3E-3
	Preliminary/Primary	0.03	0.03	0.03	0.03	0.03
	Pellet Drying	0.03	0.04	0.04	0.05	0.05
	Influent Pump Station	0.07	0.07	0.07	0.07	0.07
	Biological Treatment	0.18	0.18	0.18	0.18	0.18
	Sludge Dewatering	0.03	0.04	0.04	0.05	0.05
	Plant Water and Disinfection	-0.02	-0.02	-0.02	-0.02	-0.02
	Building Operation	0.03	3.3E-3	0.03	3.3E-3	3.3E-3
	Secondary Clarification	0.01	0.01	0.01	0.01	0.01
	Effluent Release	0.05	0.05	0.05	0.06	0.06
	Anaerobic Digestion and CHP	-0.05	-0.17	-0.02	-0.25	-0.02
Eutrophication Potential - kg N eq	WWTF, Total	0.02	0.03	0.03	0.03	0.03
	Land Application	9.0E-4	1.3E-3	1.3E-3	1.7E-3	1.7E-3
	Preliminary/Primary	2.8E-5	2.8E-5	2.8E-5	2.8E-5	2.8E-5
	Pellet Drying	6.3E-6	9.0E-6	9.2E-6	1.2E-5	1.2E-5
	Influent Pump Station	7.4E-6	7.4E-6	7.4E-6	7.4E-6	7.4E-6
	Biological Treatment	5.6E-6	5.7E-6	5.7E-6	5.8E-6	5.8E-6
	Sludge Dewatering	5.9E-5	8.6E-5	8.6E-5	1.1E-4	1.1E-4
	Plant Water and Disinfection	-2.9E-5	-2.9E-5	-2.9E-5	-2.9E-5	-2.9E-5
	Building Operation	4.7E-6	5.6E-7	4.7E-6	5.6E-7	5.6E-7
	Secondary Clarification	1.4E-6	1.4E-6	1.4E-6	1.4E-6	1.4E-6
	Effluent Release	0.02	0.02	0.02	0.03	0.03
	Anaerobic Digestion and CHP	-1.3E-5	-1.7E-5	6.5E-6	-4.7E-5	-1.2E-5
	WWTF, Total	5.0	-1.2	4.2	-5.3	2.2

Table D-5. Process LCIA Results for 100% WTE Avoided SSO Disposal Scenario

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
Cumulative Energy Demand - MJ	Land Application	-0.23	-0.32	-0.32	-0.43	-0.43
	Preliminary/Primary	1.1	1.1	1.1	1.1	1.1
	Pellet Drying	0.83	1.1	1.1	1.5	1.5
	Influent Pump Station	2.2	2.2	2.2	2.2	2.2
	Biological Treatment	1.7	1.7	1.7	1.7	1.7
	Sludge Dewatering	0.83	1.1	1.1	1.4	1.4
	Plant Water and Disinfection	-0.62	-0.62	-0.62	-0.62	-0.62
	Building Operation	0.58	0.10	0.59	0.10	0.10
	Secondary Clarification	0.41	0.41	0.41	0.41	0.41
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.8	-8.0	-3.1	-13	-5.2
Fossil Depletion Potential - kg oil eq	WWTF, Total	0.05	-0.06	0.02	-0.14	-0.03
	Land Application	-4.1E-3	-5.9E-3	-5.9E-3	-7.9E-3	-7.9E-3
	Preliminary/Primary	0.02	0.02	0.02	0.02	0.02
	Pellet Drying	0.01	0.01	0.01	0.02	0.02
	Influent Pump Station	0.03	0.03	0.03	0.03	0.03
	Biological Treatment	0.02	0.02	0.02	0.02	0.02
	Sludge Dewatering	0.01	0.02	0.02	0.02	0.02
	Plant Water and Disinfection	-7.5E-3	-7.5E-3	-7.5E-3	-7.5E-3	-7.5E-3
	Building Operation	0.01	1.2E-3	0.01	1.2E-3	1.2E-3
	Secondary Clarification	4.9E-3	4.9E-3	4.9E-3	4.9E-3	4.9E-3
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-0.05	-0.15	-0.08	-0.24	-0.13

Table D-5. Process LCIA Results for 100% WTE Avoided SSO Disposal Scenario

	AD Scenario	Base	Base	Low	Base	Low
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
Particulate Matter Formation Potential - kg $PM_{2.5}$ eq	WWTF, Total	5.4E-5	2.1E-5	5.9E-5	1.6E-6	5.0E-5
	Land Application	1.7E-6	2.3E-6	2.3E-6	3.2E-6	3.2E-6
	Preliminary/Primary	1.6E-5	1.6E-5	1.6E-5	1.6E-5	1.6E-5
	Pellet Drying	1.8E-5	2.7E-5	2.8E-5	3.7E-5	3.7E-5
	Influent Pump Station	9.1E-6	9.1E-6	9.1E-6	9.1E-6	9.1E-6
	Biological Treatment	6.8E-6	6.9E-6	6.9E-6	7.0E-6	7.0E-6
	Sludge Dewatering	1.1E-5	1.5E-5	1.5E-5	1.9E-5	1.9E-5
	Plant Water and Disinfection	7.1E-8	7.1E-8	7.1E-8	7.1E-8	7.1E-8
	Building Operation	5.7E-6	4.0E-7	5.7E-6	4.0E-7	4.0E-7
	Secondary Clarification	1.7E-6	1.7E-6	1.7E-6	1.7E-6	1.7E-6
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.6E-5	-5.8E-5	-2.6E-5	-9.2E-5	-4.4E-5
Acidification Potential - kg SO_2 eq	WWTF, Total	1.0E-3	7.0E-4	1.2E-3	6.1E-4	1.2E-3
	Land Application	4.1E-4	5.8E-4	5.8E-4	7.8E-4	7.8E-4
	Preliminary/Primary	1.8E-4	1.8E-4	1.8E-4	1.8E-4	1.8E-4
	Pellet Drying	1.9E-4	2.8E-4	2.8E-4	3.7E-4	3.7E-4
	Influent Pump Station	1.3E-4	1.3E-4	1.3E-4	1.3E-4	1.3E-4
	Biological Treatment	1.0E-4	1.0E-4	1.0E-4	1.0E-4	1.0E-4
	Sludge Dewatering	9.6E-5	1.3E-4	1.3E-4	1.7E-4	1.7E-4
	Plant Water and Disinfection	-6.3E-6	-6.3E-6	-6.3E-6	-6.3E-6	-6.3E-6
	Building Operation	6.7E-5	6.0E-6	6.7E-5	6.0E-6	6.0E-6
	Secondary Clarification	2.5E-5	2.5E-5	2.5E-5	2.5E-5	2.5E-5
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-1.8E-4	-7.2E-4	-3.2E-4	-1.2E-3	-5.5E-4

Table D-5. Process LCIA Results for 100% WTE Avoided SSO Disposal Scenario

	AD Scenario	**Base**	**Base**	**Low**	**Base**	**Low**
	Feedstock Scenario	**Baseline**	**Partial Capacity**	**Partial Capacity**	**Full Capacity**	**Full Capacity**
Smog Formation Potential - kg O_3 eq	WWTF, Total	0.02	0.01	0.02	7.4E-3	0.02
	Land Application	-3.0E-4	-4.3E-4	-4.3E-4	-5.5E-4	-5.5E-4
	Preliminary/Primary	3.6E-3	3.6E-3	3.6E-3	3.6E-3	3.6E-3
	Pellet Drying	3.6E-3	5.3E-3	5.4E-3	7.2E-3	7.2E-3
	Influent Pump Station	4.6E-3	4.6E-3	4.6E-3	4.6E-3	4.6E-3
	Biological Treatment	3.6E-3	3.6E-3	3.6E-3	3.7E-3	3.7E-3
	Sludge Dewatering	1.6E-3	2.1E-3	2.1E-3	2.5E-3	2.5E-3
	Plant Water and Disinfection	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3
	Building Operation	7.6E-4	2.1E-4	7.7E-4	2.1E-4	2.1E-4
	Secondary Clarification	8.6E-4	8.6E-4	8.6E-4	8.6E-4	8.6E-4
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	-3.0E-4	-8.5E-3	1.5E-4	-0.01	-4.9E-5
Water Use - m^3 H_2O	WWTF, Total	-0.13	-0.12	-0.12	-0.12	-0.12
	Land Application	-3.4E-4	-4.7E-4	-4.7E-4	-6.4E-4	-6.4E-4
	Preliminary/Primary	8.4E-5	8.4E-5	8.4E-5	8.4E-5	8.4E-5
	Pellet Drying	8.8E-5	1.2E-4	1.2E-4	1.7E-4	1.7E-4
	Influent Pump Station	2.5E-4	2.5E-4	2.5E-4	2.5E-4	2.5E-4
	Biological Treatment	1.9E-4	1.9E-4	1.9E-4	1.9E-4	1.9E-4
	Sludge Dewatering	1.1E-4	1.4E-4	1.4E-4	1.8E-4	1.8E-4
	Plant Water and Disinfection	-0.13	-0.13	-0.13	-0.13	-0.13
	Building Operation	4.7E-4	4.6E-4	4.7E-4	4.6E-4	4.6E-4
	Secondary Clarification	4.6E-5	4.6E-5	4.6E-5	4.6E-5	4.6E-5
	Effluent Release	-	-	-	-	-
	Anaerobic Digestion and CHP	7.0E-5	8.9E-4	1.3E-3	1.9E-3	2.5E-3

Table Acronyms: AD – anaerobic digestion, CHP – combined heat and power, LCIA – life cycle impact assessment, SSO – source separated organics, WTE – waste-to-energy, WWTF – wastewater treatment facility

Appendix E:
Data Quality Documentation

Appendix E
Data Quality Documentation

Table E-1 documents data quality scores corresponding to source reliability, completeness, temporal correlation, geographical correlation and technological correlation for developed LCI data and background unit processes drawn from existing LCI databases.

Table E-1. Documentation of Data Quality.

			Data Quality Indicator							
Scenario	**Input/output data**	**Data Description**	**Source Reliability**	**Completeness**	**Temporal Correlation**	**Geographical Correlation**	**Technological Correlation**	**LCA unit process name (if applicable)**	**LCA process, source database**	**Note**
Baseline	Inventory, electricity consumption	Baseline - Utility records:	1	1	1	1	1	electricity, ISO New England 2016, at user	n.a.	Plant records of total facility electricity and natural gas purchases for 2016
Partial capacity, Full capacity	Inventory, electricity consumption	Partial and full capacity - scaled baseline values	3	n.a.	n.a.	1	1	electricity, ISO New England 2016, at user	n.a.	see main report text for details.
Baseline	Inventory, natural gas consumption	Utility records: Plant records of total facility electricity and natural gas purchases for 2016.	1	1	1	1	1	Heat, natural gas at industrial furnace >100 kW	n.a.	
Partial capacity, Full capacity	Inventory, natural gas consumption	Partial and full capacity - scaled baseline values	3	n.a.	n.a.	1	1	Heat, natural gas at industrial furnace >100 kW	n.a.	see main report text for details.
All	Allocation factors, electricity	Electricity use was allocated to individual unit processes using allocation data from a 2009 energy efficiency evaluation. Values were adjusted to reflect estimated 2016 pellet drying energy demand	2	n.a.	3	1	1	n.a.	n.a.	See main report text for discussion of how 2016 electricity consumption records were used to inform electricity use in the partial and full capacity scenarios.
Base	Inventory, biogas production and use	Production - GPS-X model, validated against energy feasibility study Allocation to combustion units - hierarchy of use coupled with facility specific heat and electricity demand of pellet drying facility.	2	n.a.	n.a.	n.a.	1	Biogas production - Anaerobic digestion Biogas use - allocated to combustion processes	developed for this study	

Table E-1. Documentation of Data Quality.

Scenario	Input/output data	Data Description	Data Quality Indicator: Source Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation	LCA unit process name (if applicable)	LCA process, source database	Note
Base	Inventory, effluent quality & LCI unit process	Based on Annual 2016 DMR Data	1	1	1	1	1	Effluent release; MA case-study; wastewater treatment unit; m3 wastewater	developed for this study	
Partial capacity, Full capacity	Inventory, effluent quality & LCI unit process	Scaled 2016 DMR Releases based on calculated removal rate accounting for increased nutrient content of SSO	3	1	1	1	1	Effluent release; MA case-study; wastewater treatment unit; m3 wastewater	developed for this study	
All	Inventory, influent quality	BOD and TSS data were drawn from plant records for the year 2016	1	1	1	1	1	n.a.	n.a.	
All	Inventory, influent quality	VS, N and P data were based on representative values from the literature	2	n.a.	n.a.	2	n.a.	n.a.	n.a.	
All	Inventory, activated carbon	Based on volume data provided by facility and assumed material density	2	1	1	1	1	Granular activated carbon production; MA Case Study	developed for this study	
All	LCI unit process	Granular activated carbon production; MA Case Study	3	4	4	3	1	Granular activated carbon production; MA Case Study	developed for this study	Original study is based on production of 1 ton of GAC from bituminous coal. Study notes 3 tons of coal, 1600kwh, 330m3 of natural gas, and 400 km of transport are required. Study also notes that transport distance is arbitrary, but that the analysis showed low sensitivity to this parameter (Bayer et al. 2005)
All	Inventory, grit disposal	Grit disposal, based on plant records for 2016	1	1	1	1	1	disposal, inert waste, 5% water, to inert material landfill	ecoinvent 2.2	Held constant across scenarios.

Table E-1. Documentation of Data Quality.

Scenario	Input/output data	Data Description	Data Quality Indicator: Source Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation	LCA unit process name (if applicable)	LCA process, source database	Note
All	LCI unit process	disposal, inert waste, 5% water, to inert material landfill	3	3	4	3	1	disposal, inert waste, 5% water, to inert material landfill	ecoinvent 2.2	
All	Inventory, process GHG emissions	Estimates of N2O and CH4 process emissions from the aeration basin, AD and receiving waters	2	n.a.	n.a.	n.a.	2/3	included in biological treatment, anaerobic digestion, and effluent release	n.a.	See report text for details
All	Inventory, sodium bisulfite	Plant purchasing records	1	1	1	1	1	Sodium hydrogen Sulfite, 38% in solution	n.a.	
All	LCI unit process	Sodium hydrogen Sulfite, 38% in solution	3	3	4	2	1	Sodium hydrogen Sulfite, 38% in solution	Ecoinvent 3, adapted	Adapted to US context. Solution strength only affects transport processes per ecoinvent 2.2 documentation. (i.e. inventory quantity refers to pure chemical).
All	Inventory, sodium hypochlorite	Plant purchasing records	1	1	1	1	1	sodium hypochlorite, 15% in H2O, at plant	n.a.	
All	LCI unit process	sodium hypochlorite, 15% in H2O, at plant	3	3	4	3	1	sodium hypochlorite, 15% in H2O, at plant	ecoinvent 2.2	Solution strength only affects transport processes per ecoinvent 2.2 documentation. (i.e. inventory quantity refers to pure chemical).
All	Inventory, avoided potable water	Plant staff recommendation - internal reuse Plant records (2018) - offsite industrial reuse	1	1	1	1	1	Drinking Water Treatment; MA case study	n.a.	Estimated LCI quantity based on revenue using value of non-potable reuse water from literature.
Base	Inventory, ferric chloride	Plant chemical purchasing records	1	1	1	1	1	iron (III) chloride, 34% in H2O, at plant	n.a.	
Partial capacity, Full capacity	Inventory, ferric chloride	Scaled baseline value based on increase in AD capacity	2	n.a.	n.a.	n.a.	1	iron (III) chloride, 34% in H2O, at plant	n.a.	

Table E-1. Documentation of Data Quality.

Scenario	Input/output data	Data Description	Data Quality Indicator: Source Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation	LCA unit process name (if applicable)	LCA process, source database	Note
All	LCI unit process	iron (III) chloride, 34% in H2O, at plant	3	3	4	3	1	iron (III) chloride, 34% in H2O, at plant	ecoinvent 2.2	Solution strength only affects transport processes per ecoinvent 2.2 documentation. (i.e. inventory quantity refers to pure chemical).
All	LCI unit process	electricity, ISO New England 2016, at user	1	1	1	1	1	electricity, ISO New England 2016, at user	this study	2016 grid mix for New England.
All	LCI unit process	Heat, natural gas at industrial furnace >100 kW	3	3	4	3	1	Heat, natural gas at industrial furnace >100 kW	ecoinvent 2.2	
All	LCI unit process	Flare, CHP, glycol boiler and pellet dryer emissions from air permit application	1	1	1	1	1	Biogas, burned in CHP engine biogas, burned in flare, US biogas, burned in glycol boiler biogas, burned pellet dryer	developed for this study	Based on air permit application emission quantities specific to the installed units.
All	LCI unit process	electricity production, from biomass	3	3	4	2	1	Electricity, biomass, at power plant, adapted USLCI	US LCI, adapted	Added Biomass energy content
All	LCI unit process	electricity production, from coal	3	3	4	2	1	Electricity, bituminous coal, at power plant, adapted US LCI	US LCI, adapted	Replaced Dummy Flows:
All	LCI unit process	electricity production, hydropower	3	3	4	3	1	electricity, hydropower, at reservoir power plant, non-alpine regions	ecoinvent 2.2	
All	LCI unit process	electricity production, natural gas	3	3	4	2	1	Electricity, natural gas, at power plant, adapted USLCI	US LCI, adapted	Replaced 'Dummy Transport, pipeline, unspecified' by 'Transport, pipeline, natural gas'
All	LCI unit process	electricity production, solar	3	3	4	2	1	electricity, solar	EPA harmonized database	

Table E-1. Documentation of Data Quality.

Scenario	Input/output data	Data Description	Data Quality Indicator: Source Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation	LCA unit process name (if applicable)	LCA process, source database	Note
All	LCI unit process	electricity production, wind	3	3	4	2	1	electricity, wind	EPA harmonized database	
All	LCI unit process	electricity production, nuclear	3	3	4	2	1	electricity, nuclear, at power plant, ecoinvent US	ecoinvent adapted	
Partial capacity, Full capacity	Inventory, steel	Steel	2	4	n.a.	n.a.	n.a.	steel product manufacturing, average metal working	ecoinvent 2.2	
Partial capacity, Full capacity	Inventory, gravel	Gravel	2	4	n.a.	n.a.	n.a.	gravel, crushed, at WWTP, MA	ecoinvent 2.2, adapted	substituted regional electricity grid, added 50 km of transport.
Partial capacity, Full capacity	Inventory, concrete	Concrete	2	4	n.a.	n.a.	n.a.	ready mixed concrete, 20 MPa, at MA plant	Data extracted from U.S. Portland Cement Association's LCI Report on Portland Cement Concrete 2003	substituted regional electricity grid
Partial capacity, Full capacity	Inventory, CHP building	Building construction	2	4	n.a.	n.a.	n.a.	building, multi-story	ecoinvent 2.2	
Partial capacity, Full capacity	Inventory, excavation	Excavation	2	4	n.a.	n.a.	n.a.	excavation, hydraulic digger	ecoinvent 2.2	
All	Inventory, tractor use	Tractor, land application	2	3	4	3	2/3	Diesel, combusted in industrial equipment	EPA harmonized database	
All	Inventory, pellet transport	Truck, pellet hauling	2	3	4	2	1	Transport, combination truck, short-haul, diesel powered, Northeast	US LCI	
All	Inventory, land application emissions	Emissions associated with biosolids pellet land application	3	n.a.	n.a.	n.a.	n.a.	Digestate Pellets; Land Applied; MA case-study; per m3 wastewater	this study[1]	See Section 3.3.11
All	Inventory, potassium permanganate	Facility specific budget and chemical cost data	2	1	1	1	1	potassium permanganate, at plant	n.a.	

Table E-1. Documentation of Data Quality.

Scenario	Input/output data	Data Description	Source Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation	LCA unit process name (if applicable)	LCA process, source database	Note
			Data Quality Indicator							
All	LCI unit process	potassium permanganate, at plant	3	3	4	3	1	potassium permanganate, at plant	ecoinvent 2.2	
All	Inventory, septage and municipal solids hauling	Plant records of volume accepted and assumed transport distance.	2	n.a.	n.a.	n.a.	n.a.	Truck transport, class 8, heavy heavy-duty (HHD), diesel, long-haul, load factor 0.5	EPA harmonized database	
Baseline	Inventory, polymer	Plant records of polymer purchased	1	n.a.	n.a.	n.a.	n.a.	polyacrylamide S	n.a.	
Partial capacity, Full capacity	Inventory, polymer	Applied chemical dose rates to GPS-X estimates of solids processed	2	n.a.	n.a.	n.a.	n.a.	polyacrylamide S	n.a.	
Partial capacity, Full capacity	LCI unit process	Source Separated Organics, at WWTP	3	5	1	5	5	Source Separated Organics, at WWTP	developed for this study	Includes transport, electricity and water use. Uses very generalized assumptions due to a lack of other available data sources.
Partial capacity, Full capacity	LCI unit process	steel product manufacturing, average metal working	3	3	4	3	1	steel product manufacturing, average metal working	ecoinvent 2.2	
Partial capacity, Full capacity	LCI unit process	gravel, crushed, at WWTP, MA	3	3	4	3	1	gravel, crushed, at WWTP, MA	ecoinvent 2.2, adapted	substituted regional electricity grid, added 50 km of transport.
Partial capacity, Full capacity	LCI unit process	ready mixed concrete, 20 MPa, at MA plant	3	3	4	2	1	ready mixed concrete, 20 MPa, at MA plant	Data extracted from U.S. Portland Cement Association's LCI Report on Portland Cement Concrete 2003	substituted regional electricity grid

Table E-1. Documentation of Data Quality.

Scenario	Input/output data	Data Description	Source Reliability (Data Quality Indicator)	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation	LCA unit process name (if applicable)	LCA process, source database	Note
Partial capacity, Full capacity	LCI unit process	building, multi-story	3	3	4	3	1	building, multi-story	ecoinvent 2.2	
Partial capacity, Full capacity	LCI unit process	excavation, hydraulic digger	3	3	4	3	1	excavation, hydraulic digger	ecoinvent 2.2	
All	LCI unit process	Diesel, combusted in industrial equipment	3	3	4	2	1	Diesel, combusted in industrial equipment	EPA harmonized database	
All	LCI unit process	Transport, combination truck, short-haul, diesel powered, Northeast	3	3	4	2	1	Transport, combination truck, short-haul, diesel powered, Northeast	US LCI	
All	LCI unit process	Digestate Pellets; Land Applied; MA case-study; per m^3 wastewater	2	n.a.	n.a.	n.a.	n.a.	Digestate Pellets; Land Applied; MA case-study; per m^3 wastewater	this study[1]	See Section 3.3.11
All	LCI unit process	Drinking Water Treatment; MA case study	1	2	2	2	3	Drinking Water Treatment; MA case study	developed for this study	
All	LCI unit process	Heat, natural gas at industrial furnace >100 kW	3	3	4	2	1	Heat, natural gas at industrial furnace >100 kW	EPA harmonized database	
Partial capacity, Full capacity	LCI unit process	Avoided SSO landfilling - U.S.	2	2	2	2	1	Avoided SSO landfilling - U.S.	developed for this study	Based on modeling from MSW DST model
Partial capacity, Full capacity	LCI unit process	Avoided SSO Waste-to-Energy	2	2	2	2	1	Avoided SSO Waste-to-Energy	developed for this study	Based on modeling from MSW DST model, supplemented with emissions data from local WTE facility.
Partial capacity, Full capacity	Inventory, Avoided SSO landfill	Based on MA waste diversion, 2016/2017	1	n.a.	n.a.	n.a.	n.a.	Avoided SSO landfilling - U.S.	n.a.	
Partial capacity, Full capacity	Inventory, Avoided SSO WTE	Based on MA waste diversion, 2016/2017	1	n.a.	n.a.	n.a.	n.a.	Avoided SSO Waste-to-Energy	n.a.	

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