DECISION-MAKING IN THE SELECTION OF FOOD WASTE DIVERSION SYSTEMS FOR BOONE, NORTH CAROLINA: COMPARING COMPOSTING AND ANAEROBIC DIGESTION BY LIFE CYCLE ASSESSMENT AND COST BENEFIT ANALYSIS

A Thesis
by
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Abstract

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In modern society, food waste is a big environmental issue in terms of greenhouse gas emission and contamination of local soil and groundwater. Food waste is the largest waste stream dumping into landfills in the US. When food waste rots in landfills under anaerobic conditions, it generates methane and acid. Methane is a heat-trapping greenhouse gas that has 21 times greater global warming potential than carbon dioxide, and acid leaches into soil and groundwater causing soil and groundwater contamination in many old unlined landfills. In fact, food waste could be diverted into valuable resources through special treatment such as aerobic digestion (commonly called composting) and anaerobic digestion: compost and biogas. We can reduce environmental impacts of food waste by not dumping it into landfills and at the same time can generate valuable resources through food waste diversions.

Selecting an optimal diversion system for a specific site is not a simple process and varies depending on local conditions such as amount of food waste, market price of compost, electricity rate, and so on. The main purpose of this study is to gain a better understanding of the relative environmental burdens and economic benefits of alternative food waste diversion systems (i.e., aerobic and anaerobic digestions) and the current system (i.e., landfilling) and to provide baseline information for deciding the most appropriate food waste diversion system in Boone, North Carolina, USA. By conducting a life cycle assessment and cost-benefit analysis, quantified data of environmental impacts and economic benefits over the life cycle of all three options (i.e., landfill, aerobic and anaerobic digestions) were achieved. There have been storing indications that anaerobic digestion is the most environmentally beneficial food waste diversion system due to the avoidance of fossil fuel use for electricity and heat energy generation; however, aerobic digestion becomes more economically beneficial system when the total organic waste is 10,000 tons annually because of relatively cheaper capital cost and energy prices in the US. The results of this study can be beneficial for decision makers in selecting a rational food waste management system for their specific sites.

Acknowledgments

This study would not have been done without great help from many people. My sincere appreciation goes to my committee chair, Dr. James Houser, for his great advice and constant support throughout my M.S. program. Also, I would like to express many thanks to my committee members, Dr. Marie Hoepfl for her considerable guidance, caring, and patience, and Dr. Jeff Ramsdell for the noble academic advice and suggestions.

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I received strong support and encouragement from my family. I could not complete my study without the financial and mental support, and the knowledge from my husband, Dr. Ok-Youn Yu and big smile from my children, Jimin and Soomin. They helped me keep going forward. My accomplishment would have not been possible without their love.

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CHAPTER 1: INTRODUCTION

In modern society, food waste is a big environmental issue in terms of greenhouse gas (GHG) emission and contamination of local soil and groundwater. According to the United States Environmental Protection Agency (USEPA, 2013a), approximately 35 million tons of food waste, which is 21% of the total waste stream after recovery, was disposed in landfills, and only 3% of food waste was diverted from landfills and incinerators by composting in 2010 (Figure 1).

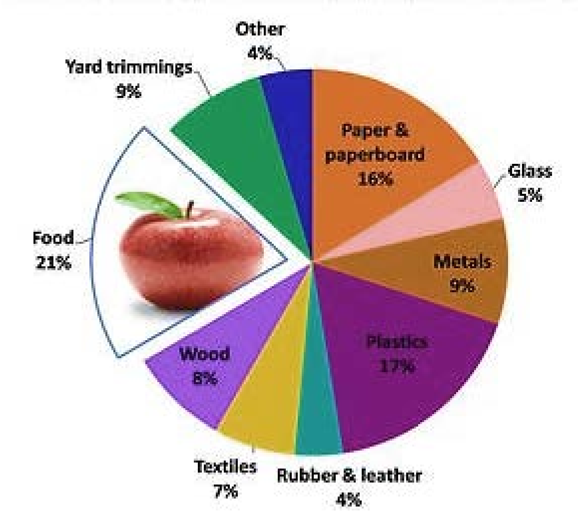


Figure 1. Components of municipal solid waste disposed in U.S., 2010 (USEPA, 2013a).

Landfills are the third largest source of human activity-related methane (CH_4) generation (Figure 2). When food waste rots in landfills under anaerobic conditions, it generates methane and acid. Methane is a heat-trapping greenhouse gas that has 21 times more global warming potential than carbon dioxide (USEPA, 2013b), and acid leaches into soil and groundwater causing soil and groundwater contamination in many old unlined landfills (Ahmed & Sulaiman, 2001). In addition, dumping food waste also causes wasting resources such as water, energy, chemicals used for food production, food packaging, and transportation by throwing away food waste (Gunders, 2013).

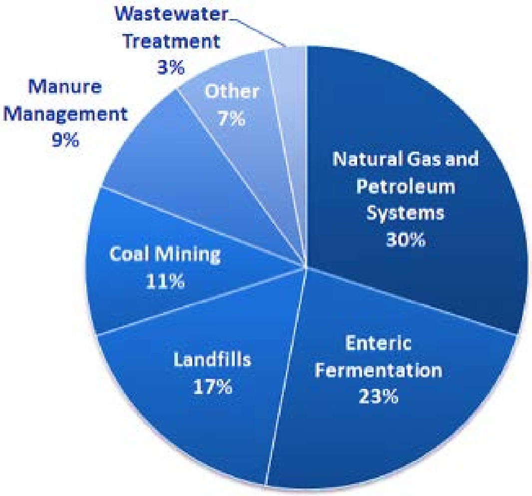


Figure 2. Methane emissions by source in the US, 2010 (USEPA, 2013c).

The USEPA has introduced the Food Waste Hierarchy, which presents, in descending order, the strategies it recommends for reducing food waste. These are (1) source reduction/prevention, (2) feeding hungry people, (3) feeding animals, (4) industrial uses, (5) composting and anaerobic digestion, and (6) landfills (USEPA, 2013a). Around 40% of edible food is wasted in the United States (Hall, Guo, Dore, & Chow, 2009), and the average American throws away about 20 pounds of edible food every month (Gustavsson, Cederberg, Sonesson, van Otterdijk, & Meybeck, 2011). If we generated approximately 15% less food waste, 25 million more people in the US could have adequate diets (Hall et al., 2009). We also generate inevitable food waste such as peels of potato, onion, fruit, egg, and so on. These kinds of food waste could be diverted through special treatments such as aerobic digestion (commonly called composting) and anaerobic digestion, yielding value-added products: compost and biogas (USEPA, 2013a; USEPA, 2014).

Bioenergy, such as biogas, biodiesel, and bioethanol, is a renewable energy that can be a solution for mitigating greenhouse gas emissions, minimizing fossil fuel dependency, and reducing waste disposal costs (Khanal, Surampili, Zhang, Lamsal, Tyagi, & Kao, 2010). The USEPA (2013d) describes several benefits of compost: Its use can reduce the need for chemical fertilizer, promote higher yield of agriculture crops, and amend contaminated, compacted, and marginal soils. If we can reduce environmental impacts by not dumping food waste into landfills and can at the same time generate valuable resources, why are we not diverting food waste?

Statement of the Problem

The North Carolina Department of Environment and Natural Resources (NCDENR) found that more than 1.1 million tons of food waste is generated annually in North Carolina (2012). Scott Mouw, the director of the state's recycling program, mentioned that food waste diversion represents a major opportunity for the state to increase material recovery and should become an increasing priority for local and state recycling programs (Oakes, 2012). In fact, Watauga County does not have any county-driven food waste collection or diversion system. In the county, only Appalachian State University (ASU) has a food waste composting facility and the town of Boone provides compost bins for town residents (Watauga County Sanitation Department [WCSD], 2012). The town of Beech Mountain operates a composing facility at its wastewater treatment plant (WWTP) site but only processes solids from the WWTP, chipped tree limbs, and collected leaves (WCSD, 2012).

Boone is located in the Appalachian Mountains and is known as a city of natural beauty. Residents of this area and students at ASU are proud of being a part of nature and take many efforts to protect the area's natural beauty. ASU's composting facility is one great example of the effort. This originally student-driven project was started with 18 tons of the school's food waste in 1999 and remodeled to 275-ton capacity in 2011 (ASU, 2014). The university is the only entity that is able to take advantage of this facility. In order to protect nature and meet one of university's goals, direct collaboration and connection with the community for its social and economic well-being, it would be worthwhile for the university to consider adding a larger size food waste diversion system that can treat the community's food waste as well. UW-Oshkosh's collaboration with the community could be a successful example.

As a starting point toward initiating the state's food waste recycling program, this study will be a useful resource to help municipalities predict the more beneficial future food waste diversion system in terms of environment and economy. Also, the methodology developed in this study could be a model to other communities that seek to build effective food waste diversion systems.

Research Questions

This study was guided by five research questions, which can be organized into two groups. Questions 1 and 2 will yield data that is critical to conducting the analyses that will be needed to answer questions 3, 4, and 5.

1. Approximately how much commercial food waste could be collected in Boone if a food waste collection system was implemented?

2. From the food waste collected, what amount of value-added outputs could be generated, in terms of the two processes of interest, namely (a) composting/compost, and (b) anaerobic digestion/biogas and digestate?
3. Based on the findings from a life-cycle assessment, what environmental benefits will be realized from composting and anaerobic digestion, respectively, in terms of climate change?
4. Based on the findings from a cost-benefit analysis, what economic benefits could be realized from composting and anaerobic digestion, respectively, in terms of cost avoidance compared to landfill and in terms of sales of value-added products?
5. Overall, what are the most critical factors that make one of these systems superior to the other in terms of greenhouse gas reduction and net present value?

Purpose of the Study

The purpose of this study is to gain a better understanding of the relative environmental burdens and economic benefits of alternative food waste diversion systems (aerobic and anaerobic digestion) and the current system (landfilling), and to provide baseline information for deciding the most appropriate food waste diversion system in Boone. By conducting a life-cycle Assessment and cost analysis, we can quantify environmental impacts and economic benefits over the life cycle of all three of these options.

Significance of the Study

This research may be beneficial for decision makers at Appalachian State University, the Town of Boone, and Watauga County regarding adoption of future food waste management systems. This study could be easily adapted to other locations, since the assessment is achieved by building a quantified database of environmental and economic benefits.

CHAPTER 2: REVIEW OF LITERATURE

Greenhouse Gases and the Greenhouse Effect

The earth's atmosphere acts like a blanket to keep the earth warm enough for living things: the so-called greenhouse effect (Halmann & Steinberg, 1999). The atmosphere absorbs some solar radiation directly from the sun, as well as reflected solar radiation from the earth's surface, but not all the gases in the earth's atmosphere can absorb heat. Carbon dioxide (CO_2) and water vapor (H_2O), which make up a small part of the atmosphere, can absorb heat due to their molecular structures. When the incoming solar radiation to the earth and the outgoing radiation from the earth are in energy balance, the earth reaches an equilibrium state (Halmann & Steinberg, 1999). In this state, the greenhouse effect is a good thing. The problem occurs when CO_2 concentrations in the atmosphere increase above the equilibrium point (Halmann & Steinberg, 1999). Increased CO_2 traps more heat; and then, the earth's surface temperature goes up, which puts more water vapor into the atmosphere. The resulting effect is called global warming, and global warming causes climate change (Halmann & Steinberg, 1999; USEPA, 2013c). There are other greenhouse gases that can absorb solar radiation and trap heat (USEPA, 2013c). As seen in Figure 3, the most important greenhouse gases emitted by human activities are carbon dioxide, methane, nitrous oxide, and fluorine-containing halogenated substances (USEPA, 2012). Earth's average temperature has risen by up to 1.4 °F over the past century due to those increased greenhouse gases (USEPA, 2013c). This global warming could affect human health and agricultural crop yields and could lead to ecosystem changes (USEPA, 2013c). As human activities, lifestyles, and world population have been changing for centuries, the concentrations of greenhouse gases in the atmosphere have also been continuously increasing (USEPA, 2012).

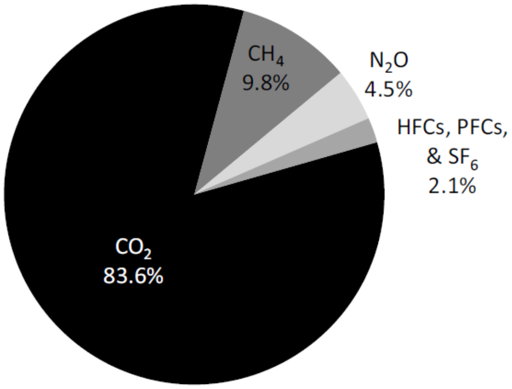
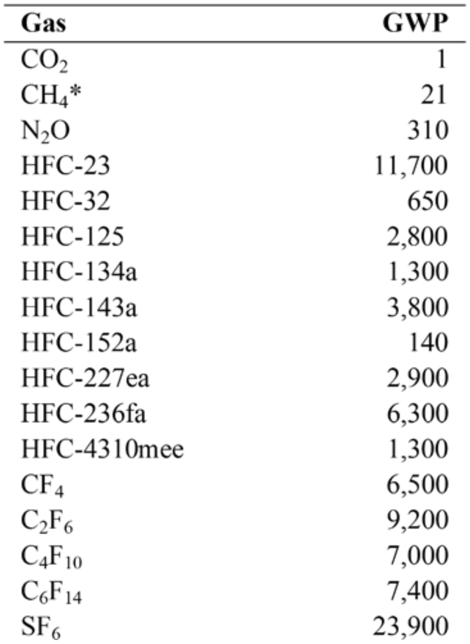


Figure 3. U.S. Greenhouse gas emissions by gas in 2010 (USEPA, 2012, p. 44).

Each greenhouse gas has different capability to absorb solar radiation. Global warming potential (GWP) is derived to provide a measure of the relative heat-absorbing effects of various greenhouse gases (Houghton, 1996). Table 1 shows GWPs of various greenhouse gases. GWP can be defined as cumulative heat radiation absorption of an emitted greenhouse gas over a certain period of time (usually 100 years), compared to a reference gas (CO_2); therefore, a global warming commitment of a certain greenhouse gas can be calculated by multiplying GWP by its emitted mass.

Table 1

Global Warming Potential of GHG (USEPA, 2012, p. 25)



Gas	GWP
CO_2	1
CH_4*	21
N_2O	310
HFC-23	11,700
HFC-32	650
HFC-125	2,800
HFC-134a	1,300
HFC-143a	3,800
HFC-152a	140
HFC-227ea	2,900
HFC-236fa	6,300
HFC-4310mee	1,300
CF_4	6,500
C_2F_6	9,200
C_4F_{10}	7,000
C_6F_{14}	7,400
SF_6	23,900

Methane (CH_4)

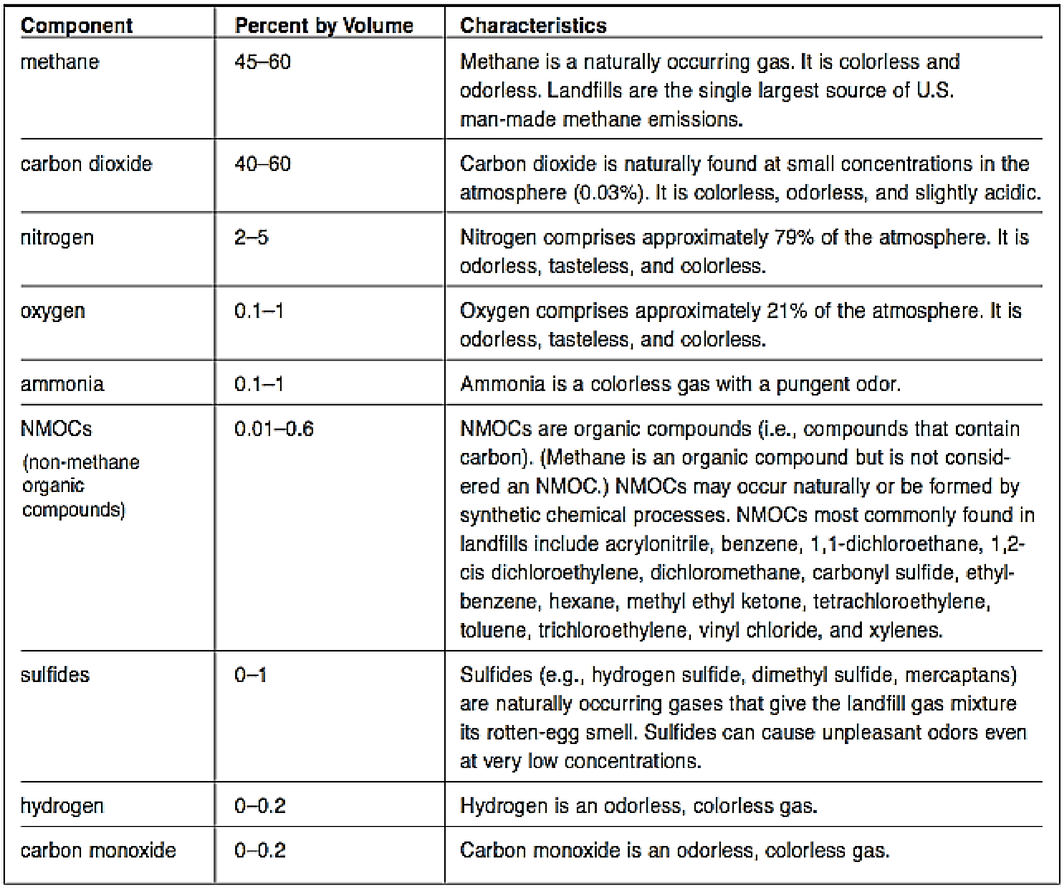
Methane is the second most common GHG emitted in the US (Figure 3), but its GWP is 21 times greater than the GWP of CO_2. Methane is emitted from various sources, including the oil industry, domestic livestock's digestive process, and the decomposition of organic matter such as carbohydrates, lipids, protein, and cellulosic materials (USEPA, 2013b). Even though methane is a potent greenhouse gas, it can also be an attractive fuel gas (Smith, Reay & Van Van Amstel, 2012). Methane, which is a main component of natural gas, is a flammable gas, so it can be utilized as an alternative fuel. CO_2 is a dominant greenhouse gas that is affecting global warming, but recent research suggests that reducing methane is a more efficient and cost-effective way to mitigate climate change (Smith, Reay & Van Van Amstel, 2012).

Landfills and Landfill Gases: The Third-largest Methane Generation Sector

Landfills are one of the main sources of methane gas in the US (Table 2). There are hundreds of different gases emitted by landfills, including greenhouse gases and acidifying gases (Table 2), but emissions typically contain 45% to 60% methane and 40% to 60 % carbon dioxide by volume (Agency for Toxic Substances & Disease Registry [ATSDR], 2001). Methane and carbon dioxide are major landfill gases and are produced from mostly organic waste such as food waste in landfills. Landfill gases are usually formed through three processes: bacterial decomposition, volatilization, and chemical reaction (ATSDR, 2001).

Table 2

Typical Landfill Gas Composition (ATSDR, 2001, p. 4)



Component	Percent by Volume	Characteristics
methane	45–60	Methane is a naturally occurring gas. It is colorless and odorless. Landfills are the single largest source of U.S. man-made methane emissions.
carbon dioxide	40–60	Carbon dioxide is naturally found at small concentrations in the atmosphere (0.03%). It is colorless, odorless, and slightly acidic.
nitrogen	2–5	Nitrogen comprises approximately 79% of the atmosphere. It is odorless, tasteless, and colorless.
oxygen	0.1–1	Oxygen comprises approximately 21% of the atmosphere. It is odorless, tasteless, and colorless.
ammonia	0.1–1	Ammonia is a colorless gas with a pungent odor.
NMOCs (non-methane organic compounds)	0.01–0.6	NMOCs are organic compounds (i.e., compounds that contain carbon). (Methane is an organic compound but is not considered an NMOC.) NMOCs may occur naturally or be formed by synthetic chemical processes. NMOCs most commonly found in landfills include acrylonitrile, benzene, 1,1-dichloroethane, 1,2-cis dichloroethylene, dichloromethane, carbonyl sulfide, ethylbenzene, hexane, methyl ethyl ketone, tetrachloroethylene, toluene, trichloroethylene, vinyl chloride, and xylenes.
sulfides	0–1	Sulfides (e.g., hydrogen sulfide, dimethyl sulfide, mercaptans) are naturally occurring gases that give the landfill gas mixture its rotten-egg smell. Sulfides can cause unpleasant odors even at very low concentrations.
hydrogen	0–0.2	Hydrogen is an odorless, colorless gas.
carbon monoxide	0–0.2	Carbon monoxide is an odorless, colorless gas.

Bacterial decomposition. Bacteria that exist in waste and soil degrade organic waste, and most landfill gases are produced through this process. Bacterial decomposition occurs in four phases, and each phase has different gas compositions. Figure 4 provides the gas composition by percentage in each bacterial decomposition phase.

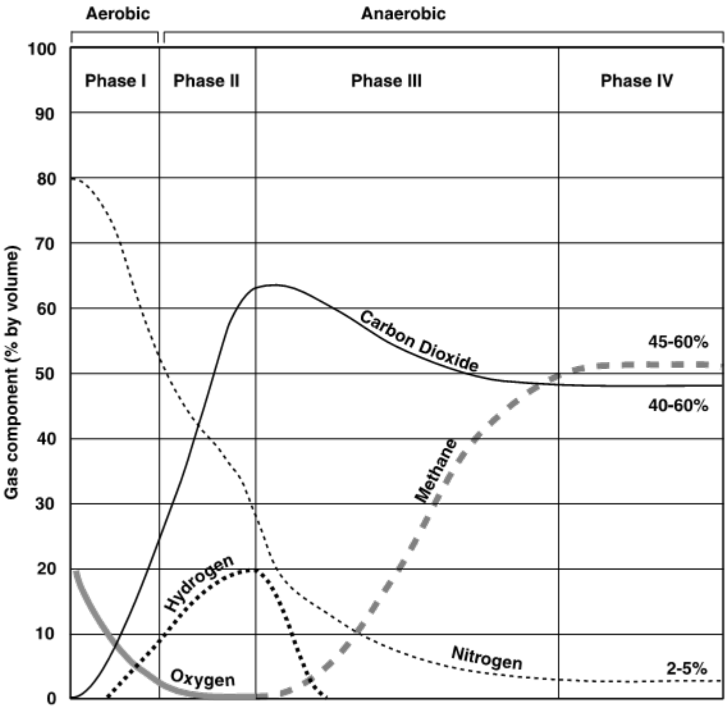


Figure 4. Landfill gas formation: bacterial decomposition (ATSDR, 2001, p. 6).

Phase I is initiated by aerobic bacteria, which consume oxygen on breaking down the long molecular chains of carbohydrates, proteins, and lipids in organic waste. Carbon dioxide and nitrogen are dominant gases in this phase, but the amount of nitrogen continues to decrease through the four phases. Phase I may take days to months, depending on the amount of oxygen available for the aerobic bacteria. As available oxygen is used up, Phase II starts, which begins the process of anaerobic decomposition. Anaerobic bacteria convert the compounds from Phase I to acids such as acetic, lactic, and formic, and alcohols such methanol and ethanol. The landfill turns acidic. Primary byproducts of this phase are carbon dioxide and hydrogen. When certain anaerobic bacteria produce acetate from the acids formed in Phase II, Phase III starts. Methanogenic bacteria consume acetate and carbon dioxide to form methane. In Phase IV, gas production and decomposition rates become relatively stable, and the stable rates usually continue for about 20 years. This phase usually contains 45% to 60% methane by volume, 40% to 60% carbon dioxide, and 2% to 9% other gases, such as sulfides (ATSDR, 2001).

Volatilization. This refers to the phase change of certain organic waste from a liquid or a solid to a gas phase. Volatilization results in non-methane organic compounds (NMOCs) such as trichloroethylene, benzene, and vinyl chloride, which are organic hazardous air pollutants. (ATSDR, 2001).

Chemical reaction. Chemical reactions occur when different waste materials are dumped and mixed together in a landfill. Some waste contains chemical components that can easily react together under certain conditions. For example, chlorine bleach can chemically react with other waste to create toxic landfill gas (ATSDR, 2001).

Organic Waste Generation and Recovery in the US

Total municipal solid waste (MSW) generation increased between 1960 and 2007, correlating with population growth (USEPA, 2009). The waste generation rate per capita per day was 2.68 pounds in 1960 but increased to 4.72 pounds in 2000. Since then, it has decreased slowly but continuously, down to 4.34 pounds in 2009. Yard, food, and paper wastes are organic materials that can be decomposed in landfills and generate carbon dioxide and methane. Figure 5 illustrates the components of MSW and shows that the amount of organic waste, including food and paper waste, has increased and are a major source of total MSW.

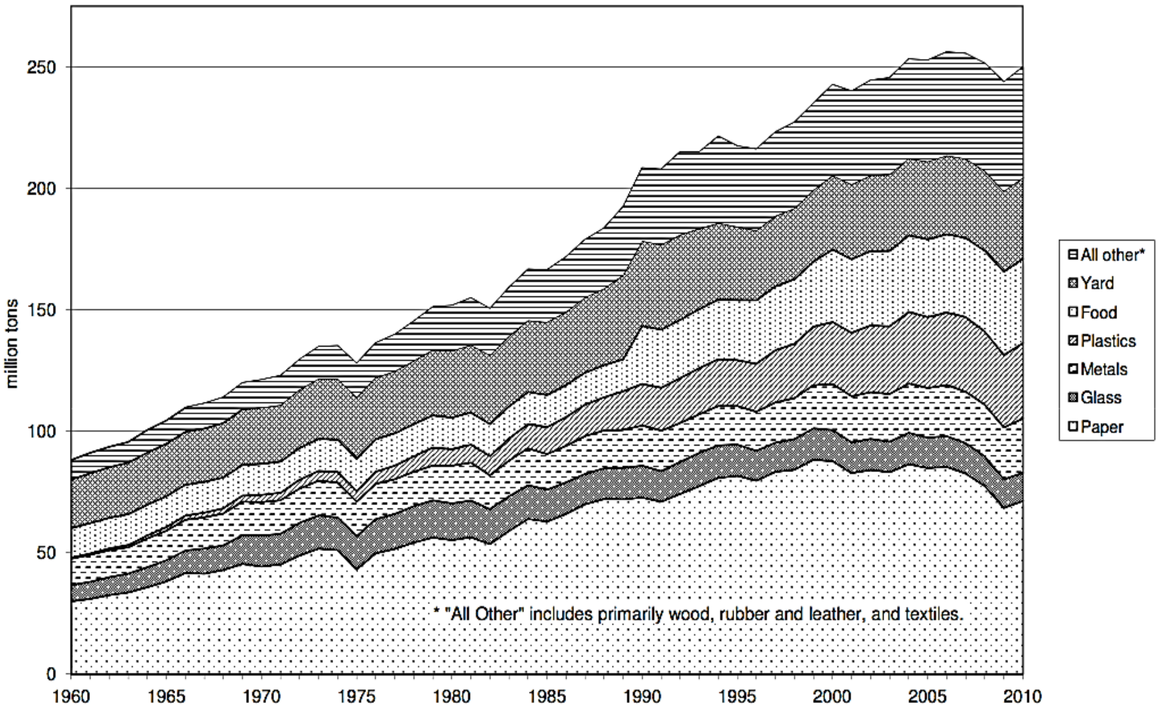


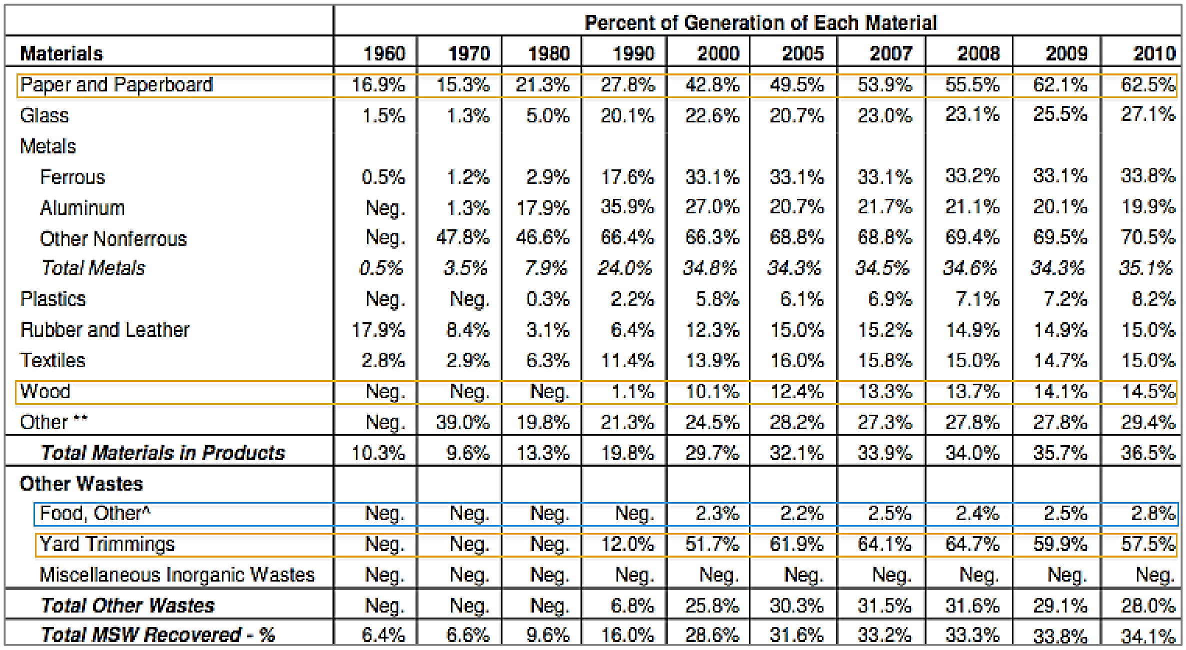
Figure 5. Generation of materials in MSW, 1960 to 2010 (USEPA, 2011a, p. 42).

Table 3 shows recovery rates of each waste sector. The recovery rates of yard waste and paper waste jumped to 57.5% and 62.5%, respectively, while that of food waste has stayed under 3%. It means most food waste is dumped into landfills where it generates methane. Compared to other waste sectors, food waste collection is likely more difficult due to its high moisture content and odor. These factors could discourage food waste recycling.

The USEPA (2014) recommends composting and anaerobic digestion as food waste diversion systems to reduce GHG emissions. The compost created from food waste improves soil health and structure. Compost increases water retention time and reduces the need for fertilizer and pesticides (USEPA, 2013d). Anaerobic digestion can turn the food waste into renewable energy, i.e. biogas, along with digestate that can be used as a soil amendment (USEPA, 2013e).

Table 3

Recovery of Materials in MSW, 1960 to 2010 (USEPA, 2011a, p. 15)



	Percent of Generation of Each Material									
Materials	**1960**	**1970**	**1980**	**1990**	**2000**	**2005**	**2007**	**2008**	**2009**	**2010**
Paper and Paperboard	16.9%	15.3%	21.3%	27.8%	42.8%	49.5%	53.9%	55.5%	62.1%	62.5%
Glass	1.5%	1.3%	5.0%	20.1%	22.6%	20.7%	23.0%	23.1%	25.5%	27.1%
Metals										
Ferrous	0.5%	1.2%	2.9%	17.6%	33.1%	33.1%	33.1%	33.2%	33.1%	33.8%
Aluminum	Neg.	1.3%	17.9%	35.9%	27.0%	20.7%	21.7%	21.1%	20.1%	19.9%
Other Nonferrous	Neg.	47.8%	46.6%	66.4%	66.3%	68.8%	68.8%	69.4%	69.5%	70.5%
Total Metals	*0.5%*	*3.5%*	*7.9%*	*24.0%*	*34.8%*	*34.3%*	*34.5%*	*34.6%*	*34.3%*	*35.1%*
Plastics	Neg.	Neg.	0.3%	2.2%	5.8%	6.1%	6.9%	7.1%	7.2%	8.2%
Rubber and Leather	17.9%	8.4%	3.1%	6.4%	12.3%	15.0%	15.2%	14.9%	14.9%	15.0%
Textiles	2.8%	2.9%	6.3%	11.4%	13.9%	16.0%	15.8%	15.0%	14.7%	15.0%
Wood	Neg.	Neg.	Neg.	1.1%	10.1%	12.4%	13.3%	13.7%	14.1%	14.5%
Other **	Neg.	39.0%	19.8%	21.3%	24.5%	28.2%	27.3%	27.8%	27.8%	29.4%
Total Materials in Products	10.3%	9.6%	13.3%	19.8%	29.7%	32.1%	33.9%	34.0%	35.7%	36.5%
Other Wastes										
Food, Other^	Neg.	Neg.	Neg.	Neg.	2.3%	2.2%	2.5%	2.4%	2.5%	2.8%
Yard Trimmings	Neg.	Neg.	Neg.	12.0%	51.7%	61.9%	64.1%	64.7%	59.9%	57.5%
Miscellaneous Inorganic Wastes	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.
Total Other Wastes	Neg.	Neg.	Neg.	6.8%	25.8%	30.3%	31.5%	31.6%	29.1%	28.0%
Total MSW Recovered - %	6.4%	6.6%	9.6%	16.0%	28.6%	31.6%	33.2%	33.3%	33.8%	34.1%

Benefits of Food Waste Diversion

Environmental benefits. The amount of methane emission from landfills is determined by the quantity of decomposable solid waste deposited in landfills. As shown in Figure 6, methane emissions from landfills decreased from 1990 to 2001 due to the greater levels of recycling of decomposable municipal solid waste such as paper, paperboard, and yard trimmings, and recovery of landfill gas over decades since the first commercial landfill gas to energy project started in 1975 (U.S. Energy Information Administration [USEIA], 2011). The very low recycle rate of food waste (Table 3) and the increase in total decomposable solid waste generation (Figure 5) have caused an increase of annual total methane emissions since 2003 (USEIA, 2011). Simultaneous efforts on both recycling and reducing of food waste can mitigate methane emission from landfills.

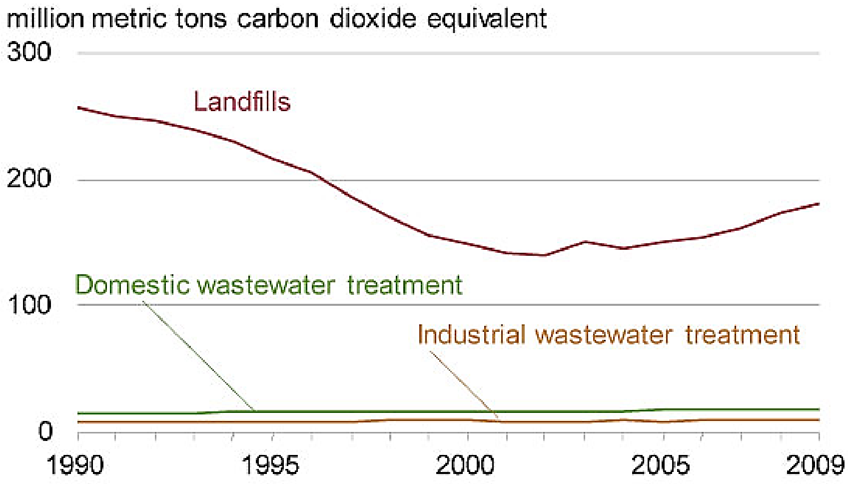


Figure 6. U.S. methane emissions from waste management by sources, 1990-2009 (USEIA, 2011, p. 39).

The digested material that results from both composting and anaerobic digestion (as digestate) is an extremely beneficial soil amendment (Environment Canada, 2013). It contains high levels of humus and plant nutrients, which improve soil quality as well as the plant's health. Use of this digested material can result in a decrease in the use of synthetic fertilizers, which enhances long-term soil health, and reduces environmental impacts from commercial fertilizer production (Environment Canada, 2013).

Economic benefits. Recycling food waste through composting and anaerobic digestion can bring economic benefits like lower disposal costs and creation of value-added products such as compost and biogas (USEPA, 2014). Organic compost is sold at higher prices than commercial fertilizer. Biogas can be used to generate electricity and heat. The digestate, a final product from anaerobic digestion, is also a valuable nutrient-rich soil amendment like organic compost. It can be applied directly to land or after a curing process (Environment Canada, 2013; Rapport, Zhang, & Williams, 2008). The USEPA (2013d) emphasizes that if half of all food waste were diverted to biogas in anaerobic digesters in the US, enough electricity would be generated to provide power to 2.5 million homes per year.

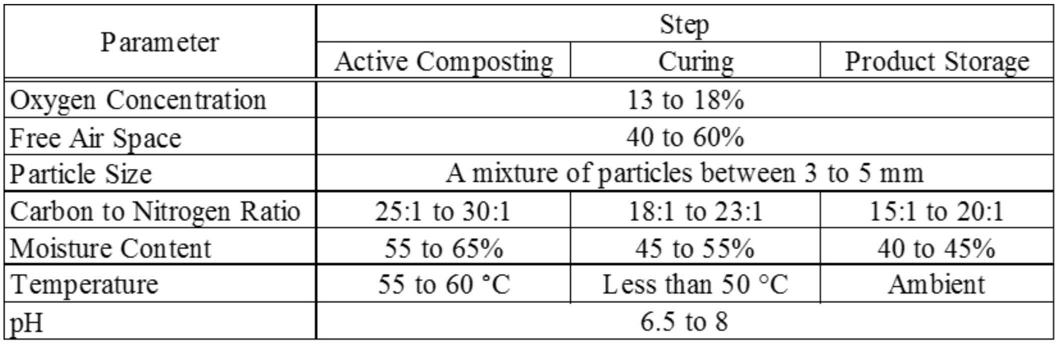
Social benefits. By reducing the potential for landfill gas emissions through food waste diversion, we can lower greenhouse gas and other pollutant emissions, which in turn decelerates global warming and protects the ecosystem (Environment Canada, 2013). The accumulation of methane underground has a potential risk of explosion, which could threaten the community near the landfill sites, so landfill gas reduction provides a safety benefit. Finally, diverting food waste can extend the life of a landfill by preserving space for non-recyclable waste or other use.

Diversion of Food Waste into Value-Added Products: Composting

Aerobic composting has two major benefits: creation of a soil amendment product and greenhouse gas emission reduction (USEPA, 2013d; Integrated Solid Waste Management at Tinos [ISWM-TINOS], 2011). In aerobic composting systems, organic matter can be turned into compost by bacterial decomposition in the presence of oxygen (Drapcho, Nhuan, & Walker, 2008). Since compost can provide an excellent condition for the methanotrophic bacteria that oxidize methane to carbon dioxide and water, it has been found that compost can reduce methane emissions up to 100% under test site conditions (Office of Solid Waste and Emergency Response [OSWER], 2002). The composting process consists of three steps: active composting, curing, and product storage (Environment Canada, 2013). There are several factors that affect composting conditions, and those are described in Table 4.

Table 4

Summary of Optimal Composting Conditions (Environment Canada, 2013)



Parameter	Step		
	Active Composting	Curing	Product Storage
Oxygen Concentration	13 to 18%		
Free Air Space	40 to 60%		
Particle Size	A mixture of particles between 3 to 5 mm		
Carbon to Nitrogen Ratio	25:1 to 30:1	18:1 to 23:1	15:1 to 20:1
Moisture Content	55 to 65%	45 to 55%	40 to 45%
Temperature	55 to 60 °C	Less than 50 °C	Ambient
pH	6.5 to 8		

In order to achieve the optimal aeration, temperature control, feedstock mixing, and retention time, several methods are applied to composting, and the types of composting are defined by these methods (American Planning Association [APA], 2006; Environment Canada, 2013). The most commonly used types are windrow, aerated static pile, and in-vessel composting (APA, 2006).

Windrow composting is the most common type used in North America due to a wide range of applicable feedstock and capacity, and the relatively low infrastructure requirements (Environment Canada, 2013). The feedstock is formed into long and low piles and regularly moved or turned for blending and porosity (Cooperband, 2002; Environment Canada, 2013). During the turning, air is reintroduced inside of the pile, and the gas and water vapor generated can escape.

Aerated static pile (ASP) also involves the use of feedstock piles, but forced air is introduced through pipes instead of mechanical turning (APA, 2006). Airflow can be controlled and adjusted by changing frequency and duration of the blower (Cooperband, 2002); therefore, ASP is more technically controllable than windrow type. It also requires less labor than windrow type composting.

In-vessel type is a higher level of technology than windrow and ASP (APA, 2006). The composting process takes place in an enclosed vessel into which forced air is introduced. It offers shorter retention time, minimizing odor, and temperature control (APA, 2006), which means better environmental and quality controls (Cooperland, 2002). Less land area requirement is another advantage of this method; however, it requires more capital and has higher operation cost than windrow and ASP (APA, 2006).

Institutional composting: Appalachian State University composting facility. The Appalachian State University composting facility is the only food waste composting facility in Boone, NC. It was built in 1999 as a student-driven project using simple static piles. The upgraded facility was opened in 2011 with a 275 tons per year (TPY) capacity (ASU, 2012). An average 100 tons of pre-consumer food waste was collected from the school's cafeterias from 2008 to 2010 (ASU, 2014), which exceeded the capacity of the old facility and motivated the capacity expansion (ASU, 2014). The new composting facility is a covered (under roof) aerated bin type, an advanced form of ASP (Figure 7). The under-floor piping provides air circulation, and the leachate is collected and reused to provide moisture to the piles (ASU, 2012). Instead of long and low piles, the feedstock is placed into the bins, installed under roof (Figure 7). The roof can protect the compost from weather exposure like rain or sunlight, which could prevent the piles from having the proper moisture content. In 2012, the system treated about 130 tons of pre-consumer food waste, wood chips, and tree trimmings, according to the ASU Office of Sustainability (Jennifer Maxwell, personal interview, September 20, 2013). The nutrient-rich compost made from the food scraps helps the campus keep its natural beauty.

Figure 7. Covered aerated bin composting at Appalachian State University.

Community composting: Green Mountain Compost. Green Mountain Compost is located in Williston, Vermont. They treat organic waste including food waste and yard waste collected from Chittenden County as a program of Chittenden Solid Waste District (Green Mountain Compost, 2014). The facility is a covered aerated bay type and has 20,000 TPY capacity. Since they upgraded the facility from windrow into the current type, Green Mountain Compost (2014) has found it can produce higher quality compost more efficiently with covered bays, a concrete pad, and an aerated system (Figure 8).

Figure 8. Covered aerated bays at Green Mountain Compost (Green Mountain Compost, 2014).

Diversion of Food Waste into Value-Added Products: Anaerobic Digestion

Through anaerobic digestion (AD), organic matter is degraded by naturally occurring bacteria into methane, carbon dioxide, inorganic nutrients, and compost (called digestate), in an oxygen-depleted environment (Mitchell & Gu, 2010). The produced gases, called biogas, can be collected and can replace natural gas to generate electricity and heat or to fuel natural gas vehicles. Anaerobic digestion has a good reputation for higher control over methane production and lower carbon footprint of the food waste management system than does aerobic composting (Levis, Barlaz, Themelis, & Ulloa, 2010). The methane production in AD involves integrated microbial community (Drapcho et al., 2008). The microbes have specialized functions for each step, which cannot be performed by one single species. Organic matter undergoes four main reactions to form methane: hydrolysis, fermentation (acidogenesis), acetogenesis, and methanogenesis (Figure 9). Organic macromolecules such as carbohydrates, proteins, and fats are decomposed into monomers such as simple sugars, amino acids, and fatty acids by enzymes in the hydrolysis stage. Fermentation is carried out by bacteria, which transform the products of the hydrolysis into simple organic acids, alcohols, carbon dioxide, and hydrogen. Those organic acids, alcohols, carbon dioxide, and hydrogen are turned to acetic acid, carbon dioxide, and hydrogen in the acetogenesis step. Methanogens, or methanogenic bacteria, consume hydrogen and reduce carbon dioxide to form methane. (Drapcho, 2008; Mitchell & Gu, 2010).

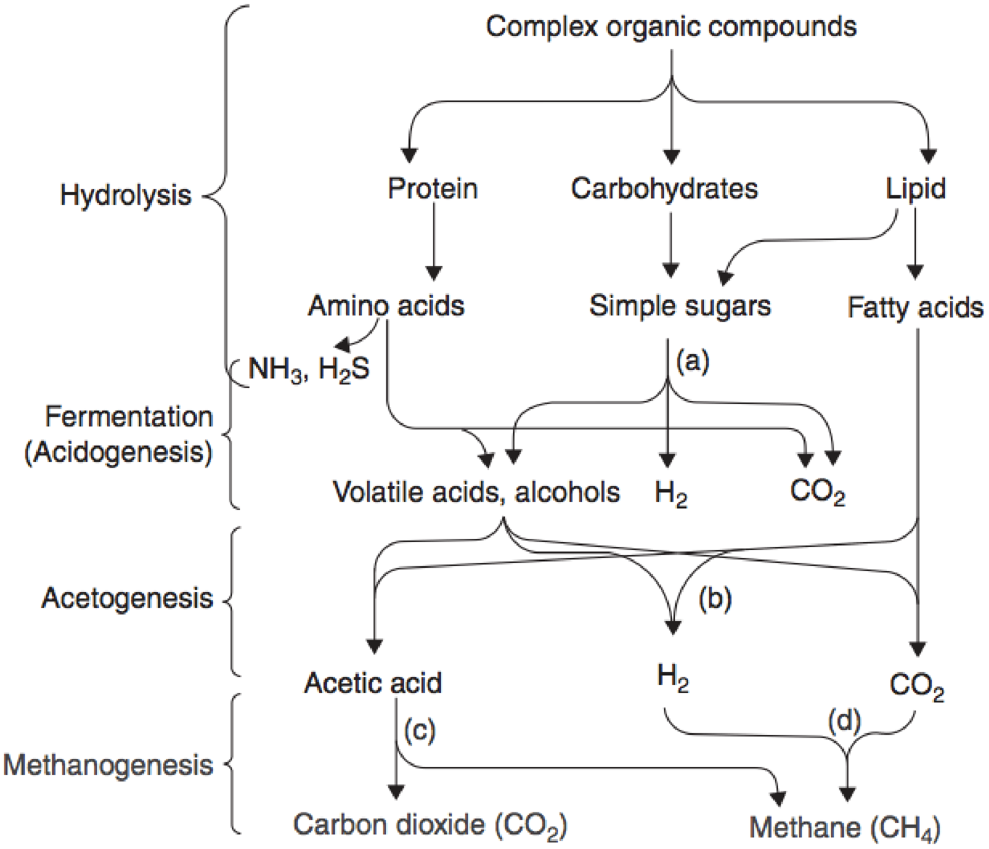


Figure 9. Four stages of biological methane production (Drapcho et al., 2008, p. 330).

AD systems can be configured according to process temperature, number of stages, and moisture content, but moisture content (or solid content) is most generally used to categorize AD systems (Environment Canada, 2013). Wet type (which conversely means low solids) AD systems treat the feedstock with greater than 80% moisture content. The feedstock is dissolved in liquid and treated like a liquid. This system is suitable for co-digestion of animal manure or biosolids. Due to higher moisture content, wet type digesters require more energy and water use for water heating and pumping, and for dewatering. A potentially lower gas yield is another disadvantage of this system.

Dry type (high solid) systems can be further categorized according to feedstock loading method into continuous (slurry) type or batch (stackable) type (Environment Canada, 2013; Rapport, Zhang, Jenkins, & Williams, 2008). In a continuous dry type system, the feedstock is loaded continuously, thus it has a more stable digestion condition and it is possible to control the process more easily than in the stackable type, where the feedstock is loaded all at once (Rapport et al., 2008). Continuous type AD systems are more common in Europe because these systems have lower land area requirements and potential for higher biogas yields. Batch dry type was first inspired by landfill bioreactors (Rapport et al., 2008). It simplifies material handling, which results in cost reduction, and requires even less moisture content. Batch type systems can treat solids concentrations as high as 30% to 45%, and require less operational energy (Environment Canada, 2013).

Institutional AD system: University of Wisconsin-Oshkosh. The University of Wisconsin-Oshkosh (UW-Oshkosh) owns the first commercial-scale dry batch type anaerobic digester in the US, constructed by BIOFerm Energy Systems in 2011 (Mckiernan, 2012, Figure 10). It recirculates the digestate and leachate (also called percolate) to maintain optimal bacterial condition and moisture content. The biogas is collected and delivered to a 370 kW combined-heat-and-power (CHP) unit, which can generate up to 2320 MWh of electricity and 7918 MMBtu of thermal energy annually, using 8000 tons of degradable feedstock including agricultural plant waste, yard waste, and campus-generated food waste (BIOFerm Energy, 2012). The facility supplies up to 10% of the electricity needs on campus. The University of Wisconsin project expects 20 years of lifetime and 10,755 metric tons (MT) CO_2 equivalent of annual reduction by methane displacement and renewable energy generation (BIOFerm Energy, 2012).

Figure 10. Schematic of dry fermentation system of BioFerm (Mckiernan, 2012, p. 4).

Other dry batch type AD system in the US. Zero Waste Energy (ZWE) is a company that designs, builds, and operates integrated solid waste facilities located in California (ZWE, 2013). ZWE utilizes the dry batch type system. Their patented semi-mobile digesters, named SMARTFREM (Figure 11), have the unique feature that shop-fabricated digesters are delivered to the site. Their design includes a CHP system for energy generation as well as a Compressed Natural Gas (CNG) system to use for natural gas fueled vehicles. ZWE estimates 1726 MWh of electricity generation, 6120 MMBtu of heat energy available after parasitic loads, 4441 tons of organic compost (digestate) with a 10,000 TPY system, and 184,828 diesel equivalent gallons of CNG with a 20,000 TPY system.

Figure 11. SMARTFERM of 5,000 TPY capacity in Marina, California (ZWE, 2013).

Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is an assessment tool for industrial systems with a “cradle-to-grave” approach (Scientific Applications International Corporation [SAIC], 2006, p. 1). The basic purpose of the LCA is to figure out a better industrial system to minimize the environmental load throughout the whole life cycle of a product, process, or service for achieving environmentally sound and sustainable development (International Organization of Standardization [ISO], 2006; National Pollution Prevention Center for Higher Education [NPPCHE], 1995; SAIC, 2006).

LCA of a specific product or service is a method of quantifying the amount of material, energy consumption, and emissions during the processes of raw material acquisition and processing, manufacturing, transportation, distribution, use, recycling, and waste management—in other words, the whole life cycle—to evaluate the impact on the environment and on human health (ISWM-TINOS, 2011).

Harry E. Teasley, who was managing the packaging process for the Coca-Cola Company, performed the first formal analytical study of LCA in 1969 (Franklin & Hunt, 1996; NPPCHE, 1995). At that time, The Coca-Cola Company was considering which type of beverage packaging to use, refillable bottles or disposable containers. Teasley analyzed the energy, materials, and environmental impacts over the life cycle of these different forms of packaging, including extraction of raw materials through to disposal.

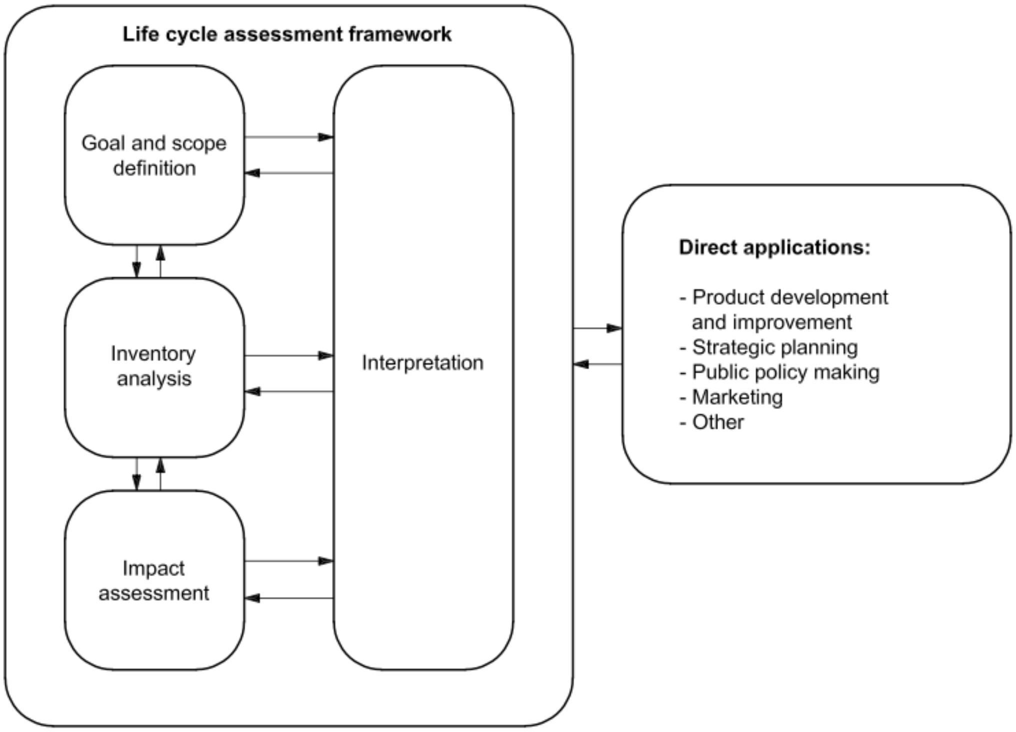


Figure 12. Stages of a LCA (ISO, 2006, p. 8).

The LCA process consists of four systematic components: goal definition and scoping, inventory analysis, impact assessment, and interpretation (Figure 12). Goal definition and scoping is a step that defines and describes the purpose, boundaries, and functional units of the study (Curran, 2012). Data collection, analytical methods, and results will vary depending on the purpose, so the purpose of the LCA must be clarified first. The inventory analysis step involves a flow diagram development, followed by data collection and quantification of process inputs such as raw materials and energy, and of outputs related to the production system such as products, air emissions, water emissions, solid waste, and so on (Curran, 2012). Flow chart development is started from the boundary set at the previous step. It consists of a series of subsystems, each defined as an individual step of the whole production or service system. Every subsystem includes inputs such as energy, water, and raw materials, and outputs such as gas emissions, wastewater, solid waste, byproducts, and products. In order to quantify these inputs and outputs, data collection is required. Since the accuracy and quality of data is very important, a data collection plan is needed and should be built before gathering data. A data collection plan should include data quality goals, data source and types, data quality indicators, and a checklist. The impact assessment step aims to evaluate the significance of the potential environmental impacts, including ecological and human health effects, using the results of the inventory analysis step (Curran, 2012). In this step, the impacts categories and indicators are selected, and the selected indicators are assigned to their related categories. The assigned indicators within the same categories are characterized using science-based conversion factors. For example, carbon dioxide and methane could be indicators in the category of climate change and these indicators can be summed under the same unit, such as CO_2 equivalent. In the interpretation step, a final conclusion is made by identifying, reviewing, and evaluating the information obtained from the inventory analysis and impact assessment steps as the final stage of the life cycle assessment (Curran, 2012). Table 5 provides a description of common life cycle impact categories, their indicating gases, and the characterization factors.

Table 5

Commonly used Life Cycle Impact Categories and Indicators (SAIC, 2006, p. 47)

Impact Category	**Scale**	**Examples of LCI Data (i.e. classification)**	**Common Possible Characterization Factor**	**Description of Characterization Factor**
Global Warming	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH_3Br)	Global Warming Potential	Converts LCI data to carbon dioxide (CO_2) equivalents Note: global warming potentials can be 50, 100, or 500 year potentials.
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH_3Br)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.
Acidification	Regional Local	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH_4)	Acidification Potential	Converts LCI data to hydrogen (H+) ion equivalents.
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates Ammonia (NH_4)	Eutrophication Potential	Converts LCI data to phosphate (PO_4) equivalents.
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)	Photochemical Oxident Creation Potential	Converts LCI data to ethane (C_2H_6) equivalents.
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Human Health	Global Regional Local	Total releases to air, water, and soil.	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Resource Depletion	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve.
Land Use	Global Regional Local	Quantity disposed of in a landfill or other land modifications	Land Availability	Converts mass of solid waste into volume using an estimated density.
Water Use	Regional Local	Water used or consumed	Water Shortage Potential	Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve.

Benefits of Conducting LCA

Decision-makers can learn about a system, process, or project that results in the least environmental impacts by conducting a LCA (SAIC, 2006). LCAs can also provide information about the most effective points in a product’s life cycle to improve total environmental impacts (ISO, 2006). Because LCAs can provide information about the full life cycle, the problem of transferring environmental impacts from one unit to another (e.g., eliminating air emissions by creating a wastewater effluent instead) can be identified and recognized. The transfer of environmental impact might not be noticed without a LCA (SAIC, 2006). The information gained from conducting a LCA can be combined with other factors, such as economic analysis, for a better decision-making and marketing resource (ISO, 2006; SAIC, 2006).

Limitations of LCA

Conducting a LCA can be a resource and time intensive task depending on the user’s demand. The accuracy of final data produced can vary according to the availability of data used in the assessment; therefore, the user must first consider the availability of data, the time necessary to conduct the study, and the financial resources required (SAIC, 2006).

Life Cycle Assessment of GHG Emissions of Organic Waste Management

Biological organic waste treatments, including composting and anaerobic digestion, are advantageous in terms of waste volume reduction, valuable end products, and GHG reduction (Intergovernmental Panel on Climate Change [IPCC], 2006). Even though these biological treatments are proven waste management methods for GHG reduction, a specific comparison of all available options through life cycle assessment is a great resource in decision-making. The USEPA (2006) introduced a LCA approach for analysis of GHG reduction through solid waste management. Their methodology for the assessment is based on three fundamental elements: (a) emissions over the life cycle of the waste material, (b) the carbon sinks occurring via waste material production and its disposal by a chosen treatment option, and (c) the avoided or recovered energy of a chosen treatment option. The life cycle emissions of the waste material could be defined from either material production or waste generation to its disposal. For example, the boundary for paper waste can be defined from either tree acquisition or paper waste generation. The former case, whose starting point is "Raw Materials Acquisition" in Figure 13, should include the emissions from raw material transportation and material manufacturing. The reduction of carbon sequestration by cutting wood should also be considered in this case. If the paper is recycled before disposing, the avoidance by saving the energy that should have been used for manufacturing and the increased carbon sinks by not cutting wood should be considered and included. The latter case starts at "Waste Management" in Figure 13, which excludes the emissions and carbon sinks of material acquisition, manufacturing, and recycling.

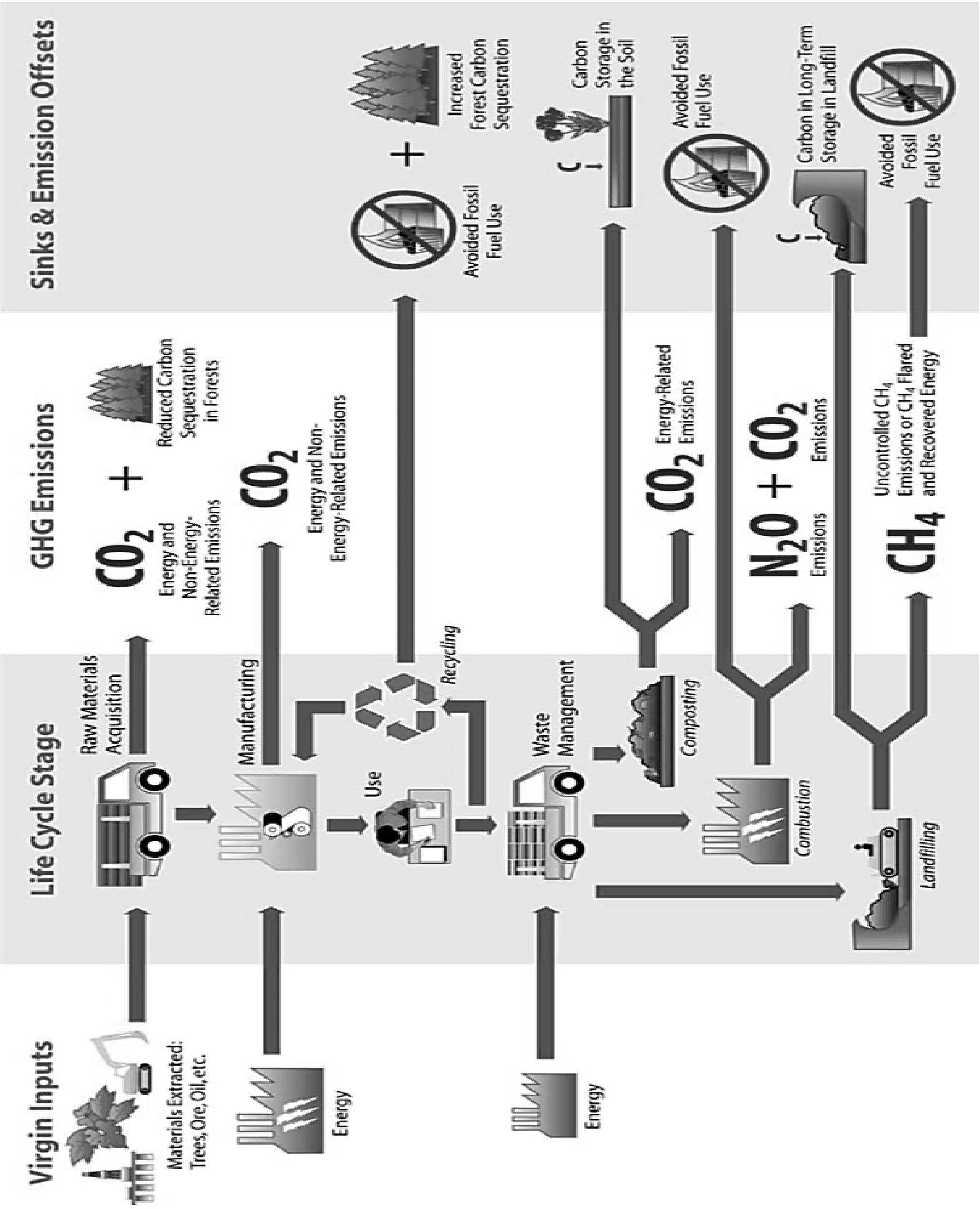


Figure 13. GHG sources and sinks associated with the material life cycle (USEPA, 2006, p. 9).

Accounting biogenic CO_2 differs from accounting CO_2 emissions from fossil fuels. Biogenic CO_2 is defined as the CO_2 emitted by the decomposition of biomass, which absorbs CO_2 by photosynthesis as it grows; therefore, biogenic CO_2 emissions are considered as an extended part of the natural carbon cycle within a closed loop (USEPA, 2006). The United

States as a signed member of the United Nations Framework Convention on Climate Change (UNFCCC), an international agreement to address the danger of global climate change whose signatories agree to adhere to the standard developed by the IPCC on accounting for national level GHG emissions. The goal of UNFCCC is to stabilize GHG concentrations in the atmosphere over time, and it focuses on anthropogenic CO_2 emissions. Biogenic CO_2 emissions are not counted because they are excluded from human activity related CO_2 emissions, while CO_2 emissions from fossil fuel use are counted (USEPA, 2006). In the same manner, methane emissions from landfills are considered as anthropogenic emissions.

The carbon flow in landfills is illustrated in Figure 14. The carbon sources that enter landfills exit as gas emissions and leachate, or remain stored. The biogenic CO_2 of landfill gas is not counted, but methane should be counted. If the landfill recovers energy by capturing landfill gas, the methane is converted to CO_2 by combustion. The landfill with energy recovery option has advantages such as the methane conversion to biogenic CO_2 and the avoidance of GHG emissions by fossil fuel energy. Carbon storage can be defined as the remaining carbon after gas emissions and dissolution of carbon in leachate, from a mass balance aspect. The GHG emissions from waste collection should also be counted.

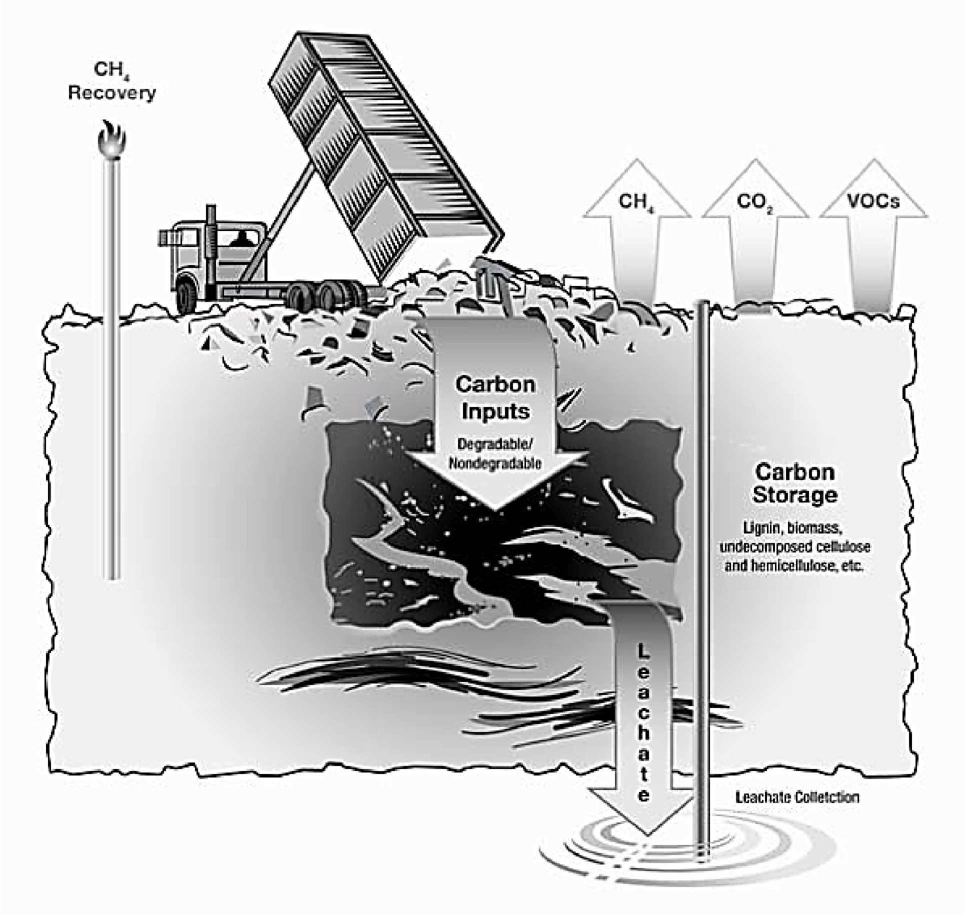


Figure 14. Carbon flow in landfills (USEPA, 2006, p. 81).

Composting is one of the biological organic waste treatments that emits biogenic CO_2 and, theoretically, no methane. Even though some methane could be generated in the center of a composting pile, it is likely to be oxidized to CO_2 under oxygen-rich conditions (USEPA, 2006). No GHG emission is considered and accounted in the composting option except the GHG emissions from the fossil fuels required for the composting process (e.g., electricity and diesel) and waste transportation. Another element that should be considered beyond the emissions in composting is potential carbon storage in soil when the compost is applied to land.

Life Cycle Assessment Tools for Municipal Solid Waste

Several LCA tools have been developed for professional use and educational use. Municipal Solid Waste Decision Support Tool (MSW DST) and Integrated Waste Management-Model (IWMM) are special LCA tools for municipal solid waste management, and are offered for free to the public.

MSW DST from RTI International (2000). Research Triangle Institute (RTI), with co-funding from the USEPA and the US Department of Energy, has developed and designed the MSW DST to aid in analyzing the cost and environmental aspects of municipal solid waste management. The web demo version of MSW DST is available for free to the public, but the web version does not contain anaerobic digestion as a waste management option. The model consists of four components: process model, waste flow model, optimization model, and a graphic user interface.

The process model is a set of Microsoft Excel spreadsheets that use default data and user-specified data to calculate the cost and life cycle inventory coefficients. These coefficients are used to calculate emissions of each unit process. The waste flow model provides a mass balance of the system with all possible pathways for the MSW, such as different collection alternatives, waste transfer, separation, treatment, and disposal. The optimization module is processed by a mass flow equation based on the quantity and composition of input waste into each unit process. These mass flow constraints preclude nonsensical model solutions, and allow users to create the objectives that reduce the total cost or environmental impacts. The graphic user interface uses Microsoft Visual Basic, which makes all components of the model integrated and provides a graphical representation for a user-friendly interface. Results are viewed as costs or as pounds of emission per ton.

IWMM from University of Waterloo (2004). Corporations Supporting Recycling (CSR) and the Environment and Plastics Industry Council (EPIC) in Canada developed this LCA tool for municipal waste management. The city of London, Ontario, was the co-participant in the IWMM development project and the initial test case for this model. This tool sets the system boundary that is from the point of discarding waste to the point of diverting waste into useful materials. Several different waste treatment systems are defined in this tool; recycling, incineration, composting, anaerobic digestion, landfilling, and landfilling with energy recovery. Using life cycle methodology, the IWMM quantifies the energy consumed and gas emitted from a user-specified waste management system in each scenario. The database in the tool has been derived from government sources in Canada, the US, and Europe, along with other material published in journals; however, ICF consulting (2007) pointed out in the review report for Environment Canada that the database on which the IWMM relies is outdated. The environmental impact categories in the model are resource depletion, climate change, acidification, health risk, smog formation, environmental degradation, water quality, and land use disruption. Because the IPCC's Guidelines for National Greenhouse Gas Inventories (2006) does not count CO_2 emissions from biogenic sources as a greenhouse gas, biogenic CO_2 emissions from organic wastes such as food waste, yard trimmings, and paper in composting, anaerobic digestion, and landfilling are not counted in this model, while CO_2 emissions arising from fossil fuel use such as truck hauling and electricity are counted.

Previous Studies of LCA on Food Waste Management and Food Waste Generation

Study of municipal solid waste in Ontario, Canada. Haight (2005) performed LCA of food waste management systems, including landfilling, composting, and anaerobic digestion in order to quantify energy consumed (produced) and emissions released for each system. Four scenarios were established: landfill, composting, anaerobic digestion, and landfill with energy recovery. In the study, anaerobic digestion was concluded to be the most significant improvement among the four scenarios. This study utilized the LCA software they had developed for municipal solid waste management that is available free of charge through University of Waterloo.

LCA studies for composting and anaerobic digestion units, Tinos, Greece. Researchers at IMSW-TINOS reviewed 55 Internet sites and 39 refereed papers about LCA of food waste management (IMSW-TINOS, 2011). From the literature review, they were able to summarize significant information about anaerobic digestion and composting:

- Anaerobic digestion systems are more complex and expensive than composting but can produce energy (biogas).
- Composting systems usually require a larger land area than anaerobic digestion and may also generate odor. Furthermore, CH_4 production cannot be controlled.
- The environmental impact of composting may vary depending on aerobic condition.
- LCA data of anaerobic digestion is sensitive to the amount of methane produced for the energy use offset.

Commercial food waste treatment systems study in Raleigh, NC. Levis and Barlaz (2011) conducted a life cycle assessment to analyze food waste diversion systems in Raleigh, NC, examining several types of aerobic digestion alternatives (windrows, aerated static pile, Gore cover system, and in-vessel system), anaerobic digestion, and four landfill scenarios including a landfill without gas collection, a landfill in which gas is collected and flared, a landfill with energy recovery, and a bioreactor landfill with energy recovery. Global warming potential, NO_x, generic term for NO and NO_2, and SO_2 emissions that may indicate acidification, and total net energy were chosen for analyzing each system. They concluded that anaerobic digestion is the most environmentally friendly option and suggested hybrid landfill-AD systems to provide an optimal trade-off between environmental and economic benefits.

Municipal Food Waste Generation Estimation

Draper & Lennon conducted studies of food waste generation by sectors to build a food waste generator database in Connecticut (2001) and Massachusetts (2002). They established food waste generation formulas for specific generator categories based on literature reviews and on the survey information acquired directly from the state of Connecticut. They included hospitals, nursing homes, colleges and universities, correctional facilities, resorts and conference facilities, supermarkets, and restaurants as food waste generator categories. The detailed formulas they generated are shown in Table 6. They also created a Geographic Information System (GIS)-based food waste density map, with the potential to display organic waste by generator, waste type, waste quantity, and location graphically. Mercer County in New Jersey conducted food waste research based on the formulas developed by Draper & Lennon. Because Draper & Lennon’s work does not include primary and secondary schools as a generator of food waste, Mercer County developed a formula for that category based on food waste generation reports from

California, Washington, and Minnesota. The formula used for primary and secondary schools is also described in Table 6.

Table 6

Formulas for Commercial Food Waste Generation Estimation (Draper & Lennon, 2002; Mercer, 2013)

Category	Formula
Universities	**Residential** = 0.35 lbs/meal * N of students * 405 meals/student/yr
	Non-residential = 0.35 lbs/meal * N of students * 108 meals/student/yr
Public Schools	= N of students * 0.14 lbs/students/day * 180 day/yr
Hospitals	= N of beds * 5.7 meals/bed/day *0.6 lbs food waste/meal * 365 days/yr
Resorts/ Conference Properties	=1.0 lbs/meal * N of meals/seat/day* N of seats * 365 days/yr
Restaurants	= N of employees * 3,000 lbs/employee/yr
Supermarkets	= N of employees * 3,000 lbs/employee/yr
Nursing homes	= N of beds * 3.0 meals/bed/day *0.6 lbs food waste/meal * 365 days/yr
Correctional facilities	= 1.0 lb/inmate/day * N of inmates * 365 days/yr

Note: N is number.

Cost Benefit Analysis

Cost-benefit analysis (CBA) is the most common and uncontroversial economic technique for assessing the relative costs and benefits of project options for decision-making (Lumley, 1998). It has been widely practiced, especially for social programs, environmental policy, transport planning, and healthcare (Organization for Economic Co-operation and Development [OECD], 2006; USEPA, 1994). CBA consists of several steps and the process of defining steps is varied (Hanley & Spash, 1993). Boardman, Greenberg, Vining, and Weimer identified the essential 10 steps for performing CBA (2006): setting the framework; deciding whose costs and benefits should be recognized; identifying and categorizing costs and benefits; allocating project costs and benefits over the life of the program; placing a dollar value on costs; placing a dollar value on benefits; discounting costs and benefits to obtain present values; computing a net present value; performing sensitivity analysis; and making a recommendation, where appropriate. Each of these will be described in more detail.

Setting the Framework

This should include the original state or circumstance that exists in the absence of the proposed project, as well as all alternatives to that proposed project (Cellini & Kee, 2010). The analysis starts with the description of the original state, which is the baseline for the analysis. The costs and benefits should be those that would occur with an alternative over those that would have occurred without any action.

Deciding Whose Benefits and Costs Should Be Recognized

Almost every project has a wide range of stakeholders and there are particular groups of people who may gain or lose by the project (Cellini & Kee, 2010). For example, in a public project, taxpayers are the large group paying the costs, but only certain groups may get benefits from the project. In this step, all the impacts that might result from the project's implementation should be identified. The definition of the society or groups who will bear the costs and benefits must have a geographical basis. The limits can be at the national, state, county, or city level, but other geographical boundaries are also applicable.

Identifying and Categorizing Costs and Benefits

In this step, all categories of costs and benefits are identified to the greatest extent possible (Cellini & Kee, 2010). Even though not all the costs and benefits can be monetized for evaluation, all possible economic effects should be identified and mentioned. Those small or negligible impacts unable to be quantified should be briefly discussed in the final step. USEPA (1994) suggested the categorized costs and benefits for a composting project. Capital costs and operation and maintenance (O&M) costs are categorized as costs from composting, and avoided costs and revenues are categorized as benefits from composting. Capital costs may contain site acquisition, site preparation and construction, vehicle and equipment procurement, training, and permits. O&M costs may contain waste collection costs, labor costs, fuel and parts costs, and outreach and marketing costs. A composting project usually has five major avoided costs: tipping fee, construction of additional landfill, environmental costs for landfilling operations, community landscaping costs, and trash collection time. Revenues can be gained from a composting project by selling compost (USEPA, 1994).

Allocating Project Costs and Benefits over the Life of the Program

The next step applies the time frame for the analysis, and it is about "how the costs and benefits will change over time" (Cellini & Kee, 2010, p. 503). Usually a time frame ranges from five to fifty years. This may be decided depending on the useful life of the project, but in some cases, the analysis is assessed for just one year, and these cases are not applicable to this step. Once the time frame is established, starting with the first year, collection of information on costs and benefits annually is typical. Then, the evaluator must predict the trend of costs and benefits such as increasing, decreasing, irregular, and so on. It is recommended that decision makers consider whether costs and benefits are one time, accruing only in the first year, or occurring every year.

Placing a Dollar Value on Costs

When setting up the costs and benefits trends over the time frame, all costs should be expressed in the same unit, which is a nominal or real dollar value. The reason for assigning a dollar value to each cost is to facilitate easier addition and comparison. When placing a dollar value on a cost, it is important to clarify its nature, ways to measure it, and any assumptions for the calculations (Cellini & Kee, 2010). Also, these assumptions should be analyzed for sensitivity in order to know how much the outcome of the analysis is affected by the assumptions made. There are several types of budgetary or accounting costs.

Cost of capital. The cost of capital assets needs to be developed over the time frame. There are two factors that affect the asset: depreciation and opportunity cost. Depreciation is an annual allowance for the wear, tear, deterioration, and obsolescence of the asset. The asset is usually depreciated equally every year over the life of the asset. Opportunity cost is expressed as an interest rate multiplied by the undepreciated portion of the asset, which means that the investor loses the benefits gained from choosing the alternative.

Sunk cost. This is the cost that is invested before the project starts, such as research and development cost; however, sunk cost should be ignored if there is no impact on the benefit of the project caused by sunk cost.

Placing a Dollar Value on Benefits

In CBA, calculating a dollar value for every major benefit is an ideal goal. USEPA (1994) offered several benefits from composting including social and environmental benefits; extending landfill lifetime, avoided costs by reducing landfilling operation, fewer landfill gas emissions, creation of new jobs, and revenues from compost. Typically, CBA is more complicated than monetizing costs because it includes multiple objectives that affect different beneficiary groups (Cellini & Kee, 2010). In addition, some social benefits are not easily monetized. Some techniques for monetizing social and environmental benefits are described below.

Nonmarket goods and services. Social benefits are not easy to estimate and sometimes are not recognized well enough to reflect their importance. For example, people do not pay fully for the benefits of public projects. In these cases, the evaluator needs to find a similar private project and its prices and then use those to assign a monetary value to the public project.

Cost avoidance. This refers to a cost reduction in the future that is realized by implementing a project. Investors will get benefits through reducing their expenses in other ways. For example, there will be a cost reduction on utility bills by installing a solar panel project. In order to calculate the future cost reduction of this project, historical data of utility bills such as electricity and natural gas, as well as utility spending trends pre- and post-installation, could be used.

Renewable Energy Certificates (RECs). When a project or program is associated with generating renewable energy, some assets can be achieved depending on its environmental attributes. Renewable energy portfolio standards (REPS) refers to state-level regulations adopted to encourage energy production from renewable sources. States often design their portfolios so that a certain portion of electricity generation is required to come from renewable energy sources. Those REPS can, in turn, create compliance markets to trade renewable energy certificates (RECs). The existence of RECs is dependent on the underlying asset (e.g., electricity) but can be severable from the underlying asset to trade. One REC generally represents 1 MWh of electricity that was generated by an eligible renewable energy source in the US.

Renewable Identification Numbers (RINs). The 2005 Energy Policy Act created the Renewable Fuel Standard (RFS) program, which originally mandated that a minimum of four billion gallons of biofuel be blended with gasoline (McPhail, Westcott, & Lutman, 2011). The new RFS (RFS2) mandates that fuel refiners are required to meet a minimum percentage of renewable fuel production by obtaining the RINs developed by the USEPA to ensure RFS2 mandates. One RIN represents 77,000 Btus of biofuel, and compliance markets are available for RINs trading. RINs can be traded bundled or unbundled with underlying biofuels, just like RECs.

Discounting Costs and Benefits to Obtain Present Value

The cash generated or used by a future project should be discounted to its current value for project valuation. The present value (PV) of a given lump sum in in the future (future value; FV) at the end of N periods at a rate r (%) is expressed below.

$$PV = \frac{FV}{(1+r)^N}$$

Discount rate, r, is a rate at which the value of money to be received in future days is expressed in present worth. It should convey change in the value of money over time, opportunity cost, and relative risk of investment. Setting a discount rate is not simple and is thus debatable. For example, the Canadian CBA guide recommended a 3% to 7% social discount rate (Treasury Board of Canada Secretariat, 2008), whereas the Asian Development Bank gave the range of 3% to 7% for developed countries and a higher rate of 8% for developing countries (Zhuang, Liang, Lin, and DeGuzman, 2007). The World Bank developed the social discount rate of 3% to 5% (Lopez, 2008).

Calculating a Net Present Value

Once you develop a series of PV of net cash flows, net present value (NPV) is calculated by summing all PV series of net cash flows (Cellini & Kee, 2010). NPV is the sum of present values of net cash flows over time. It is a standard valuation method based on time value of money. It is cash flow based, objective, and an explicit measurement of value. It can be calculated with discount rate, r, as below. CF_0 represents investment in the starting year, so it is not discounted.

$$NPV = CF_0 + \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \frac{CF_3}{(1+r)^3} + \cdots + \frac{CF_N}{(1+r)^N}$$

NPV gives a clear answer for measuring value of a project and making a decision in selection of one project or another; however, setting a discount rate is a major challenge in calculating NPV. When NPV of a future project is greater than zero, it means the investment is acceptable. When presented with a choice of one project or another, the proper selection is the project with the greatest NPV.

Sometimes internal return rate (IRR) is also useful, when the discount rate is not easy to set (Cellini & Kee, 2010). IRR is a rate of return where NPV is zero. It can also be defined as the discount rate at which the present value of all future cash flow is equal to the initial investment, or, in other words, the rate at which an investment breaks even. IRR should be used only for standard cash flows, which have regular inflows and outflows. While NPV calculates additional wealth in a given time, IRR does not. Therefore, IRR is useful to measure the desirability of projects, when the initial investments of all projects are same.

Performing a Sensitivity Analysis

Throughout a CBA, several assumptions need to be made. It is important to test sensitivity for the particular assumptions that may have relatively larger impacts on results. There are two popular types of sensitivity analysis to be used: partial sensitivity analysis and extreme case sensitivity analysis.

Partial sensitivity analysis is performed by varying one parameter at a time while keeping other parameters constant. In extreme case sensitivity analysis, each parameter is set with values of worst or best cases, and all parameters vary simultaneously. If a project has an acceptable result after sensitivity analysis, even with a worst-case scenario, it supports investment. If a project has a debatable outcome even with a best-case scenario, it is doubtful for investment.

Making a Recommendation

As a final step of CBA, making a recommendation means reaffirming the value of a project or making a proper selection based on NPV and sensitivity analysis. Possible issues, concerns, some messiness, and some categories of cost or benefits unable for quantification should be mentioned in this step. If evaluators get a relatively small NPV and there are significant environmental costs or benefits that defy quantification, it is essential for evaluators to use their best judgment in assessing the importance of those costs or benefits. If a major outcome is intangible and difficult to quantify, such as improving visibility in national parks through environmental regulation, then evaluators can treat it as a cost-effectiveness issue, in which they would assess how much it costs to improve the visibility from 10 miles to 20 miles (Cellini & Kee, 2010). This may be a better way to get a tangible answer.

CHAPTER 3: RESEARCH METHODOLOGY

Overview of Research Design and Scenarios

This study used a Life Cycle Analysis methodology to analyze the comparative environmental and economic benefits of three strategies (landfilling, composting, and anaerobic digestion) for handling the commercial food waste generated in the Boone area. The goals of this study were to understand the relative environmental burdens and economic benefits between two alternative food waste management systems (composting and anaerobic digestion) and the current system (landfilling) and to provide baseline information for deciding the most appropriate food waste diversion system in Boone.

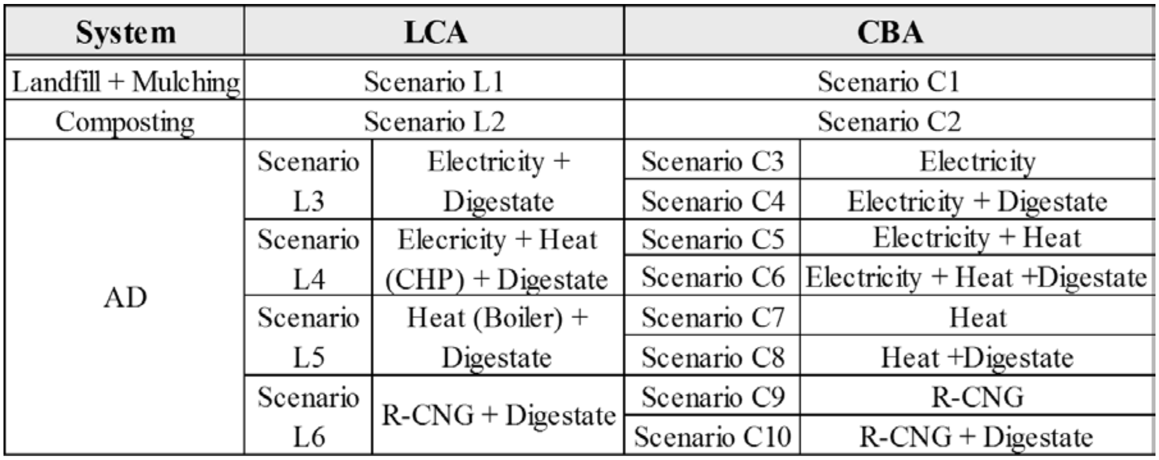
Even though this study focused on a food waste diversion system, it is common to add yard waste to food waste as a bulking agent for composting (Levis & Barlaz, 2011). Since the mixing ratio of the ASU composting facility is typically 50:50 by mass, the baseline waste stream for the study is the mixture of food waste and yard waste at a 50:50 mixing ratio with the assumption of 5% leaves and 95% branches of yard waste composition. Currently, the town of Boone does not have a food waste collection program, so most food waste generated in the Boone area is sent to the Foothills Landfill in Lenoir, NC. Residential yard waste collected by the town is ground and stockpiled at the waste transfer station and then provided to the public as mulch (WCSD, 2012). For the purpose of this study, the current system in Boone was defined as landfilling and mulching, and this was set as the baseline scenario for both LCA and CBA (scenario L1 and C1).

Covered aerated bay (bin) was the model used for the composting option (scenario L2 and C2), because it is the type of composting facility that ASU owns currently. For the anaerobic digestion option, a high-solid batch-type AD system was selected as a model. High-solid batch-type AD could be more beneficial than continuous type AD in the US, where cost saving may be more influential than biogas yield on investment decisions (Williams, 2012). Also, land limitation is not a significant factor in the US (Rapport et al., 2008). Four AD scenarios were set for LCA based on energy recovery options: electricity only (scenario L3); electricity and heat, or combined heat and power (CHP; scenario L4); heat recovery only (scenario L5); and renewable compressed natural gas (R-CNG, scenario L6). AD scenarios for CBA are based on the revenue availability of value-added products. There are eight different AD scenarios for CBA in this study: electricity only available (scenario C3); electricity and digestate (scenario C4); electricity and heat (scenario C5); electricity, heat, and digestate (scenario C6); heat only (scenario C7); heat and digestate (scenario C8); R-CNG only (scenario C9); and R-CNG and digestate (scenario C10).

Table 7 is the summary of scenarios considered in this research. While five scenarios are set for LCA depending on the recovered energy from AD system, the CBA has eight scenarios defined by the value-added products. Note that the environmental impact of scenarios C3 and C4 can be found from the scenario L3. In the same manner, scenarios C5 and C6 are equivalent to the scenario L4, the C7 and C8 are equivalent to the L5, and the C9 and C10 are equivalent to the L6. Before performing LCA and CBA, the commercial food waste generation in the Boone area was estimated to set a reference waste flow.

Table 7

Summary of Scenarios for LCA and CBA



System	LCA		CBA	
Landfill + Mulching	Scenario L1		Scenario C1	
Composting	Scenario L2		Scenario C2	
AD	Scenario L3	Electricity + Digestate	Scenario C3	Electricity
			Scenario C4	Electricity + Digestate
	Scenario L4	Elecricity + Heat (CHP) + Digestate	Scenario C5	Electricity + Heat
			Scenario C6	Electricity + Heat +Digestate
	Scenario L5	Heat (Boiler) + Digestate	Scenario C7	Heat
			Scenario C8	Heat +Digestate
	Scenario L6	R-CNG + Digestate	Scenario C9	R-CNG
			Scenario C10	R-CNG + Digestate

Estimation of Commercial Food Waste Generation in the Boone Area

Boone is a small town with a population of 18,089 (Town of Boone, 2014), but many tourists visit Boone for seasonal sports and beautiful scenery all year round; therefore, many restaurants are located in the downtown. There is also one university (Appalachian State University; ASU), two public schools (Hardin Park School & Watauga High School), six supermarkets, one hospital (Watauga Medical Center), and one company with a large in-house cafeteria (Samaritan’s Purse) as relatively larger size facilities. In order to use the formulas for food waste generation estimation shown in Table 4, six categories of commercial food waste generators were identified: universities, public schools, restaurants, supermarkets, hospitals, and companies with a cafeteria. Since the formulas in Table 14 do not include public schools and companies with a cafeteria, the formula for public schools developed by Mercer County in New Jersey was used for estimating food waste generation from public schools in Boone: Food waste (lbs/yr) = 0.14 lbs/student/day * N of students *

180 days/year (Mercer, 2013). Also, food waste generation from a company with cafeteria was estimated by using the same formula based on 250 working days per year.

Data for the number of students at ASU and in the public schools and the number of beds in Watauga Medical Center were collected through these entities' web sites (http://www.appstate.edu/about/; www.publicschoolreview.com; https://www.apprhs.org). Personal visits were carried out to obtain the number of employees in supermarkets and at Samaritan's Purse. The number obtained for restaurant employment in the Boone area was acquired from the Watauga County Database (www.wataugaedc.org) using NAICS 722511 (full-service restaurant) and 722513 (limited-service restaurant). The summary of categories, formulas, and sources used for this study is described in Table 8.

Table 8

Summary of Food Waste Generation Methods

Category	Name of facility	Formula	Data Collection
Universities	ASU	= 0.35 lbs/meal * N of students * 405 meals/student/yr	Internet
Public Schools	Hardin Park School Watauga High School	= N of students * 0.14lbs/students/day * 180day/yr	Internet
Hospitals	Watauga Medical Center	= N of beds * 5.7 meals/bed/day *0.6 lbs food waste/meal * 365 days/yr	Internet
Companies with a cafeteria	Samaritan's Purse	= N of students * 0.14lbs/students/day *250day/yr	Personal Interview
Restaurants		= N of employees * 3,000 lbs/employee/yr	Internet
Supermarkets	Walmart Food Lion 1 Food Lion 2 Harris Teeter Ingles Earth Fare	= N of employees * 3,000 lbs/employee/yr	Personal Interview

Note: N is number.

LCA Methodology

The program for life cycle analysis of GHG emissions from organic waste management was developed using Microsoft Excel, following the method described in the 3rd Edition of Solid Waste Management and Greenhouse Gases (USPEA, 2006). The boundary for this study was from waste generation to waste disposal. In order to calculate emissions from the waste collection and transportation, the waste collection plan was designed for the shortest travelling distance using Google Maps. The location for the alternative options facility was assumed to be the current transfer station (336 Landfill Road, Boone, NC 28607). The designed travelling distance for the food waste collection is 1695.2 km per year, and the same distance was assumed for yard waste collection. In fact, the residential yard waste in Boone is collected by the town of Boone on a call-in basis currently, so the travelling distance for yard waste collection varies. The travelling distance from the transfer station to the landfill in Lenoir, NC is approximately 4686 km per year.

GHG emissions from processing include the emissions from electricity and from diesel fuel used by the facility. The data on electricity and diesel use by the ASU composting facility was gained from Eddie Hyle, superintendent of ASU landscaping. The same diesel use data was applied to the AD scenarios. Actual data on the electricity and diesel use in the Foothills Landfills could not be collected, so the default inputs in IWMM were used. Also, the methane and N_2O emissions from biogas combustion were included, while the biogenic CO_2 emissions were excluded.

The avoidance of fossil fuel emissions (e.g., natural gas and electricity) was included for AD options. Due to the lack of information for the avoidance of GHG emissions from fertilizer manufacturing (which might result from use of digestate), this study excludes this avoidance. Carbon storage factors for landfilling and the composting of yard and food wastes were developed by USEPA (2006). These composting carbon factors were applied to AD. The USEPA (2011a) reported GHG emission factors of various sources and these data were used in this study. The Life Cycle Inventory database from the National Renewable Energy Laboratory (NREL) also provides gas emissions from various sectors (e.g., waste collection, diesel extraction, and truck transportation). Table 9 is a summary of emission factors and carbon storage factors used in this study.

Table 9

Emission factors and carbon storage factors (USEPA, 2006; USEPA, 2011b; NREL, 2013)

Emission Factors			
	CO2	CH4	N2O
		(kg/liter)	
Diesel Extraction	0	2.824	0
Diesel Vehicles			
Collection Truck	2.62	2.67E-04	4.01E-05
Transport Truck	2.62	7.18E-05	7.54E-06
Construction Equipment	2.70	1.53E-04	6.87E-05
		(kg/MMBtu)	
Natural Extraction site	0	0.24947	0
Natural Extracted	0.4813856	0.096277	0
Natural Gas Combustion	53.02	1.00E-03	1.00E-04
Biogas Combustion	52.07	3.20E-03	6.30E-04
SRVC (VA, NC, SC)		(kg/kWh)	
Electricity emission factor (non-base load), renewable energy	0.755	1.73E-05	1.11409E-05
Electricity emission factor (base load)	0.508	1.01E-05	8.67E-06
Emissions in Landfills			
Methane Emissions	food waste	1617	kg CO2equiv. /wet tonne
Carbon Storage			
Landfilling	food waste	81	kg CO2equiv. /wet tonne
Composting	food + yard	81	

Note. This study used the 2011 data, but USEPA updated the emission factors on April, 2014.

LCAs of each food waste treatment scenario were also conducted using the IWMM from the University of Waterloo. The IWMM tool does not include an R-CNG option for the AD scenario, so only five scenarios were established using this tool: landfilling with mulching, composting, AD with electricity, AD with CHP, and AD with heat.

CBA Methodology

Implementing CBA for this study was composed of six steps: defining scenarios, identifying costs and benefits, collecting data, quantifying value added products, monetizing costs and benefits, building cash flows, and calculating NPVs or IRRs for each scenario.

Defining Scenarios

In the same manner as the LCA component of this study, the current system of landfilling and mulching was used as the baseline scenario (C1), and composting was scenario C2; however, AD systems may have multiple value-added products depending on the installed energy recovery system. The biogas and the digestate generated from AD systems are the primary forms of products. R-CNG, electricity, and heat energy are the secondary forms of products from AD. The digestate can be used directly as fertilizer, or it can be composted before using; therefore, the AD option should have multiple scenarios depending on revenue availability of the value-added products. In this study, eight scenarios were set up for AD options: electricity only (scenario C3), electricity and digestate (scenario C4), electricity and heat (scenario C5), electricity, heat, and digestate (scenario C6), heat only (scenario C7), heat and digestate (scenarios C8), R-CNG only (scenario C9), and R-CNG and digestate (scenario C10).

Identifying Costs and Benefits

Because Watauga County does not operate a landfill, the costs for the current landfilling and mulching system are tipping fees and mulching costs. The costs for a composting facility or an AD facility include capital costs and operation costs. The capital costs for both alternative options include system design and engineering, system materials and equipment, and construction. Even though the capital costs of AD scenarios may vary (e.g., with CHP or with R-CNG systems), the capital cost of the AD with CHP system was used for all AD scenarios due to the lack of data about the various system types. The costs and benefits of waste collection were excluded from this study due to the lack of information. The benefits from each system may vary depending on what and how much of the value-added products are generated; therefore, the estimated amounts of value-added products and their market prices should be studied. There is no specific economic benefit of organic waste landfilling. Organic compost is a value-added product generated from a composting facility. The value-added products from AD systems in this study were defined as biogas, electricity, heat, R-CNG, and digestate. In addition, some AD options (C3, C4, C5, C6, C9, and C10) are eligible for RECs or RINs.

Collecting Data

The cost data for each option were gained through personal interviews, emails, and literature review. The rates for tipping and mulching for scenario 1 were obtained from an interview with Lisa Doty, manager of Watauga Recycling (L. Doty, personal interview, September 4, 2013).

The capital cost for the composting option (scenario C2) was based on data collected from Green Mountain Composting in Vermont and Amboy Compost Site in New York.

Green Mountain Composting operates a 20,000 TPY-capacity covered aerated bay composting facility (D. Goossen, personal communication, February 14, 2014). Amboy Compost Site recently opened a 9,600 TPY aerated bay composting facility, but it does not have a roof. Using the breakdown capital cost from Green Mountain Compost, the estimated roof cost was added to the capital cost of the Amboy Compost site. The operation and maintenance cost for this type of composting facility was obtained from Eddie Hyle, a superintendent of Landscaping Services at ASU, including electricity cost, diesel cost, labor cost, and maintenance cost. Since the ASU composting facility treated about 130 tons of food and yard waste in 2012, the electricity and diesel costs were recalculated to a 10,000-ton basis. The labor cost was based on $21.32 per hour (including fringe and benefits), 32 hours per week, and the assumption of two positions to operate the facility.

The data about costs and value-added products for AD options were collected from Zero Waste Energy (2013). The report contains detailed information for a 10,000 TPY AD system with combined heat and power, and 20,000 TPY and 40,000 PTY AD systems with compressed natural gas.

Quantifying Value-Added Products

Mass balance of inputs and outputs of the composting process was measured at Imperial College (Mitaftsi & Smith, 2006). Based on their series of mass balance tests (see Appendix A), the trend line of mass balance depending on food to yard waste ratios was developed. Using the trend line, total compost output from 50:50 ratios of food and yard wastes was calculated. Zero Waste Energy (2013) states the process parameters including electricity and heat generation, and amount of the composted digestate, expected from a 10,000 TPY system processing this same ratio of food and yard waste.

Monetizing Value-Added Products

After qualifying the value-added products, these were monetized based on the market price of compost and the avoided cost rate of electricity generation. The current market price of organic compost was adopted from Danny’s Dumpster in Asheville, NC (http://dannysdumpster.com/). The avoided cost was calculated based on the rates stated in the power purchase agreement (PPA) between Watauga County and Duke Energy (see Appendix B). The average North Carolina natural gas rate for the commercial sector according to the US Energy Information Administration (USEIA) was adopted to monetize the biogas and the generated heat (USEIA, 2014a).

Building Cash Flows and Calculating NPVs

The cash flows for each scenario over a 20-year timeframe were built, and NPVs of each scenario were computed using Microsoft Excel and the formulas provided in Chapter 2 of this document. Due to the lack of data for discounts rates of each option, various discount rates of 4%, 6%, 8%, 10%, and 12%, were applied.

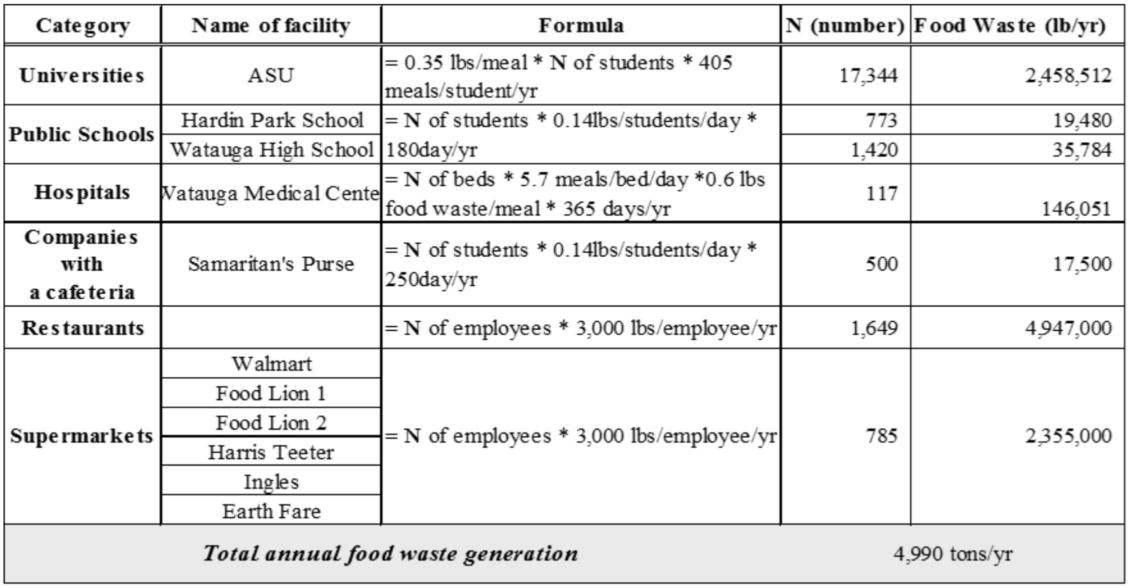
CHAPTER 4: RESEARCH FINDINGS

Food Waste Generation Estimation in Boone, North Carolina

Table 10 shows the estimated food waste generation of each sector, using the formulas from Draper and Lennon (2002) and Mercer (2013). Total estimated commercial food waste generation for Boone is 4,990 TPY; this number is higher than the number, 3,027 TPY, provided by North Carolina Department of Environment and Natural Resources (NCDENR, 2012). NCDENR estimated food waste generation per county using previous waste studies from other states and North Carolina population data; however, the higher number I calculated could be reasonable in Boone. Although Boone is a small town, it is a tourist destination and home of Appalachian State University, which ranked in the top 5% for general business growth in 2013 reported by the Nielsen Company (Torres & Song, 2013).

Table 10

Estimated Commercial Food Waste Generation in Boone, NC



Category	Name of facility	Formula	N (number)	Food Waste (lb/yr)
Universities	ASU	= 0.35 lbs/meal * N of students * 405 meals/student/yr	17,344	2,458,512
Public Schools	Hardin Park School	= N of students * 0.14lbs/students/day * 180day/yr	773	19,480
	Watauga High School		1,420	35,784
Hospitals	Vatauga Medical Cente	= N of beds * 5.7 meals/bed/day *0.6 lbs food waste/meal * 365 days/yr	117	146,051
Companies with a cafeteria	Samaritan's Purse	= N of students * 0.14lbs/students/day * 250day/yr	500	17,500
Restaurants		= N of employees * 3,000 lbs/employee/yr	1,649	4,947,000
Supermarkets	Walmart Food Lion 1 Food Lion 2 Harris Teeter Ingles Earth Fare	= N of employees * 3,000 lbs/employee/yr	785	2,355,000
Total annual food waste generation			4,990 tons/yr	

For simplicity, the estimated food waste generation was rounded up to 5,000 tons per year (TPY). After adding the same mass of yard waste to the food waste, the reference flow of available organic waste becomes 10,000 TPY in this study.

Environmental Impacts: LCA Results

LCA Results from the Self-Developed Program

All inputs are summarized in Table 11. Since IWMM requires metric units, units were converted for consistency. The emission factors (Table 9) were multiplied by input energies (i.e., electricity, diesel, and biogas) and summed to calculate subtotals of CO_2, CH_4, and N_2O emissions. In case of L1, landfill gas emissions should be included in the subtotal of CH_4 emissions. Then, biogenic CO_2, avoided emissions, and carbon storage were subtracted from the subtotal. In order to characterize global warming impact with CO_2 equivalent, the global warming potential (GWP) numbers of each GHG were multiplied by total emissions of each gas and summed. Note that the avoided fuel for AD with heat energy is natural gas in this study. Microsoft Excel was used to develop a LCA tool for this study (see Appendix C).

AD with CHP option (scenario L4) shows the best result (Table 12 & Figure 15), which means the least GHG emissions. All AD scenarios are advantageous mainly due to avoided fossil fuel emissions by renewable energy production. The reason why the AD with R-CNG option is less advantageous than the other AD option is that the amount of biogas combusted for energy, which makes the AD option superior, is less than in other scenarios. In this scenario, only a small amount of electricity is generated for the parasitic loads, and most biogas is compressed. Note that the final product, R-CNG, is not a form of energy but a form of fuel. If the boundary of this study is extended to R-CNG combustion in a vehicle, it will emit less GHG than diesel combustion; however, conversion factors from a diesel vehicle to a natural gas vehicle should be considered in this case.

Table 11

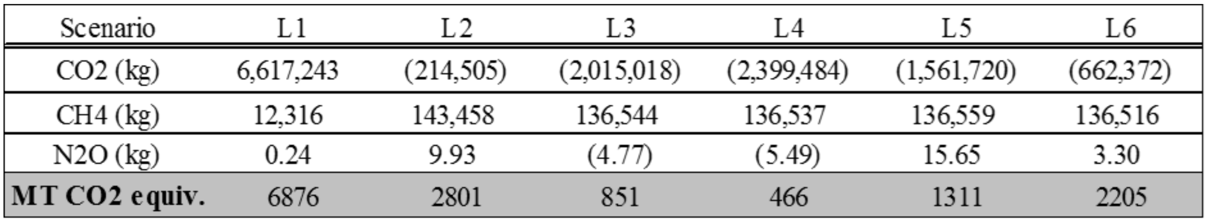
Summary of GHG Emissions and Sinks Associated with Organic Waste Life Cycle in this Study

Scenario	Waste generation	Collection	Transfer station	Transport	Final Destination				
		Diesel Truck Fuel Efficiency: 1.25 km/liter		Diesel Trucks Efficiency 2.5km/liter	Facility	Facility Energy Use	Landfill gas/ Biogenic CO2/ Biogas	Avoided from fossil fuel	Carbon Storage (MT CO2 equiv. /tonne)
L1 (landfilling +mulching)	Food Waste: 4,536 tonnes	1,695.2 km	Energy Use: 2.5 kwh/tonne for electricity, 0.124 liters/tonne for	4686.4 km	Landfill	0.29 kwh/tonne of electricity, 0.22 liters of diesel/tonnes of waste	1.6 MT CO2 equiv. of Methane emissions per tonne of waste		0.08
	Yard Waste: leaves 227 tonnes + branches 4,309 tonnes	1,695.2 km			Stockpile	0.124 liters/tonne for diesel (wood ginder)	Biogenic CO2		0.08
L2 (composting)	Food Waste: 4,536 tonnes	1,695.2 km			composting	82.9 kwh/ tonne of electricity, 5.3 liters of diesel/tonnes of waste	Biogenic CO2		0.08
	Yard Waste: leaves 227 tonnes + branches 4,309 tonnes	1,695.2 km							
L3 (AD +elect.)	Food Waste: 4,536 tonnes	1,695.2 km			AD	5.3 liters of diesel/tonnes of waste	Biogas Combustion (20066MMBtu)	20,066 MMBtu NG extraction + 1,869,384kwh electricity generation	0.08
	Yard Waste: leaves 227 tonnes + branches 4,309 tonnes	1,695.2 km							
L4 (AD +CHP)	Food Waste: 4,536 tonnes	1,695.2 km			AD	5.3 liters of diesel/tonnes of waste	Biogas Combustion (20066MMBtu)	20,067 MMBtu NG extraction + 1,869,384kwh electricity generation + 7,200 MMBtu NG combustion	0.08
	Yard Waste: leaves 227 tonnes + branches 4,309 tonnes	1,695.2 km							
L5 (AD +Heat)	Food Waste: 4,536 tonnes	1,695.2 km			AD	16kwh/tonne, 5.3 liters of diesel/tonnes of waste	Biogas Combustion (20066MMBtu)	20,067 MMBtu NG extraction + NG combustion	0.08
	Yard Waste: leaves 227 tonnes + branches 4,309 tonnes	1,695.2 km							
L6 (AD + R-CNG)	Food Waste: 4,536 tonnes	1,695.2 km			AD	5.3 liters of diesel/tonnes of waste	Biogas combustion for parasitic electricity: 376.6MMBtu	20,067 MMBtu NG extraction+110,376 kwh electricity generation	0.08
	Yard Waste: leaves 227 tonnes + branches 4,309 tonnes	1,695.2 km							
		Emiccions (+)	**Emissions (+)**	**Emissions (+)**		**Emissions (+)**	**Emissions (+), Biogenic CO2 (-)**	**Avoided emissions (-)**	**Carbon Storage (-)**

Scenario L5, which generates only heat energy, has less advantage than AD options with electricity generation in terms of GHG emissions. This is caused by the fact that electricity generation emission factors are greater than natural gas combustion. In other words, AD with heat option obtains less benefit from fossil fuel avoidance. Table 12 shows emission factors of each energy or fuel in the same unit, $MTCO_2$ equivalent per MMBtu. The electricity generated by biogas is considered as non-baseload because its generation contributes to peak time demand. The emission factor of non-baseload electricity generation is 223 kg CO_2 equivalent per MMBtu, which is over five times greater than natural gas combustion.

Table 12

Breakdown GHG Emissions of Each Scenario



Scenario	L1	L2	L3	L4	L5	L6
CO2 (kg)	6,617,243	(214,505)	(2,015,018)	(2,399,484)	(1,561,720)	(662,372)
CH4 (kg)	12,316	143,458	136,544	136,537	136,559	136,516
N2O (kg)	0.24	9.93	(4.77)	(5.49)	15.65	3.30
MT CO2 equiv.	6876	2801	851	466	1311	2205

Note. Numbers in parentheses are negative values.

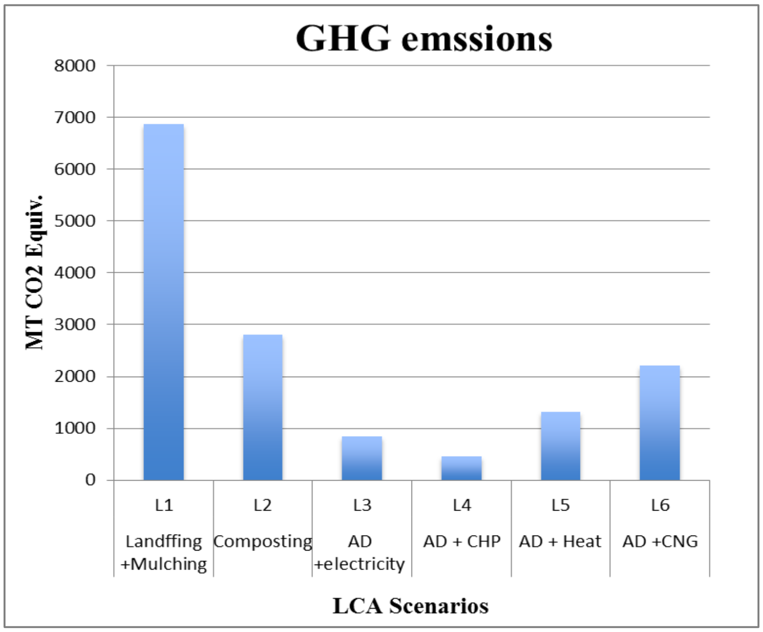


Figure 15. GHG emissions from each scenario in MT CO_2 equivalent.

In order to learn which energy or fuel source is predominant in total GHG emissions, all emission factors were converted to kg CO_2 equivalent per MMBtu (Table 13). The emissions factors of natural gas and diesel convey life cycle emissions from extraction to combustion. The emissions from a diesel vehicle are much greater than from other sources, so there would be significant advantages for GHG reduction if all the collection trucks were converted to natural gas vehicles.

Table 13

Comparison of Emission Factors of Energy Sources

Source		***Emission Factors (kg/MMBtu)***			
		CO2	CH4	N2O	CO2 Equiv.
Electricity (base load)	SRVC (VA, NC, SC)	149.08	0.003	0.0025	150
Electricity (non-base load)		221.42	0.005	0.0033	223
Biogas Combustion		52.07	0.003	0.0006	52
Natural Gas (from extraction to combustion)		53.50	0.347	0.0001	61
Diesel (from extraction to combustion)	Collection Truck	76.06	81.923	0.0012	1797
	Transport Truck	75.93	81.918	0.0002	1796
	Construction Equipment	78.24	81.920	0.0020	1799

Sensitivity analysis depending on different travelling distance. A sensitivity analysis was conducted to measure the impact of travelling distance as it relates directly to diesel emissions. Figure 16 presents the GHG emissions influenced by different collection frequency and diversion facility location. The original assumption located the diversion facility in Boone and with waste collected once a week. If the facility were located at the landfill site in Lenoir, extra travelling from the transfer station to the landfill should be added; however, even daily collection and transportation does not increase GHG emissions as much as the landfilling scenario. This sensitivity analysis indicates that the impact of landfill gas emissions is a more dominant factor than travelling distance on total GHG emissions.

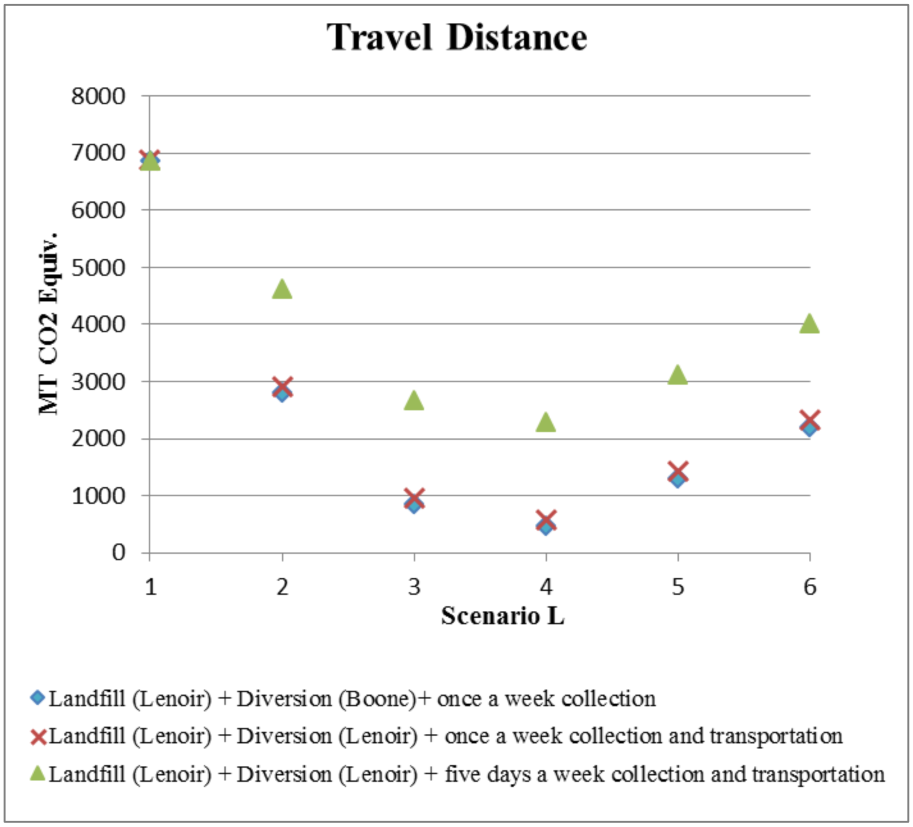


Figure 16. GHG emissions affected by the diversion facility location and collection days.

Sensitivity analysis depending on different electricity consumption. The electricity usage at the composting facility is greater than other facilities in this study due to the under-floor aeration system. Another sensitivity analysis was conducted by reducing the electricity usage at the composting facility. Figure 17 presents the changes in total GHG emissions in the composting facility for different electricity consumption levels. Even with no electricity consumption, the total GHG emission from composting is higher than from AD systems. If the composting facility utilizes the electricity fully from renewable sources such as solar energy, an additional GHG reduction by avoidance of fossil fuel use will influence total GHG emission (Figure 17, R-electricity).

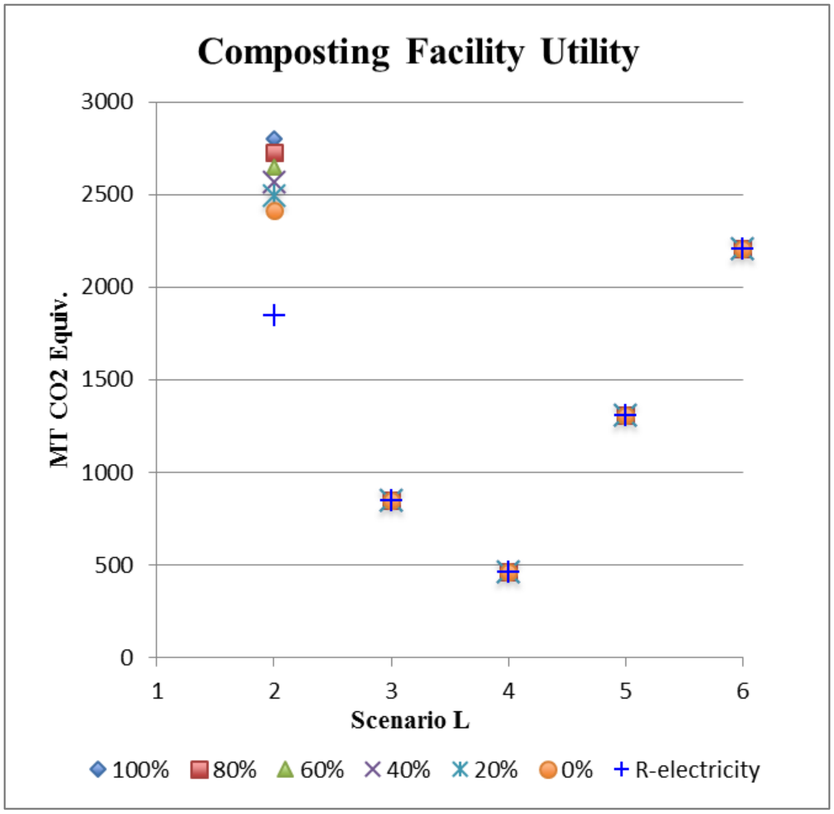


Figure 17. Composting facility GHG emissions affected by different electricity uses. The current electricity use is set as 100%.

Sensitivity Analysis depending on different biogas yield. Biogas yields and generator efficiencies are important factors for the AD system, which affects renewable energy production and additional GHG reductions. Figure 18 shows the influence on GHG emissions of AD scenarios with different biogas yields. Since the emission factors of electricity are greater than those of natural gas combustion, scenarios L3 and L4 show bigger GHG emission changes than L5. The scenario L4 produces both electricity and heat energy, so it is influenced by biogas yield slightly more than other scenarios.

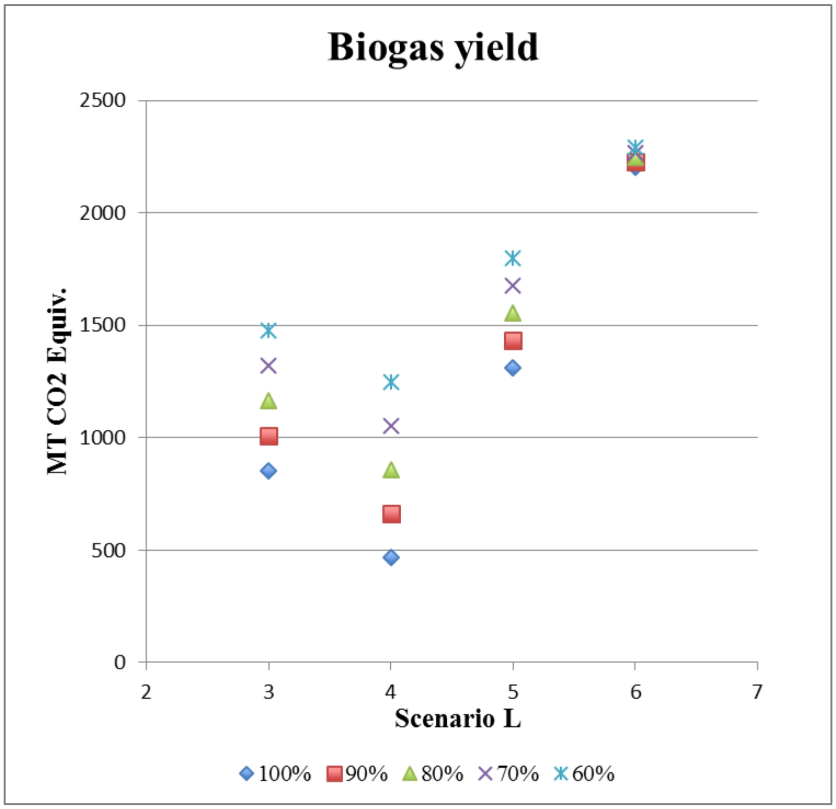


Figure 18. GHG emissions of AD scenarios depending on biogas yields. The current biogas yield is set as 100%.

Sensitivity analysis depending on different system efficiency. System (e.g., generator or boiler) efficiency is another important factor that affects renewable energy production. The generator efficiencies used in this study are 32% and 62% for L3 and L4, respectively. The GHG emissions of the scenario L4 increase up to 180% by reducing the generator efficiency to 80% of the current efficiency. The boiler efficiency does not result in GHG reduction, because the boiler efficiency affects heat energy production from both biogas and natural gas equally, while the generator efficiency affects only electricity production from biogas but not electricity from the grid to which it is being compared (Figure 19).

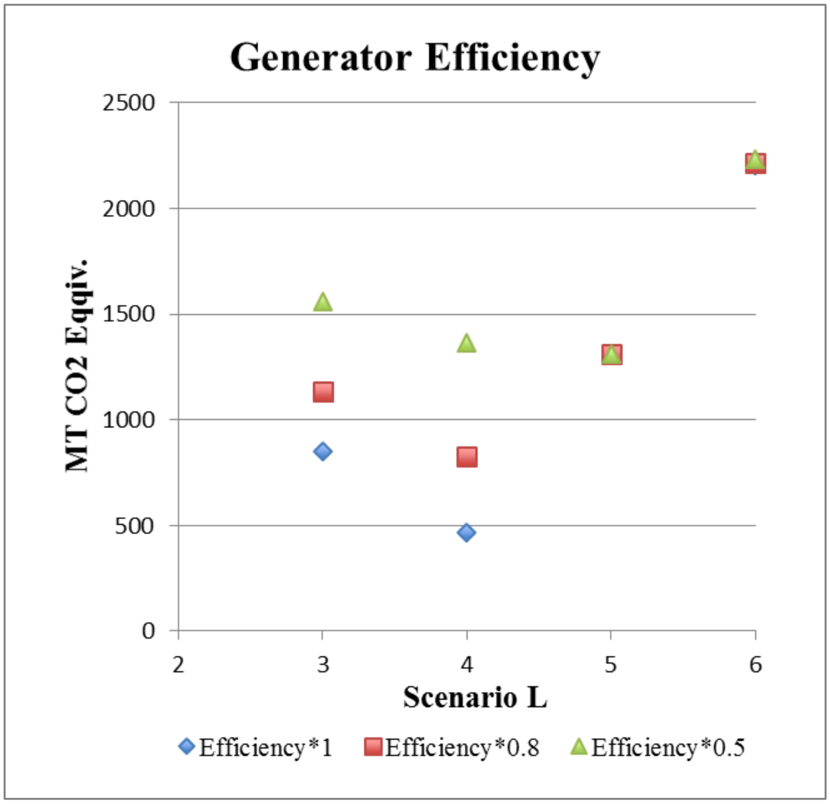


Figure 19. GHG emissions of AD scenarios depending on generator efficiency

LCA Results from IWMM

Table 14 is a summary of each scenario and inputs for Boone, NC, using IWMM, which is described in the methodology chapter. Since IWMM uses metric units, the estimated 10,000 TPY of organic waste generation in Boone was converted to 9,072 tonnes per year.

Table 14

Summary of Inputs for IWMM

Scenario	System	Waste	Transportation		Electric Grid	Trnasfer Station	System Condidtion	
			Collection Trucks (Travelling 1695.2 km)	Transport Trucks (Travelling 4686.4 km)	NC Electricity Generation			
			Fuel Efficiency: 1.25 km/liter	2.5 km/liter				
L1	Landfilling + Mulching (Current)	Total 9072 tonnes (Food waste 50% + Leaves 2.5% + Branches 47.5%)	Food waste: Garbage trucks Yard Waste: Yard waste trucks	yes	Coal 41.9% Nuclear 31.2% Natural Gas 21.1% Hydro+Other Reneawables 5.8%	yes (Energy Use: 0.124 liters/tonne for diesel , 2.5 kwh/tonne for electricity)	No energy or gas recovery, 1,210mm annual precipitation, Lined with 90% leachate collection, Sequestraion, Energy use: 0.22 liters of diesel, 0.028 m3 of neatural gas, 0.29 kwh of electricity per tonne of waste	
L2	Composting		Food waste: Source separated organic waste trucks Yard Waste: Yard waste trucks	no		no	Energy Use: 85.9 kwh of electricity, 5.3 liters of diesel per tonnes of waste	
L3	AD, Electricity generation			no		no	Biogas: 60% CH4 & 40% CO2, No residue to Landfills, Process water: 196113 liters/tonne of waste	Efficiency: 38.8%, Facility Energy: 7.7% of Electricity generated
L4	AD, Heat (steam) generation			no		no		Efficiency: 70%, Facility Energy: 22% of Heat generated, Additional Energy (fossil fuel): 0.0569GJ/tonne of waste
L5	AD, Electricity + Heat generation (CHP)			no		no		Efficiency: 75%, Facility Energy: 21% of total energy generated

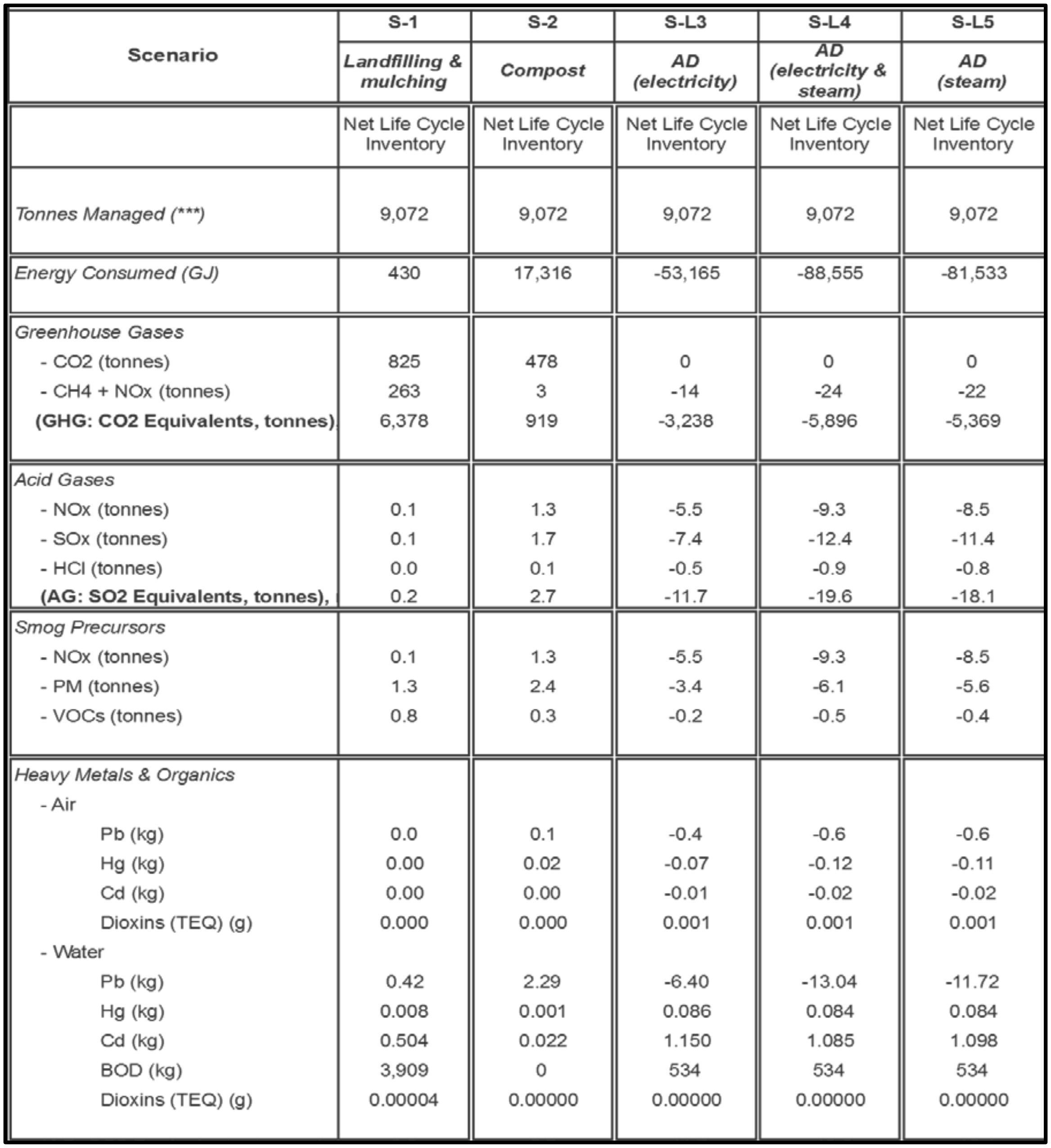
The emissions of each impact indicator were calculated based on the inputs and the life cycle inventory database adopted in IWMM (Table 15). These life cycle inventory results were assigned to the impact categories such as greenhouse gases (global warming) and acid gases (acidification). IWMM characterized global warming impact by computing CO_2 equivalent using the global warming potentials defined by the Intergovernmental Panel on Climate Change (IPCC). One thing that should be clarified in the IWMM program is why NO_x emissions are categorized as global warming indicators, because NO_x is not a direct GHG gas. N_2O, different from NO_x, is one of the major GHG with a large GWP, 310 times more than CO_2.

In order to know the acidification impact, additional computation for SO_2 equivalent was performed using Guinée's guidelines (Guinée, 2002), because IWMM does not automatically characterize acidification. Guinée (2002) provided acidification potential (AP) based on previous studies (e.g., 0.70 for nitrogen oxides, 1.00 for sulfur dioxide, and 0.88 for hydrogen chloride). The products of the AP and the molecular weight of each emitted gas were summed to compute the SO_2 equivalent of total acid gas emissions.

Those two impacts of the scenarios are illustrated in Figure 20. Both the composting (scenario L2) and the AD options (scenario L3, L4, and L5) result in the reduction of GHG emissions compared to the current system (scenario L1), mostly due to the reduction of landfill gas emission. In addition, all the AD options show a greater reduction than the composting option, since the AD options generate energy such as electricity and heat. Therefore, the AD options can reduce the fossil fuel use for energy generation. The composting option (scenario L2) indicates the highest acid gas emission because it utilizes more electricity than the other options.

Table 15

Life Cycle Inventory Results under Impact Categories in IWMM



Scenario	**S-1**	**S-2**	**S-L3**	**S-L4**	**S-L5**
	Landfilling & mulching	***Compost***	***AD (electricity)***	***AD (electricity & steam)***	***AD (steam)***
	Net Life Cycle Inventory	Net Life Cycle Inventory	Net Life Cycle Inventory	Net Life Cycle Inventory	Net Life Cycle Inventory
Tonnes Managed (***)	9,072	9,072	9,072	9,072	9,072
Energy Consumed (GJ)	430	17,316	-53,165	-88,555	-81,533
Greenhouse Gases					
- CO2 (tonnes)	825	478	0	0	0
- CH4 + NOx (tonnes)	263	3	-14	-24	-22
(GHG: CO2 Equivalents, tonnes)	6,378	919	-3,238	-5,896	-5,369
Acid Gases					
- NOx (tonnes)	0.1	1.3	-5.5	-9.3	-8.5
- SOx (tonnes)	0.1	1.7	-7.4	-12.4	-11.4
- HCl (tonnes)	0.0	0.1	-0.5	-0.9	-0.8
(AG: SO2 Equivalents, tonnes),	0.2	2.7	-11.7	-19.6	-18.1
Smog Precursors					
- NOx (tonnes)	0.1	1.3	-5.5	-9.3	-8.5
- PM (tonnes)	1.3	2.4	-3.4	-6.1	-5.6
- VOCs (tonnes)	0.8	0.3	-0.2	-0.5	-0.4
Heavy Metals & Organics					
- Air					
Pb (kg)	0.0	0.1	-0.4	-0.6	-0.6
Hg (kg)	0.00	0.02	-0.07	-0.12	-0.11
Cd (kg)	0.00	0.00	-0.01	-0.02	-0.02
Dioxins (TEQ) (g)	0.000	0.000	0.001	0.001	0.001
- Water					
Pb (kg)	0.42	2.29	-6.40	-13.04	-11.72
Hg (kg)	0.008	0.001	0.086	0.084	0.084
Cd (kg)	0.504	0.022	1.150	1.085	1.098
BOD (kg)	3,909	0	534	534	534
Dioxins (TEQ) (g)	0.00004	0.00000	0.00000	0.00000	0.00000

The negative numbers for AD options may be caused by no input function for diesel use on AD options. Scenario L5, AD with heat recovery, shows a better result than the L3 option, which is in contrast to the result from the program developed for this study (refer to

Figure 15). This may be caused by a different avoided fossil fuel such as electricity or coal. In the developed program, natural gas is set as an avoided fossil fuel for the biogas heating option. In fact, the emission factor of natural gas combustion is much lower than that of electricity generation (Table 12). Unfortunately, IWMM does not provide the avoided fossil fuel of the biogas heating option.

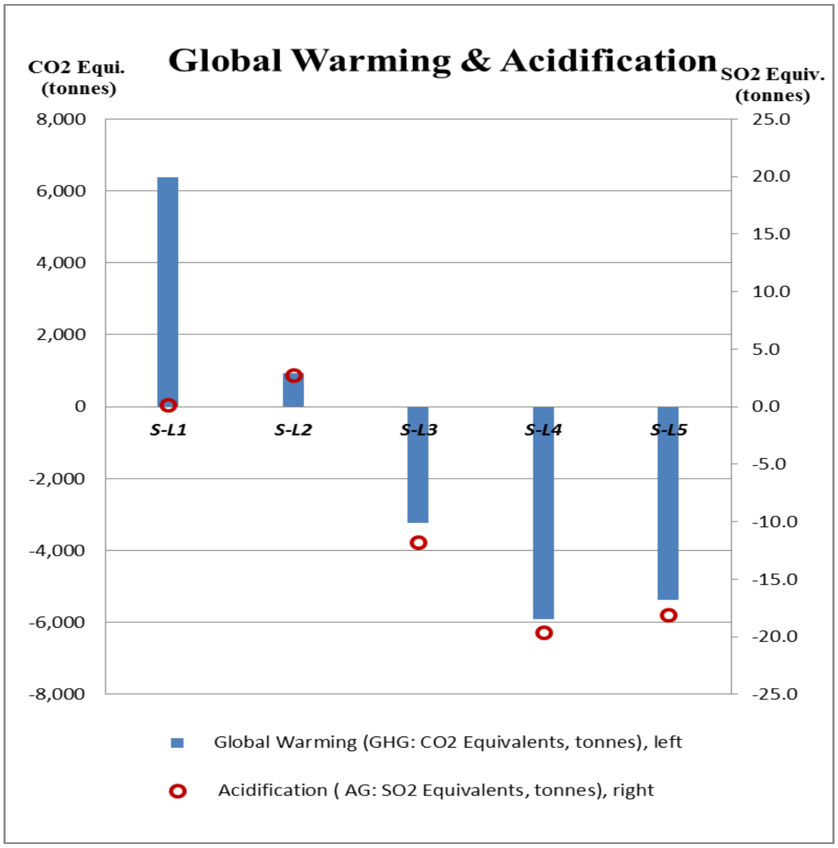


Figure 20. Environmental impacts (global warming and acidification) of all scenarios.

Economic Analysis: CBA Results

Collected Data

The weight of compost generated was calculated by using the data from Imperial College (Mitaftsi & Smith, 2006). The curve in Figure 21 was developed with the numbers based on Mitaftsi and Smith's experiments (2006; see Appendix A). The typical dry contents of food waste and yard waste are 30% and 50%, respectively (Environment Canada, 2013), thus the dry content of the mixture, 50% food and 50% yard waste by mass, is 40%. From Figure 21, it could be found that the mass of the final product is about 61% of the initial input at 40% dry content. Since the waste stream in this study was calculated as 10,000 TPY, about 6,100 tons of annual compost generation is estimated.

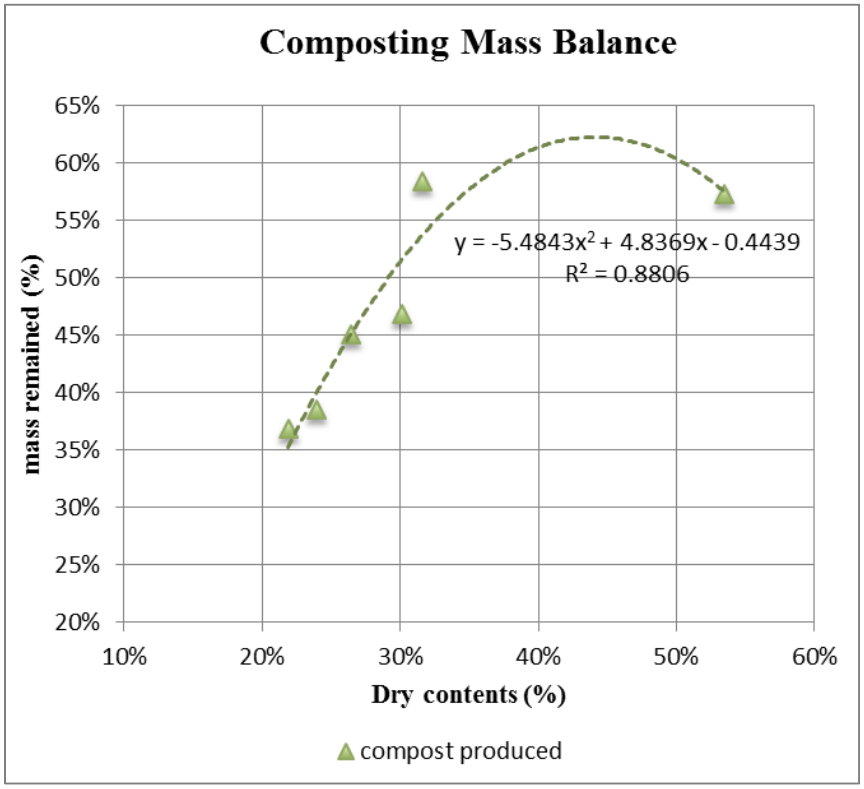


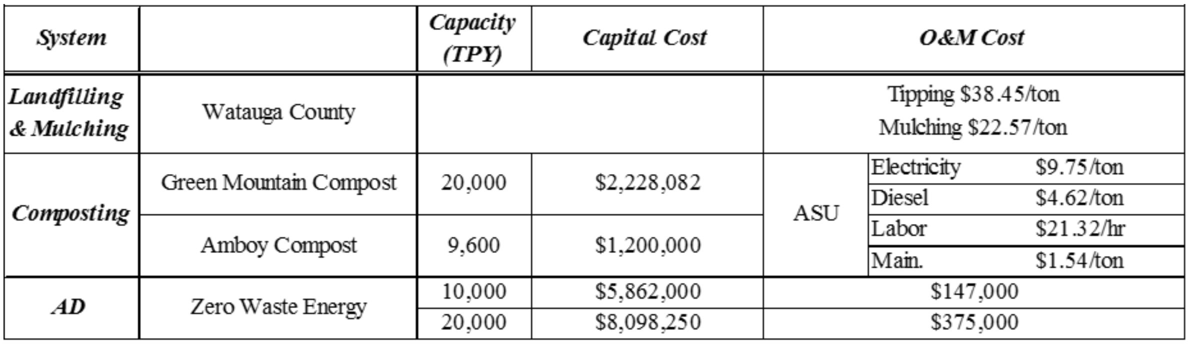
Figure 21. Mass balance of food and yard waste composting derived based on the data from Imperial College, London.

The cost data used for this study are shown in Table 16. The tipping fee and the mulching fee listed in Table 16 are the rates that Watauga County paid in 2011/2012. The capital cost for the 10,000 TPY covered aerated bay composting facility is estimated with the data from Green Mountain Compost and Amboy Compost (D. Goossen, personal communication, February 14, 2014; Onondaga County Resource Recovery Agency [OCRRA], 2011). Note that the cost data from Green Mountain Compost are the actual costs while the capital cost of Amboy Compost is the estimated cost. Since the Amboy Compost system operates without a roof, the roof structure cost from Green Mountain Compost was added to Amboy Compost capital cost to estimate the capital cost of a 10,000 TPY facility. The capital cost of $1,223,085 was estimated and used for scenario C2.

The O&M costs for the composting option were collected from the ASU composting facility through interviews with Edward A. Hyle, Superintendent of Landscape Services at ASU. It was assumed that two employees work for 32 hours a week each for a 10,000 TPY facility, and three employees work for a 20,000 TPY facility.

Table 16

The Capital Costs and the O&M Costs Used for this Study (D. Goossen, personal communication, February 14, 2014; E. Hyle, personal communication, January 27, 2014; L. Doty, personal communication, Sep 4, 2013; OCRRA, 2011; Zero Waste Energy, 2013).



System		***Capacity (TPY)***	***Capital Cost***	***O&M Cost***		
Landfilling & Mulching	Watauga County			Tipping $38.45/ton Mulching $22.57/ton		
Composting	Green Mountain Compost	20,000	$2,228,082	ASU	Electricity	$9.75/ton
					Diesel	$4.62/ton
	Amboy Compost	9,600	$1,200,000		Labor	$21.32/hr
					Main.	$1.54/ton
AD	Zero Waste Energy	10,000	$5,862,000	$147,000		
		20,000	$8,098,250	$375,000		

Zero Waste Energy (ZWE, 2013) offers the estimated breakdown costs and data regarding system performance. The example systems that they presented are a 10,000 TPY AD facility with a CHP system and a 20,000 TPY facility with a CNG system. The CNG system includes a micro CHP system to supply the parasitic loads for the facility. In order to establish all eight AD scenarios for both 10,000 TPY and 20,000 TPY, a 10,000 TPY with a CNG system and a 20,000 TPY with a CHP system were assumed using the data offered by ZWE (2013). Since ZWE (2013) excludes the heating-only option, the AD system with 85% boiler efficiency was assumed to generate heat energy only. Note that the same capital cost was applied to all three options, CHP, boiler, and CNG, due to a lack of information about some of these systems.

The prices for monetizing the value-added products are listed in Table 17. USEIA (2014a, 2014b) reports the average electricity price and natural gas price for the commercial sector by state on their website. The grid electricity price represents an average North Carolina electricity price for the commercial sector (USEIA, 2014b), and this number was used to calculate the additional electricity cost for AD with boiler option. The avoided cost rate for selling electricity to the grid was calculated according to the power purchase agreement (PPA) contracted between the Watauga County Landfill and Duke Energy in 2011 (see Appendix B). The compost price was adopted from the business Danny’s Dumpster, located in Asheville, NC. Their compost rate is \$40 per cubic yard, so \$100 per ton of compost was calculated with a density of 880 pounds per cubic yard from California Department of Transportation (2014).

The average CNG price of \$2.07 per gasoline gallon equivalent (GGE) from Piedmont Natural Gas was converted to \$2.35 per diesel gallon equivalent (DGE). For more accurate CBA results over time, the prices for energy were adjusted yearly based on energy price inflation rates from USEIA and the US Department of Energy (USEIA, 2014a; USEIA, 2014c; USDOE, 2014). Renewable energy credits (RECs) applied is $0.003 per kWh (Jason Hoyle, personal interview, March 17, 2013), and $1.35 per DGE was used for Renewable Identification Number (RIN) (ZWE, 2014).

Table 17

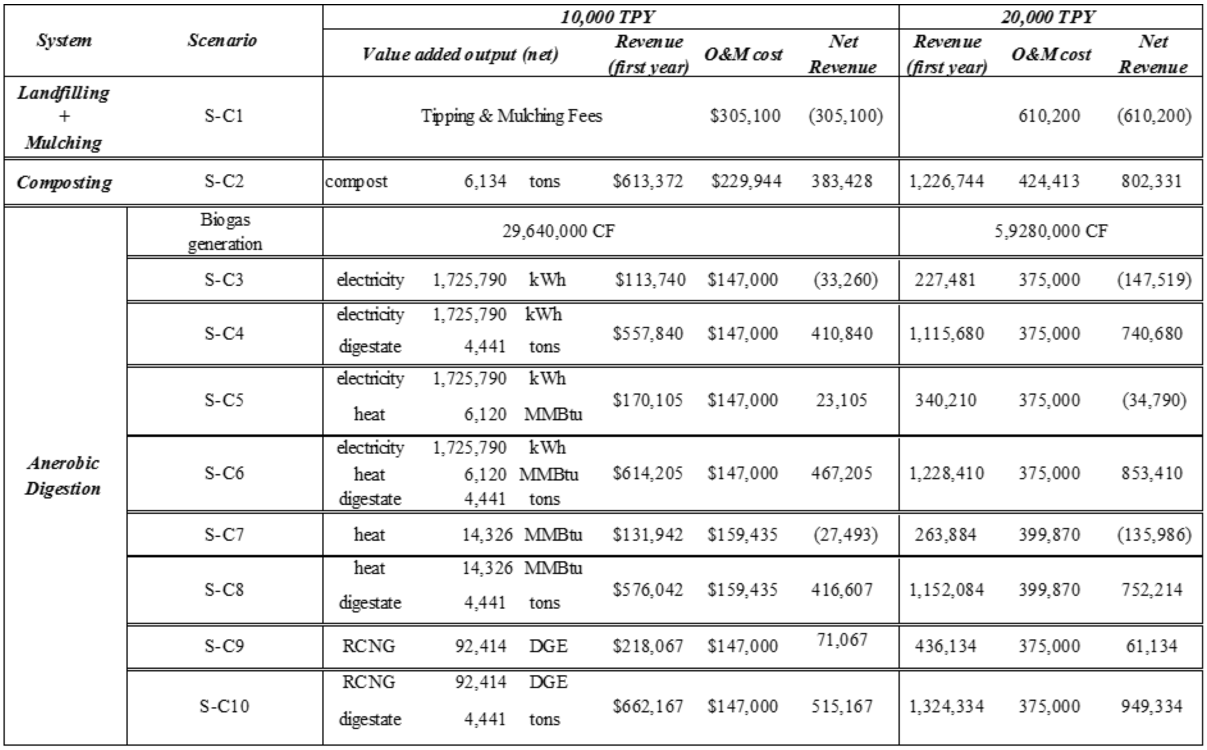
The Unit Prices of Value-Added Products Used for the Study

	Rates	***Inflation***	***Environmental Attributes***	
Electricity	$0.09/kWh	0.4%/yr		
Avoided Cost	$0.07/kWh	0.4%/yr	***RECs***	$0.003/kWh
Compost	$100/ton			
Natural Gas	$9.21/10^6 Btu	1.8%/yr		
CNG	$2.35/DGE	8%/yr	***RINs***	$1.35/DGE

Table 18 provides a detailed description of system performance and cost data for each scenario used in the study. Note that the AD with R-CNG option has the smallest amount of remainder electricity after parasitic loads.

Table 18

Inputs for Cost Benefit Analysis



System	Scenario	10,000 TPY						20,000 TPY		
		Value added output (net)			Revenue (first year)	O&M cost	Net Revenue	Revenue (first year)	O&M cost	Net Revenue
Landfilling + Mulching	S-C1	Tipping & Mulching Fees				$305,100	(305,100)		610,200	(610,200)
Composting	S-C2	compost	6,134	tons	$613,372	$229,944	383,428	1,226,744	424,413	802,331
Anerobic Digestion	Biogas generation	29,640,000 CF						5,9280,000 CF		
	S-C3	electricity	1,725,790	kWh	$113,740	$147,000	(33,260)	227,481	375,000	(147,519)
	S-C4	electricity digestate	1,725,790 4,441	kWh tons	$557,840	$147,000	410,840	1,115,680	375,000	740,680
	S-C5	electricity heat	1,725,790 6,120	kWh MMBtu	$170,105	$147,000	23,105	340,210	375,000	(34,790)
	S-C6	electricity heat digestate	1,725,790 6,120 4,441	kWh MMBtu tons	$614,205	$147,000	467,205	1,228,410	375,000	853,410
	S-C7	heat	14,326	MMBtu	$131,942	$159,435	(27,493)	263,884	399,870	(135,986)
	S-C8	heat digestate	14,326 4,441	MMBtu tons	$576,042	$159,435	416,607	1,152,084	399,870	752,214
	S-C9	RCNG	92,414	DGE	$218,067	$147,000	71,067	436,134	375,000	61,134
	S-C10	RCNG digestate	92,414 4,441	DGE tons	$662,167	$147,000	515,167	1,324,334	375,000	949,334

Note. Numbers in parentheses are negative values.

CBA Results using NPV and IRR

NPVs with various discount rates over 20-year lifetime. Figure 22 describes the net present values of all scenarios with various discount rates over a 20-year system lifetime. Several economic analysis studies on AD systems adopted 8% or 10% discount rates (Enahoro & Gloy, 2008, Giesy, Wilkie, de Vries, & Nordstedt, 2009; Moriarty, 2013;), while a 5% discount rate was used for Teague's composting research (2011). The composting option (scenario C2) exhibits greater NPVs than the other scenarios, because of the lower capital cost of the composting facility. The higher inflation rate of CNG prices makes scenario C10 more profitable than other AD options with a discount rate lower than 10%. The dotted lines in Figure 22 are AD scenarios with digestate sales included. The common factor for positive NPV in Figure 22 is the digestate, which means that the revenue availability of digestate is critical to making the AD option profitable. None of the AD scenarios without digestate exhibit positive NPVs over any of the discount rates.

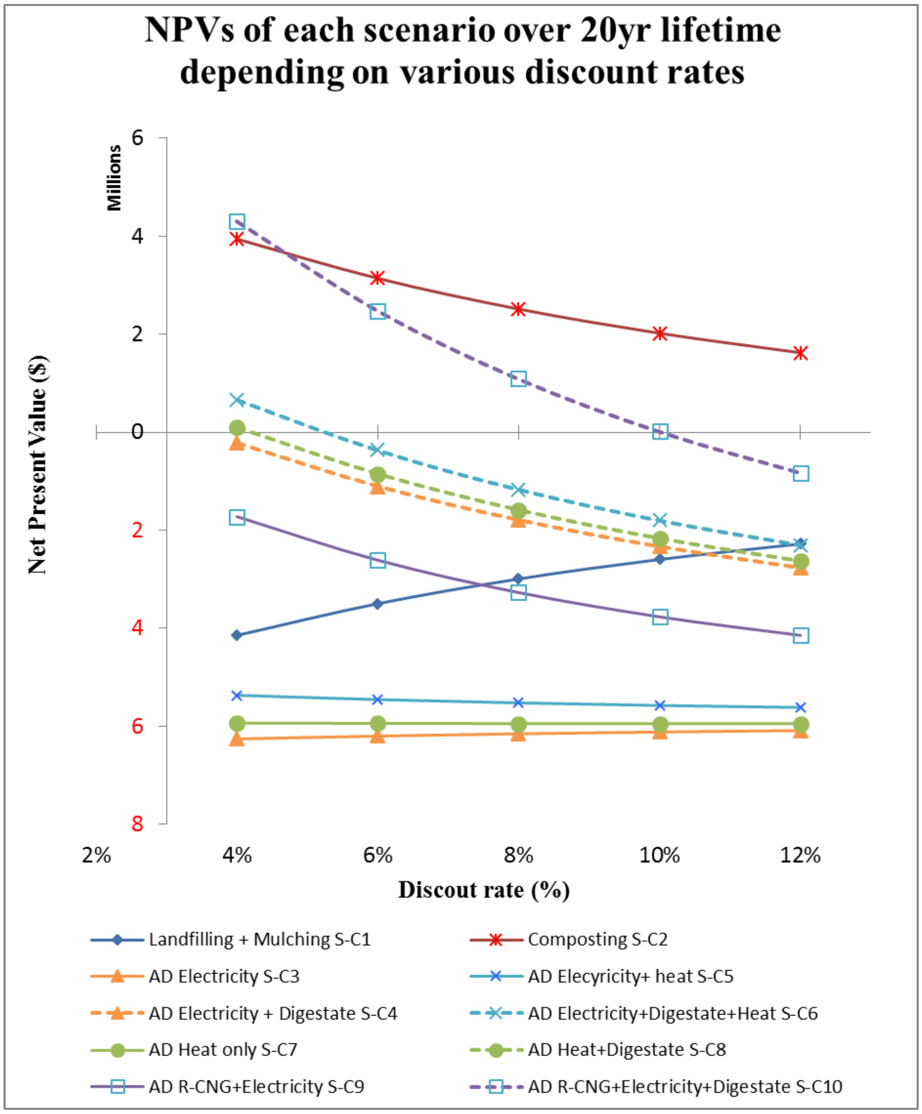


Figure 22. NPVs depending on various discount rates.

NPVs including RECs and RINs with various discount rates over 20-year lifetime. Both CNG options (scenario C9 and C10) show significant positive shifts due to the large RIN ($1.35/DGE) for CNG, while REC ($0.003/kWh) does not greatly influence the electricity options (Figure 23).

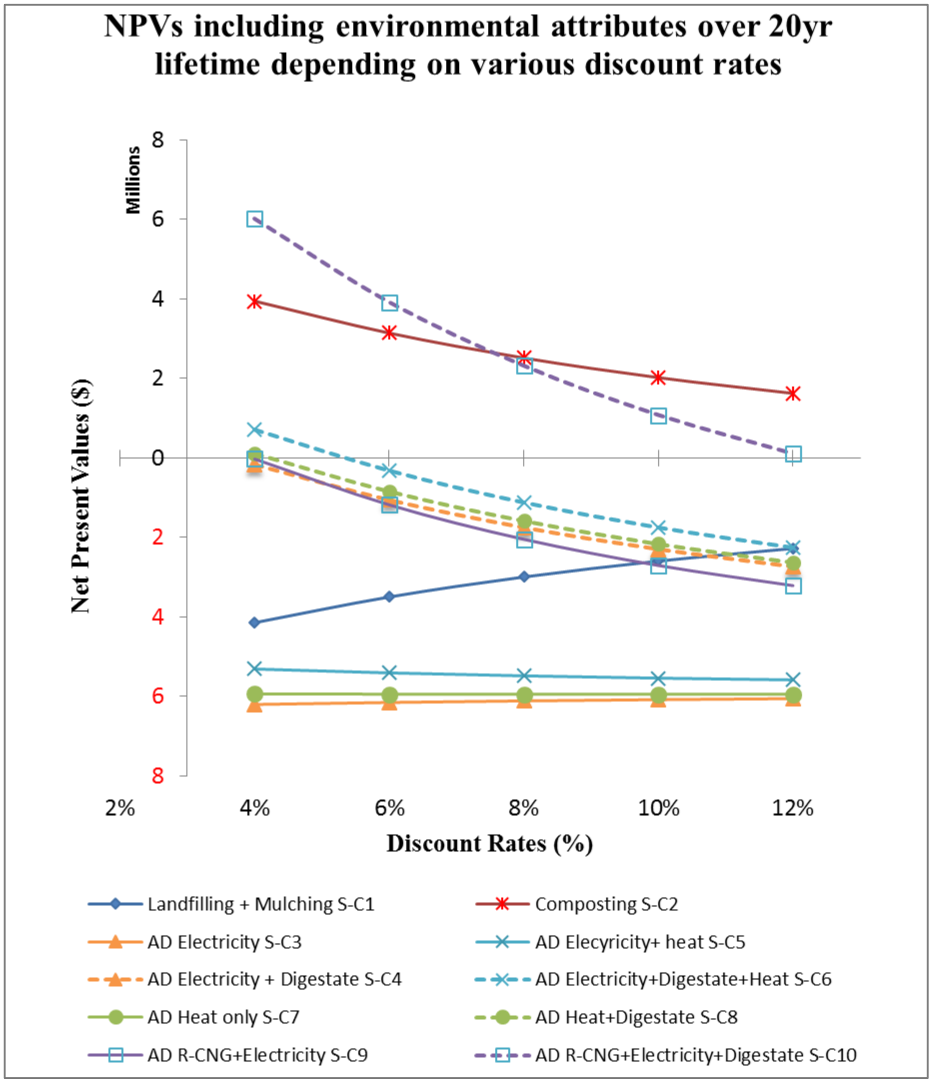


Figure 23. NPVs including environmental attributes (RIN and REC) depending on various discount rates.

Sensitivity analysis depending on different energy prices. Since the revenue from the power generated may vary depending on regions or rate schedules (e.g., power purchase agreements, feed-in tariffs, or net metering), and it creates more savings if a facility could consume all the power generated rather than selling the power to grid (Table 17), it is worthwhile to employ varied electricity costs in the analysis. Figure 24 shows the NPVs with current and increased electricity prices. The adjusted prices of natural gas were also applied proportionally to the adjusted electricity rates. The scenario C2 (composting) and the scenario C6 (AD with CHP and digestate) were compared in this sensitivity analysis. The NPVs of the composting option decrease by increasing the electricity price due to the electricity consumption of the facility, while the NPVs of scenario C6 increase due to the higher avoided costs of purchased energy and revenues from the renewable energies. Scenario C6 with energy prices of $0.2/kWh and $26.3/MMBtu becomes to be comparable to the composting option (scenario C2, Figure 24).

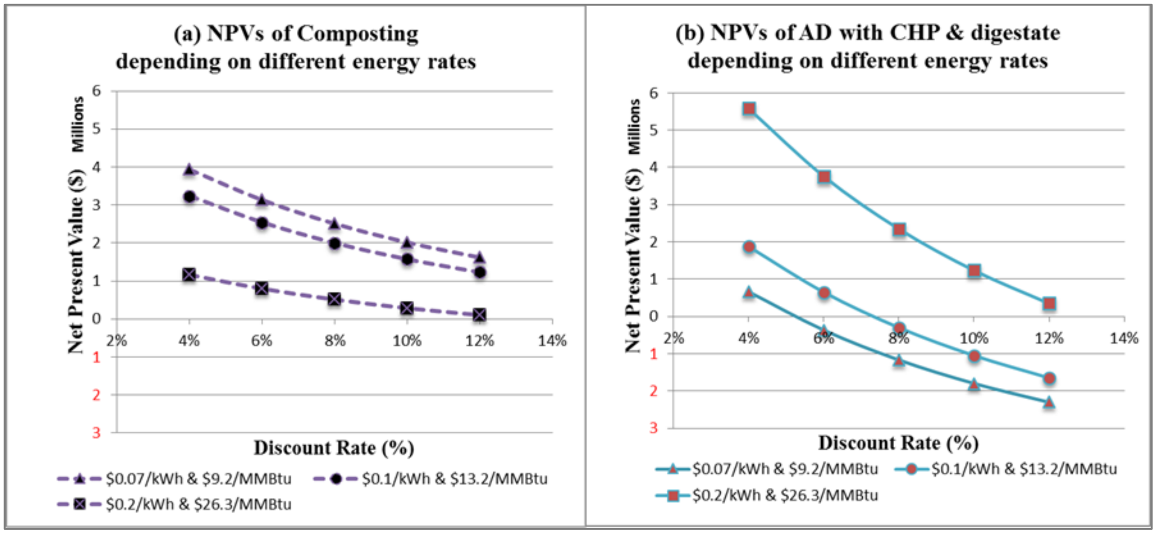


Figure 24. NPVs of scenario C2 (a) and C6 (b) with the different energy prices ($0.066/ kWh & $9.2/MMBtu; $0.1/kwh & $13.2/MMBtu; $0.2/kwh & $26.3/MMBtu). Triangle markers are current energy rate.

Sensitivity analysis depending on different compost prices. Figure 22 showed the importance of selling compost or digestate in being able to realize a profit. Therefore, the compost price could have an effect on the NPVs of each scenario. The two scenarios with relatively higher NPV, C2 and C10, were picked to examine the sensitivity of NPV to compost price. According to Figure 25, both scenarios are affected by increased or decreased compost prices, but the scenario C10 (composting option) exhibits the greater magnitude of NPV changes.

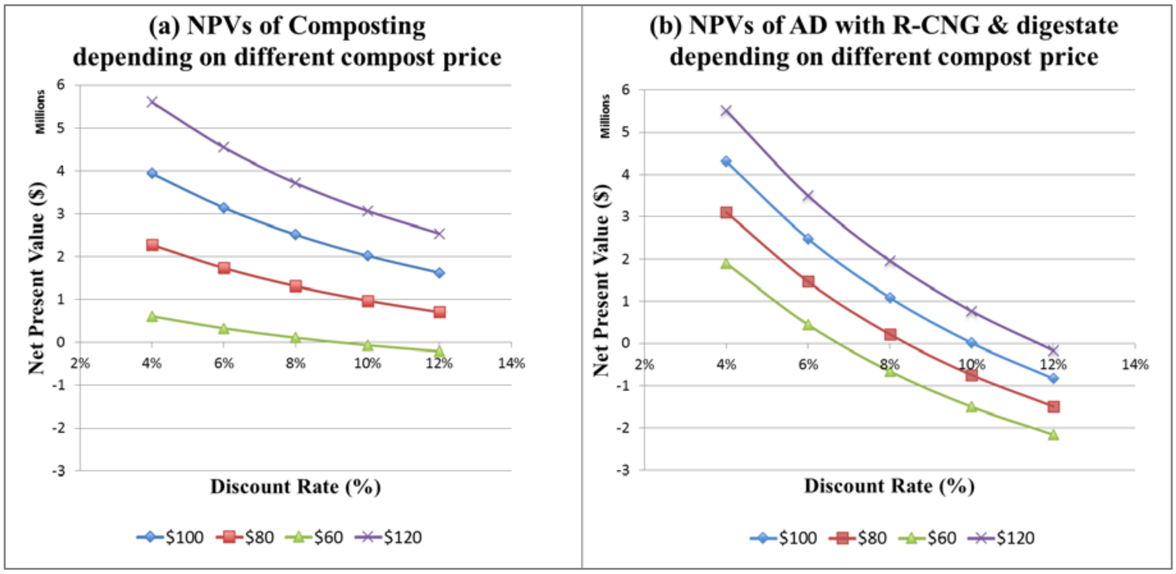


Figure 25. NPVs of the scenario C2 (a) and C10 (b) depending on different compost prices. Blue diamond markers are current compost price.

Sensitivity analysis depending on different energy inflation rates. In this study, energy prices were adjusted by the inflation rates suggested by USEIA and the US Department of Energy (USEIA, 2014a; USEIA, 2014c; USDOE, 2014). Since energy prices are an important factor in allowing AD scenarios to gain profits, the inflation rates of energy prices may affect the growth rates of AD scenarios. Due to the uncertainty of fixing the discount rate, internal return rates (IRR) were computed using the Microsoft Excel function to analyze the inflation rate effect on the AD systems. IRR is the discount rate at a NPV of zero (Denley & Herndon, 2008), and can be considered as the growth rate of a project. Thus, a higher IRR for a project means a more desirable project. Figure 26 shows that inflation rates do not affect much if the project has a positive IRR. Note that some invalid IRR results were obtained with very negative cash flows in the Microsoft Excel function.

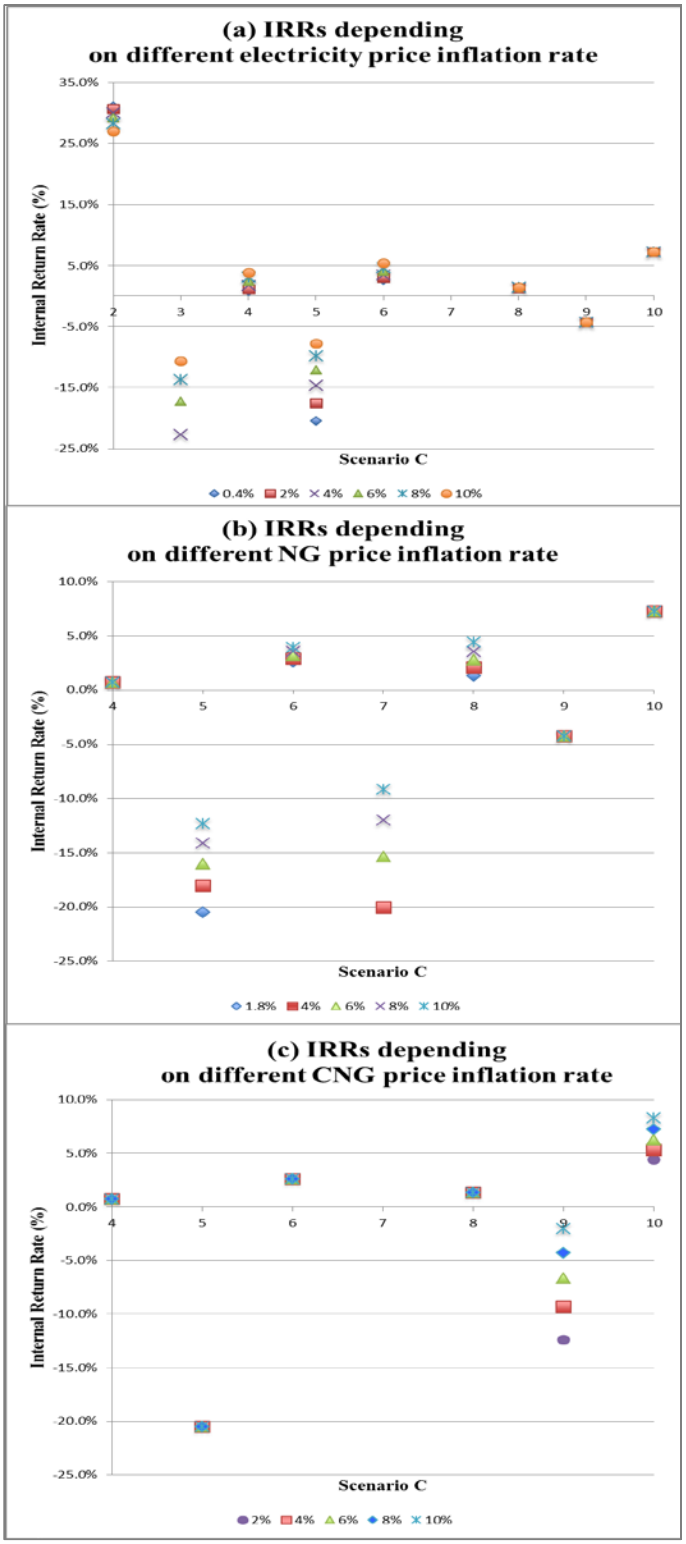


Figure 26. IRRs of AD scenarios depending on different energy inflation rates, including: (a) electricity inflation rate, (b) natural gas inflation rate, and (c) compressed natural gas energy rate. Blue diamond markers are current inflation rate.

Sensitivity analysis depending on different lifetime. Another sensitivity analysis was conducted for different lifetimes. As seen in Figure 27, the longer lifetime increases the IRRs, and is critical in scenario C9. In scenario C9, the shorter lifetime, 15 years, has a negative growth rate, but it becomes to positive with 20 and 25 year lifetimes. The change in IRRs between a 15-year lifetime and a 20-year lifetime is greater than the IRR changes between a 20-year lifetime and a 25-year lifetime, which could mean returns on the up-front investment that occur earlier in a project's life are larger than returns that occur later.

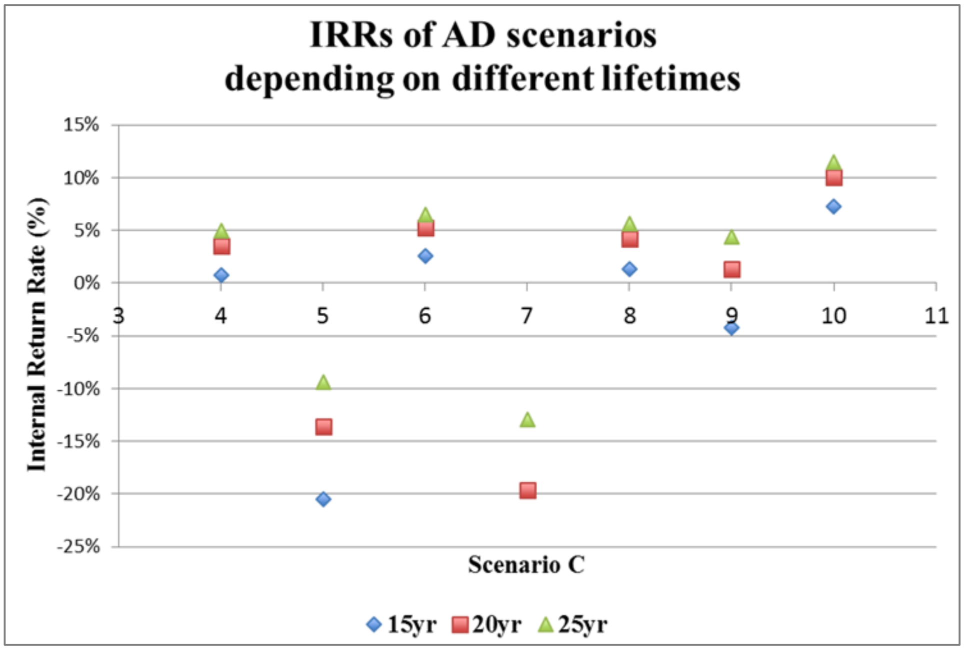


Figure 27. IRRs of AD scenarios over different lifetimes.

Sensitivity analysis depending on different system capacity. Figure 28 describes the capacity influence on AD systems. The X-axis is IRR per TPY on a 20,000 TPY system, and the Y axis is IRR per TPY on a 10,000 TPY system. The diagonal line across the chart has a slope of one. Therefore, the values on the upper side of the diagonal line mean a higher IRR per TPY on the 10,000 TPY system, and vice versa. None of the scenarios show higher IRR per TPY on the 20,000 TPY option.

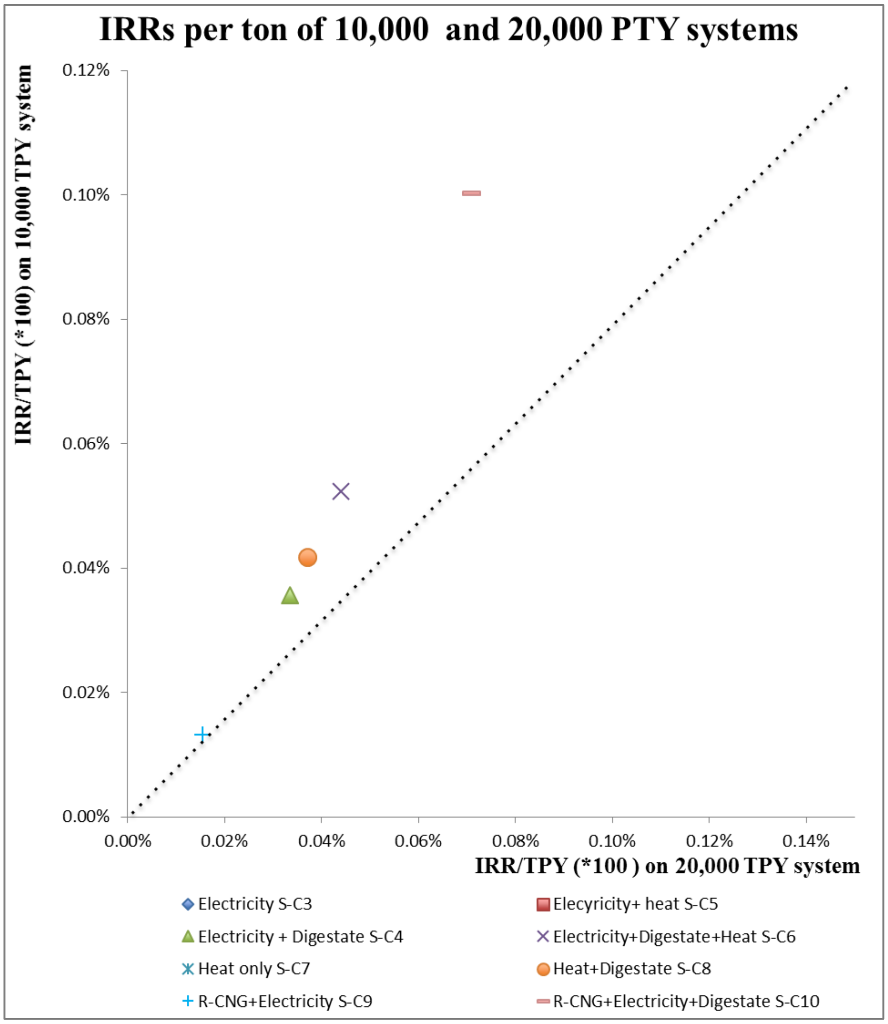


Figure 28. IRRs of AD scenarios over different system capacity.

Case Study: Possible Energy Savings and GHG Reduction in ASU by AD System

Appalachian State University has made many attempts to reduce energy consumption and GHG emissions. Even though the composting option exhibits the greater NPV, it does not provide energy. Also, AD options are superior to composting on GHG reduction. Table 19 describes the estimated savings on electricity and natural gas use on campus with two different AD options: AD with CHP and AD with boiler. As seen in Table 19, AD with CHP is superior on both savings and GHG reductions. Note that carbon storage factors are included.

Table 19

Estimated Energy Savings and GHG Reduction by AD with CHP Scenario at ASU

	ASU Energy Consumption (2011-2012)	***ZWE 10,000 TPY***		***Savings***		***GHG reductions (MT CO2 equiv.)***
Electricity Energy	63,319,393 kWh	***AD with CHP (220kW electric capacity & 312kW Themal capacity)***	*1,725,790* kWh	3%	$211,686	2,468
Natural Gas Energy	315,636 MMBtu		6,120 MMBtu	2%		
		AD with Boiler (85% efficiency)	14,326 MMBtu	5%	$131,944	1,867

CHAPTER 5: CONCLUSIONS AND DISCUSSION

This study focused on environmental and economic analyses for decision making regarding choice of food waste diversion systems in Boone, NC. The alternative systems, composting and anaerobic digestion, were compared to the current system, landfilling and mulching.

Commercial Food Waste Generation Estimation in Boone, NC

About 4,990 tons per year of food waste generation was estimated for Boone, NC, using commercial food waste generation formulas (Draper & Lennon, 2002; Mercer, 2013). The generation sectors included in this study were universities, hospitals, restaurants, supermarkets, public schools, and companies with a cafeteria.

Life Cycle Assessment of Greenhouse Gas Emissions

Environmental impact was analyzed by performing life cycle assessment of greenhouse gas emissions, which imply global warming impact. Anaerobic digestion options present lower GHG emissions than the composting option because anaerobic digestion produces biogas that could be used for renewable energy production (Figure 15). Renewable energy generation offsets the emissions from fossil fuel use, which makes anaerobic digestion more environmentally beneficial than the composting system. Anaerobic digestion with the combined heat and power system shows the least GHG emissions since it generates electricity as well as heat energy using waste heat (Figure 15). The sensitivity analyses of utility usage at the composting facility, waste truck travelling distance, biogas yield, and generator efficiency indicate that electricity production from biogas is a dominant factor in the reduction of GHG emissions. A solar-powered composting facility or R-CNG fueled waste trucks could be additional ways to avoid fossil fuel use, further reducing GHG emissions.

Cost Benefit Analysis

Cost-benefit analysis with net present values and internal return rates was conducted for economic analysis. Due to the lower capital cost and higher organic compost price, the composting option presents the greater net present value (Figure 22). In other words, energy generation from the AD system does not overcome the higher capital cost of the AD system. Since energy prices are relatively cheap in the US, the revenue availability from digestate is a critical factor for anaerobic digestion systems (Figure 22 & Figure 26); however, producing renewable compressed natural gas presents the higher net present value among other AD options due to the higher inflation rate of CNG fuel (Table 17). Anaerobic digestion with an R-CNG system can have comparable net present value with the composting system if it gains income from digestate and RINs (Figure 23).

Since the best options analyzed by LCA and CBA differ, AD with CHP and composting respectively, the final decision on the best food waste conversion system would depend on who invest**s** money in the project. For Example, AD options would be better in the Boone area if an investor such as ASU, who cares about GHG reduction, education, and community outreach, was the primary supporter.

Limitations of the Study

One of the major parts of this study was data collection. Most results, especially CBA results, rely greatly on careful data collection. In this study, I tried to use specific numbers from practical data, but some data, such as food waste collection routes, waste trucks' efficiency, landfill energy usage, and other information, was estimated based on best assumptions. This study excluded the costs and benefits of waste collection due to a lack of quantifiable information. Including this and other data could influence the CBA results of composting and AD options.

The previous pilot study on food waste generation in the Boone area conducted by Renée Blacken, a former graduate student of ASU, indicated that about 1,893 pounds of food waste was collected from a restaurant with 17 employees over six weeks. Using Draper and Lennon's formula (2002), about 5,885 pounds of food waste was estimated in the current study, which is more than three times the amount empirically measured in Blacken's pilot study.

The amount of waste generation may vary depending on the season. There may be less yard waste available in winter, for example. This study did not consider seasonal impact on waste generation. All the results of the LCA and CBA are based on annual data, in values such as tons per year and kilometer per year.

Suggestions for Further Research

Several ideas for future research are suggested by the findings from the current study. Needed areas of further inquiry include:

1. Conducting a sample study on food waste generation by sector in order to check the accuracy of the food waste generation formulas.
2. Developing capital and operation costs curves for composting facilities in the US using previous studies and surveys.
3. Identifying best methods for food waste collection in Boone, North Carolina.
4. Quantifying seasonal differences in the amount of food and yard waste generated in Boone, NC.
5. Calculating the mass balance of composting with different types and ratios of feedstock.
6. Calculating the mass balance of AD with different types and ratios of feedstock.
7. Conducting additional LCA and CBA of other types of composting systems, such as windrow and in-vessel composting.
8. Further investigation of benefits associated with GHG reduction, such as carbon credits.

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Appendices

APPENDIX A

Mass balance of inputs and outputs of food and yard waste home composting
From Imperial College, London (Mitaftsi & Smith, 2006).

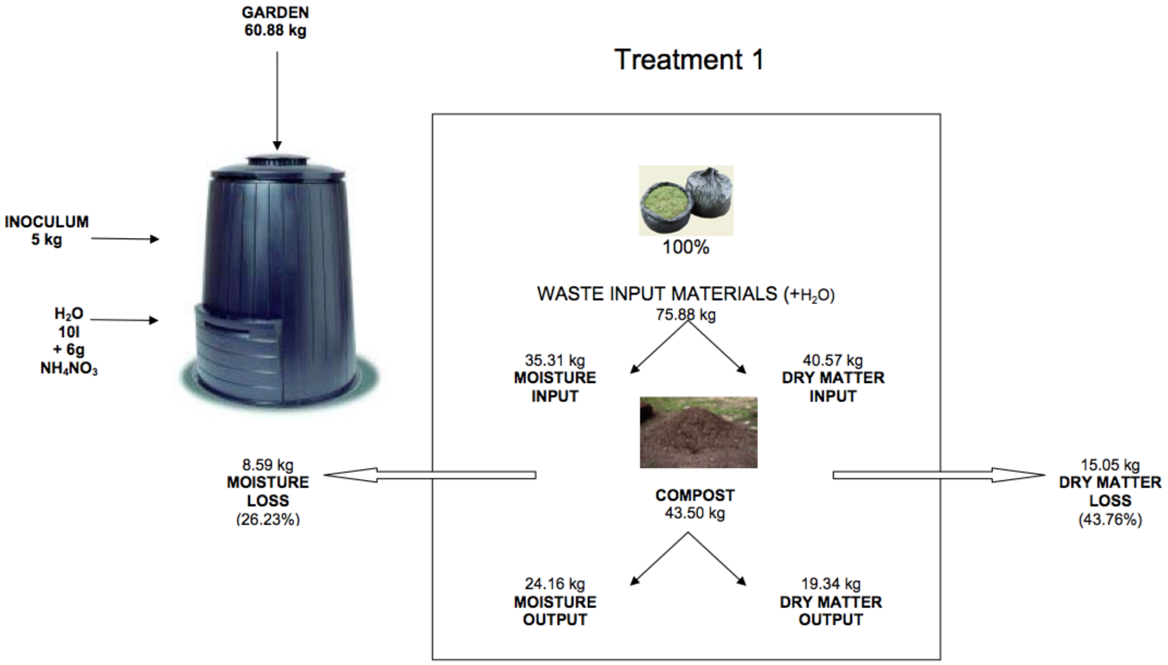


Figure 4.1 Total mass balance of waste processed in Treatment 1 between February and July 2005

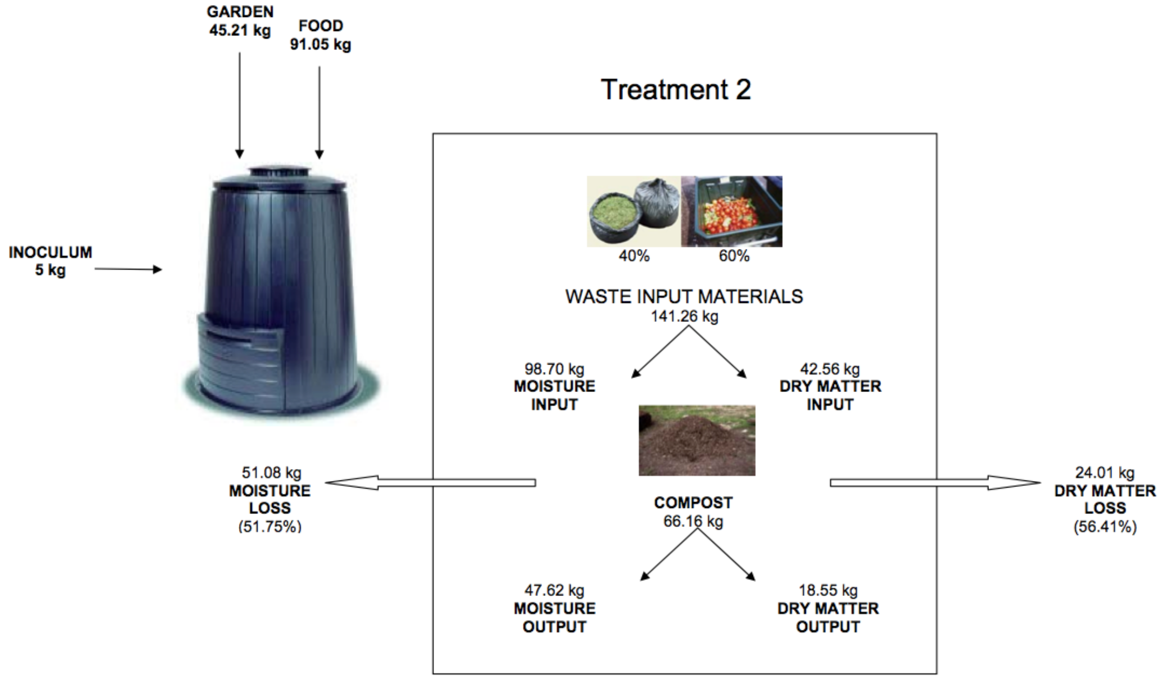


Figure 4.2 Total mass balance of waste processed in Treatment 2 between February and July 2005

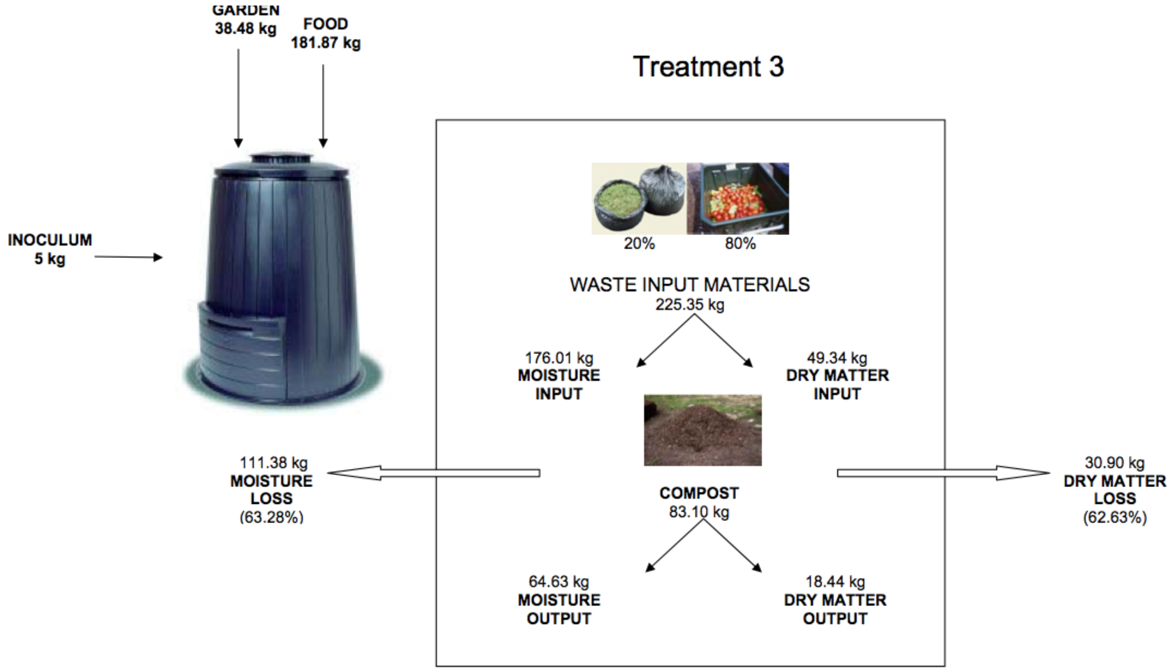


Figure 4.3 Total mass balance of waste processed in Treatment 3 between February and July 2005

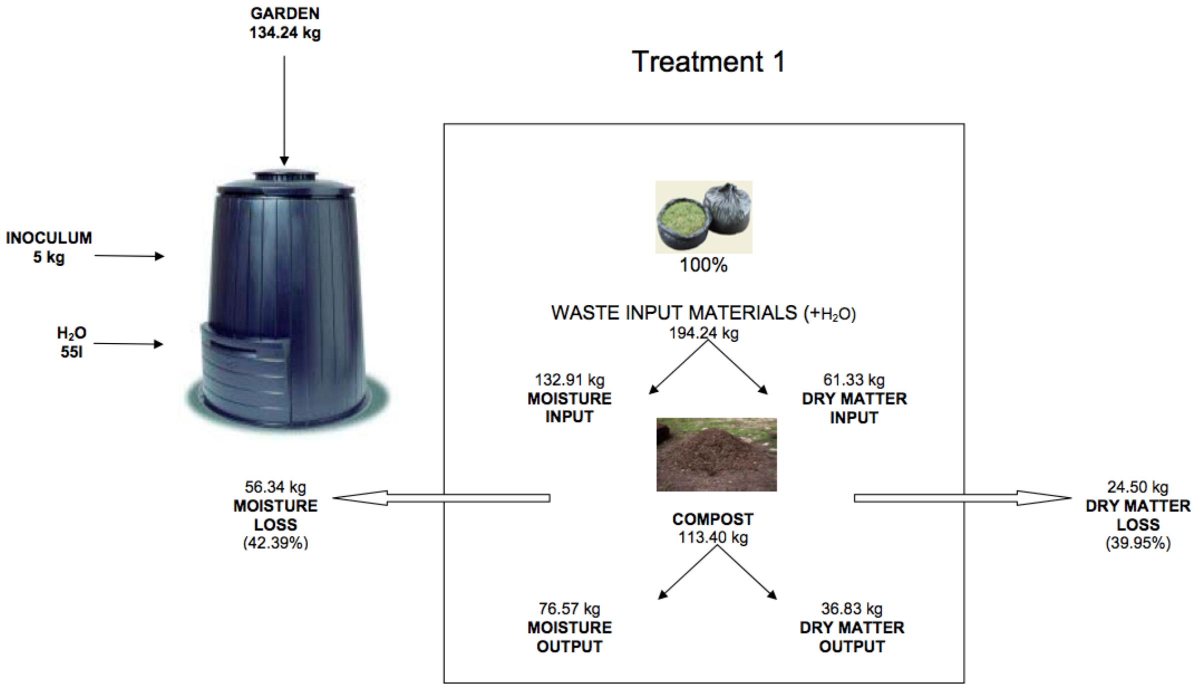


Figure 4.8 Total mass balance of waste processed in Treatment 1 between February 2005 and March 2006

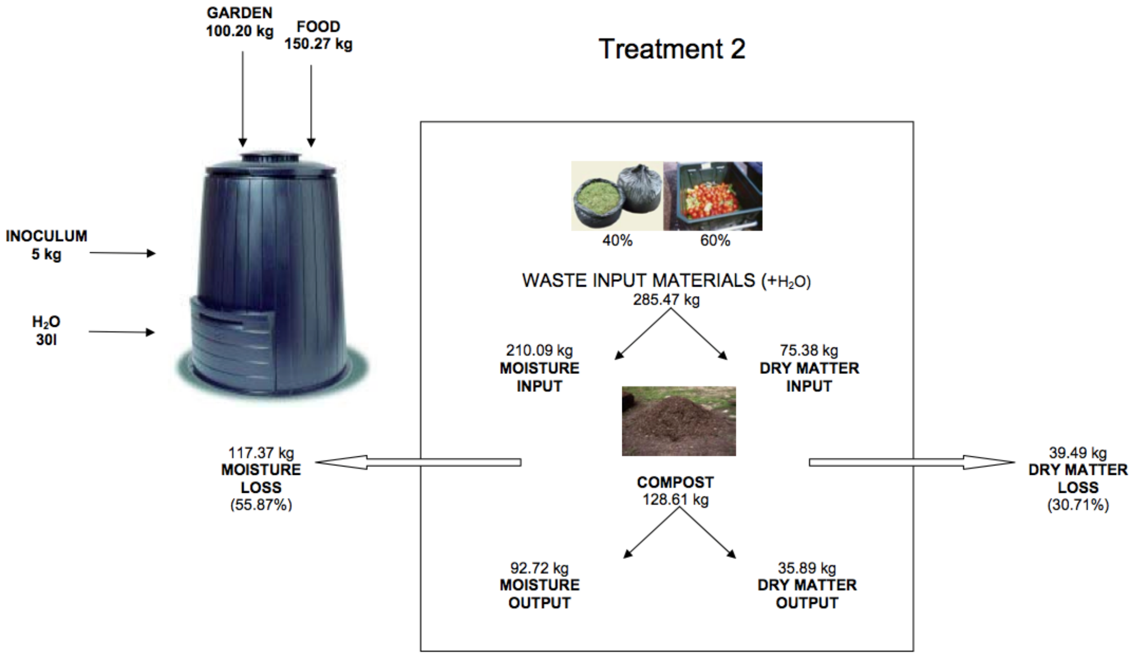


Figure 4.9 Total mass balance of waste processed in Treatment 2 between February 2005 and March 2006

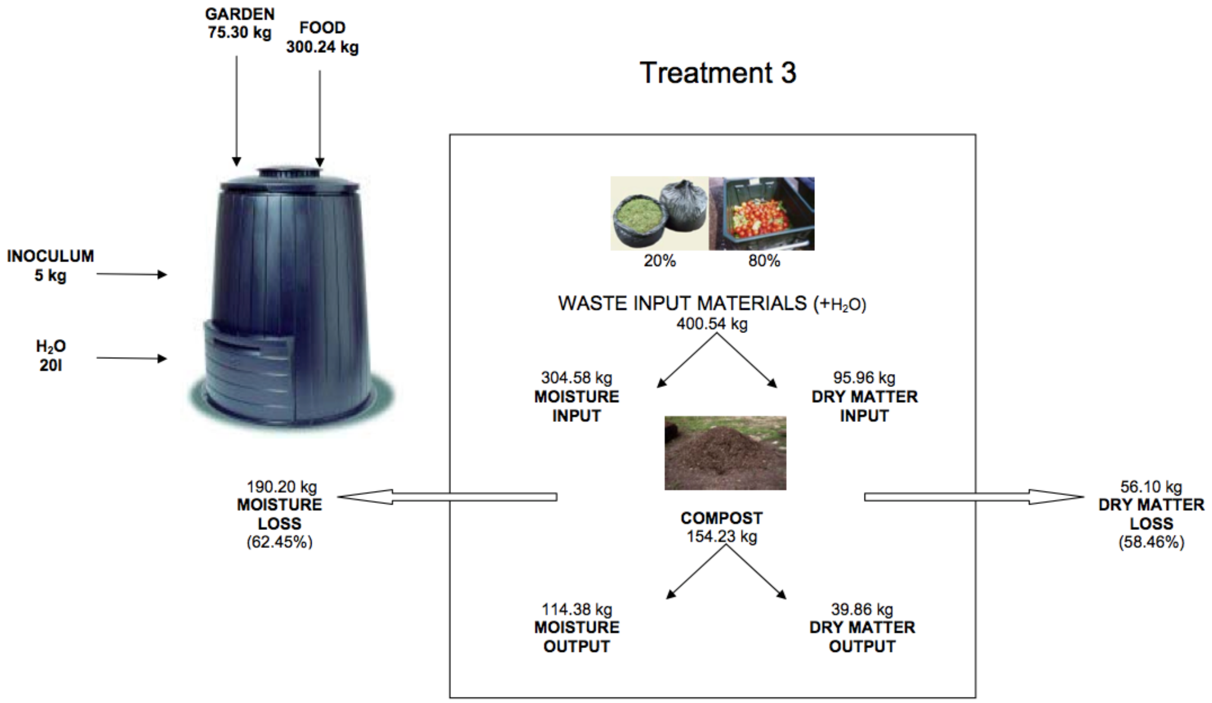


Figure 4.10 Total mass balance of waste processed in Treatment 3 between February 2005 and March 2006

Benefits from Composting

user input

Data from http://www3.imperial.ac.uk/ewre/research/currentresearch/environmentalcontrolandwastemanagement/homecompostingphase2

	Inputs							outputs										
	garden waste (kg)	food waste (kg)	water (kg)	inoculum (kg)	**total input (kg)**	wet input (kg)	dry Input (kg)	**total output (kg)**	wet output (kg)	dry output (kg)	food waste %	moist/total input	Dry/total input	moist/total output	dry/total output	moist remained	dry remained	compost produced
1.1	60.88	0	10	5	75.88	35.31	40.57	43.5	24.16	19.34	0%	0.47	53%	0.56	0.44	68%	48%	57%
1.2	45.21	91.05	0	5	141.26	98.7	42.56	66.17	47.62	18.55	67%	0.70	30%	0.72	0.28	48%	44%	47%
1.3	38.48	181.87	0	5	225.35	176.01	49.34	83.07	64.63	18.44	83%	0.78	22%	0.78	0.22	37%	37%	37%
2.1	134.24	0	55	5	194.24	132.91	61.33	113.4	76.57	36.83	0%	0.68	32%	0.68	0.32	58%	60%	58%
2.2	100.2	150.27	30	5	285.47	210.09	75.38	128.61	92.72	35.89	60%	0.74	26%	0.72	0.28	44%	48%	45%
2.3	75.3	300.24	20	5	400.54	304.58	95.96	154.24	114.38	39.86	80%	0.76	24%	0.74	0.26	38%	42%	39%

	Inputs				Outputs		
	annual waste generation	round-up	moist % (1)	dry % (2)	remaining rate		output (tons)
food waste	4989.663 tons/yr	5000	70%	30%	dry	0.58275	2331
yard waste	4989.663 tons/yr	5000	50%	50%	wet	0.64188	3851
total organic waste input (tons/yr)		10000	60%	40%		sum	6182
					total	0.61337	6134
					estimated compost		6134

APPENDIX B

Avoided cost calculation based on rate schedules in the PPA between Watauga County and Duke Energy (2011).

PPA 2011 Option B distribution, Variable

			days	total hours
on peak	summer: Mon-Fri, 1pm-9pm	June-Sep	87.14286	697
	non-summer:Mon-Fri:6am-1pm	Oct-May	173.5714	1215
off peak	other week day hours & all weekend			6848
				8760

		$/kwh	hours	($/kwh)*hours	sum	Avoided Cost	
capacity	a. on peak summer	0.0908	697	63.30	0.009168	0.064	$/kwh
	b. on peak non-summer	0.014	1215	17.01			
Energy	a. on peak	0.0659	1912	126.01	0.055034		
	b. off peak	0.052	6848	356.09			

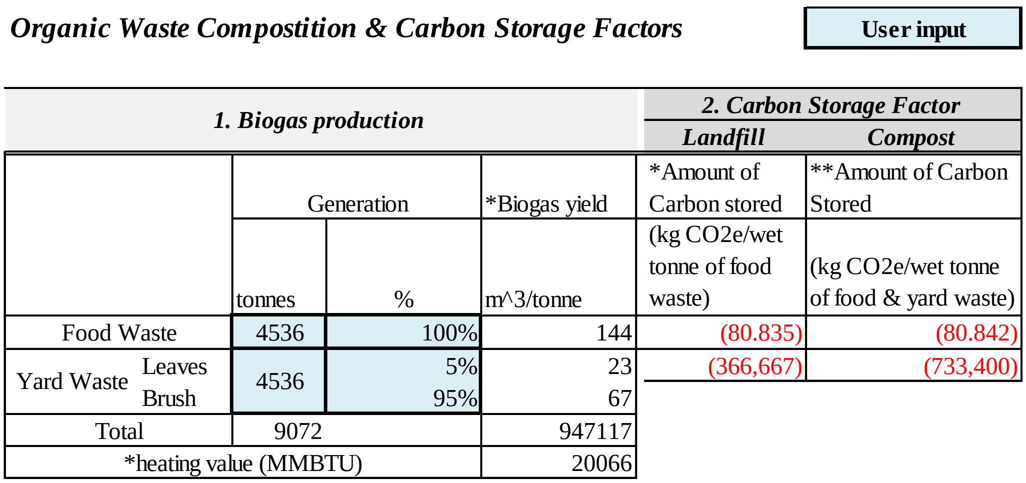
PPA 2011 Option B distribution, Fixed 15

			days	total hours
on peak	summer: Mon-Fri, 1pm-9pm	June-Sep	87.14286	697
	non-summer:Mon-Fri:6am-1pm	Oct-May	173.5714	1215
off peak	other week day hours & all weekend			6848
				8760

		$/kwh	hours	($/kwh)*hours	sum	Avoided Cost	
capacity	a. on peak summer	0.1134	697	79.06	0.011452	0.066	$/kwh
	b. on peak non-summer	0.0175	1215	21.26			
Energy	a. on peak	0.0679	1912	129.83	0.054454		
	b. off peak	0.0507	6848	347.19			

APPENDIX C

Calculations of life cycle GHG emissions of organic waste (using the Microsoft Excel).



Organic Waste Compostition & Carbon Storage Factors **User input**

1. Biogas production					**2. Carbon Storage Factor**	
					Landfill	***Compost***
		Generation		*Biogas yield	*Amount of Carbon stored (kg CO2e/wet tonne of food waste)	**Amount of Carbon Stored (kg CO2e/wet tonne of food & yard waste)
		tonnes	%	m^3/tonne		
Food Waste		4536	100%	144	(80.835)	(80.842)
Yard Waste	Leaves	4536	5%	23	(366,667)	(733,400)
	Brush		95%	67		
Total		9072		947117		
*heating value (MMBTU)				20066		

* heating value of biogas : Methane 60% , Meathane heating value = 1000btu/cf, 1m^3=35.31ft^3

* Biogas yield: Environment Canada, 2013

* Amount of Carbon stored in landfills: USEPA, 2006

** Amount of carbon stored by compost:USEPA, 2006

Note that the carbon storage factor for compost is simulated data with 20% of food waste and 80% of yard waste.

Diesel Fuel Emissions **User input**

Total Diesel Emissions	*Vehicle Efficiency	*Travel dist.	Emission (kg/liter of diesel)		
(Extraction + Transportation)	km/liter	km/yr	CO2	CH4	N2O
Collection Truck	1.25	1695.2	2.6221080	2.82426735	0.00004010
Transport Truck	2.5	4686.4	2.6176471	2.82407176	0.00000754
Construction Equipment			2.6972000	2.82415322	0.00006868

		emission (kg/liter)		
		CO2	CH4	N2O
Diesel Extraction		0	2.824	0
Transportation	*Collection Truck	2.6221080	0.00026735	0.00004010
	*Transport Truck	2.617647	0.00007176	0.00000754
	*Construction Equipment	2.697200	0.00015322	0.00006868

* Total Diesel Emissions=*Diesel Extraction + *Transportation
* Vehicle efficiency from IWMM, U of Waterloo
*Travel Distance: 32.6km*52weeks
*Diesel Extraction: emission factors from NREL
*Collection Truck: emission factors from NREL (Transport, refuse truck, diesel powered, Southeast)
*Transport Truck: emission factors fromNREL (Transport, single unit truck, short-haul, diesel powered, Southeast)
*Construction Equipment: emissiosn factors from USEPA, 2011

Energy Emissions

Electricity Generation	Electricity emission factor (base load)				Electricity emission factor (non-base load), renewable energy			
	SRVC (VA, NC, SC)	emissions(kg/kWh)			SRVC (VA, NC, SC)	emissions(kg/kWh)		
		CO2	CH4	N2O		CO2	CH4	N2O
		0.5084	0.000010118	0.000008673		0.75505	0.00001728	0.00001114

Biogas	*Biogas Combustion	emission (kg/MMBTU)		
		CO2	CH4	N2O
		52.07	0.0032	0.00063

Natural gas	*Natural Gas total emissions	emission (kg/MMBTU)		
		CO2	CH4	N2O
		53.5013856	0.346748128	0.0001
	*Natural Gas Extraction site	emission (kg/MMBTU)		
		CO2	CH4	N2O
		0	0.249471008	0
	*Natural Gas Extractioned	emission (kg/MMBTU)		
		CO2	CH4	N2O
		0.4813856	0.09627712	0
	*Natural Gas Combustion	emission (kg/MMBTU)		
		CO2	CH4	N2O
		53.02	0.001	0.0001

*Electricity generation: emission factors from USEPA, 2011
*Biogas combustion emission factor from USEPA, 2011
*Natural gas total emissions=
emissions from (extraction site+extractioned+combustion)
*Natural Gas Extraction site: emission factors from NREL
*Natural Gas Extractioned: emission factors from NREL
*Natural Gas Combustion: emission factors from USEPA, 2011

Facility Energy Use

User input

	Electricity kwh/tonne	Diesel liter/tonne
*Compost Facility	82.85	5.3
*Transfer Station	2.5	0.124
*Landfill	0.29	0.22

*Compost Facility: utility and fuel consumption at ASU composting facility
*Transfer state: from IWMM, U of Waterloo
*Ladfill: from IWMM, U of Waterloo

Renewable Energy generation at AD facility

User input

Biogas Composition (Methane 60% + CO2 40%)

	*Biogas heating value	*Efficiency	*facility E consumption (mmbtu)	*additional energy use (kwh)	*Initial energy output	*Net energy output		Type of renwable energy generated
Electricity only	20066	32%			1,869,384	1725790	kwh/yr	electricity
CHP	20066	62%			1,869,384	1725790	kwh/yr	electricity
					8850	6120	MMBTU/yr	heat
*Heat only	20066	85%	2729.6	143594	17056	14326	MMBTU/yr	heat
Renewable CNG	20066	28%	1345		110,374	10,376	kwh/yr	electricity
						11968	MMBTU/yr	*CNG

*Biogas heating value : Methane 60% , Meathane heating value = 1000btu/cf, 1m^3=35.31ft^3
*Efficiency: the efficiecies of generator, CHP, and micro-generator for CNG were calculated based on the data from Zero Waste Energy (2013).
*Heat only: 85% of boiler efficiency is assumed.
*facility E consumption: parasitic loads for AD facility, the data are calculated based on Zero Waste Energy (2013).
*Initail Energy output & Net energy output: based on Zero Waste Energy (2013), R-CNG data was calculated based on 20,000TPY option.
Initial energy output for heat only option was calculated based on biogas generation and 85% boiler efficiency.
Net energy output for heat only option was calculated by subtracting the thermal parasitic load.
* It was assumed that the required process heat is provided from the waste heat of the generator for electricity only, CHP, and R-CNG options.

*CNG energy values:	129500	BTU/DGE	
	92,414	DGE	(R-CNG production, based on Zero Waste Energy, 2013)

Scenario 1. Landfilling + Mulching

Generation	*Collection*		*Transfer station*		*Transport*		*Landfill*			
	***Input**		**Input**		**Input**		**Input**			
food waste	*diesel	1356	**diesel (liter)	562	*diesel (liter)	1875	diesel (liter)	5.3		
			*electricity (kwh)	11340			electricity (kwh)	0.29		
			Mulching							
yard waste	diesel (liter)	1356	diesel (liter)	562						
			***Carbon Storage (kg CO2e)**				***Carbon Storage (kg CO2e)**			
				(366700)				(366667)		
	***Output (kg)**		***Output (kg)**		***Output (kg)**		***Output (kg)**		***landfill gas (kgCO2e)**	
	CO_2	3556	CO_2	8799	CO_2	4907	CO_2	14		
	CH_4	3830	CH_4	3177	CH_4	5294	CH_4	15	CH_4	7333333
	N_2O	0.0544	N_2O	0.1756	N_2O	0.0141	N_2O	0.00		

	*Total Emissions	GWP
CO_2	6617243	1
CH_4	12316	21
N_2O	0.244	310
***MT CO2 equi.**	6876	

Landfill gas production	
* CH4 emission factor (kg CO2e/wet tonne of food waste)	
	1617
*Total (kg CO2e)	7333333

*Input: energy and fuel inputs for process

*diesel (liter) = annual tralvel distance(km)/ vehicle efficiency (km/liter)

**diesel (liter)= facility diesel use (liter/tonne)* waste generation(tonne)

*electricity (kwh) = facility electricity use (kwh/tonne) * waste generation (tonne)

carbon storage = the amount of organic waste carbon storage factors

*output (kg) = diesel (liter)*emission factor(kg/liter) +electricity(kwh)*emission factor(kg/kwh)

*landfill gas (kg) : calculated based on the landfill gas compostion, Note that it is already characterized from methane to CO_2 equivalent.

* CO_2 total: biogenic CO_2 from landfill is not counted (IPCC).

*Total Emissions:

emissiosns (collection+transfer station+transport to landfill+landfill operation+landfill gas) - carbon storages

*MT CO_2 equi. = (CO_2(kg)*1+CH_4(kg)*21+N_2O(kg)*310)/1000

* CH_4 emissions in Landfills: USEPA, 2006

*Total Ladfill gas emissions: the amount of food waste diposted to landfill * emission factors, Note that it is kg CO_2 equivalent.

Scenario2. Composting : *Theoretical degration to completely CO2*

Generation	*Collection*		*Composting Facility*					
	***Input**		**Input**					
food waste	*diesel (liter)	1356	**diesel (liter)	48082				
yard waste	diesel (liter)	1356	electricity (kwh)	751615				
	***Output (kg)**		***Output (kg)**		**Carbon storage**		*Total Emissions	GWP
	CO2	7112	CO2	511,783	(733400)	*CO2	(214505)	1
	CH4	7660	CH4	135,797		CH4	143458	21
	N2O	0.1088	N2O	10		N2O	10	310

***MT CO2 equiv.**	2801

*Input: energy and fuel inputs for process
*diesel (liter) = annual tralvel distance(km)/ vehicle efficiency (km/liter)
**diesel (liter)= facility diesel use (liter/tonne)* waste generation(tonne)
*electricity (kwh) = facility electricity use (kwh/tonne) * waste generation (tonne)
carbon storage = the amount of organic waste carbon storage factors
*output (kg) = diesel (liter)*emission factor(kg/liter) +electricity(kwh)*emission factor(kg/kwh)
*CO2 total: biogeneic CO2 generation from composting is not counted.
*Total Emissions:
emissiosns (collection+ composting facility) - carbon storages
*MT CO2 equi. = (CO2(kg)*1+CH4(kg)*21+N2O(kg)*310)/1000

Scenario3. AD + Electricity only

Alternative	*Conventioanl*	*Savings*
Biogas electricity generation	electricity from grid	electricity from grid, NG extraction

Generation	*Collection*		*AD facility*								
	***Input**		***Input**		**Value added products**		**Net Revenue**				
food waste	*diesel (liter)	1356	**diesel (liter)	48082	Heating value of biogas (mmbtu)	20066	electricity (kwh)	1,725,790			
yard waste	*diesel (liter)	1356			*electricity from Biogas (kwh)	1,869,384					
	***Output (kg)**		****Output (kg)**		***Carbon Storage (kg CO2e)**		*Avoidance		*Total emissions		GWP
	CO2	7112	CO2	1,174,502	(733400)		CO2	(1418416)	*CO2	(2015018)	1
							*Biogenic CO2	(1044817)			
	CH4	7660	CH4	135,854			CH4	(6970)	CH4	136544	21
	N2O	0.1088	N2O	16			N2O	(21)	N2O	(5)	310
									MT CO2 equiv.	851	

*Input: energy and fuel inputs for process
*diesel (liter) = annual tralvel distance(km)/ vehicle efficiency (km/liter)
**diesel (liter)= facility diesel use (liter/tonne)* waste generation(tonne)
*electricity from biogas (kwh): initial electricity generation before parasitic load (kwh)
carbon storage = the amount of organic waste carbon storage factors
*output (kg) = diesel (liter)*emission factor(kg/liter)
**output (kg) = diesel (liter)*emission factor(kg/liter) +Biogas combustion for electricity generation
*Avoidance (saving): environmental benefits by avoiding natural gas extraction and electricity generation from fossil fuel
*Biogenic CO2: CO2 generated by Biogas combustion.
*CO2 total : biogenic CO2 from AD is not counted.
*Total Emissions:
emissiosns(collection+diesel consumption at AD facility+Biogas combustion) -avoided emissions of natural gas extraction & electricity generation-Biogenic CO2- carbon storage
*MT CO2 equi. = (CO2(kg)*1+CH4(kg)*21+N2O(kg)*310)/1000
Note: It is assumed that parasitic thermal energy is provided by waste heat, so it's not counted.

Scenario4. AD + CHP

Alternative	*Ordinary*	*Savings*
biogas heating & electricity generation	electricity from grid & natural gas heating	electricity from grid, NG extraction & combustion

Generation	*Collection*		*AD*								
	***Input**		***Input**		Value added products		Net Revenue				
food waste	*diesel (liter)	1356	**diesel (liter)	48082	Heating value of biogas (mmbtu)	20066	electricity (kwh)	1725790			
yard waste	diesel (liter)	1356			*electricity from Biogas (kwh)	1,869,384	heat (mmbtu)	6120			
	***Output (kg)**		****Output (kg)**		***Carbon Storage**		***Avoidance (kg)**		*Total Emissions		GWP
	CO2	7112	CO2	1174502	(733400)		CO2	(1802882)	CO2	(2399484)	1
							Biogenic CO2	(1044817)			
	CH4	7660	CH4	135854			CH4	(6977)	CH4	136537	21
	N2O	0.1088	N2O	16			N2O	(22)	N2O	(5)	310
									***MT CO2 equi**	466	

*Input: energy and fuel inputs for process
*diesel (liter) = annual tralvel distance(km)/ vehicle efficiency (km/liter)
**diesel (liter)= facility diesel use (liter/tonne)* waste generation(tonne)
*electricity from biogas (kwh): initial electricity generation before parasitic load (kwh)
carbon storage = the amount of organic waste carbon storage factors
*output (kg) = diesel (liter)*emission factor(kg/liter) +electricity(kwh)*emission factor(kg/kwh)
**output (kg) = diesel (liter)*emission factor(kg/liter) +Biogaas combustion for energy recovery
*Avoidance (saving): environmental benefits from avoid natural gas extraction, electricity generation from fossil fuel and heating (combustion) from natural gas
*CO2 total : biogenic CO2 from AD is not counted.
*Total Emissions:
emissiosns (collection+diesel consumption at AD facility+Biogas combustion) -avoided emissions (of natural gas extraction & combustion+electricity generation)-Biogenic CO2- carbon storage

Scenario5. AD + Heating only

Alternative	*Ordinary*	*Savings*
Biogas heating	natural gas heating	NG extraction & combustion

Generation	*Collection*		*AD*								
	***Input**		***Input**		Value added products		Net Revenue				
food waste	*diesel (liter)	1356	**diesel (liter)	48082	Heating value of biogas (mmbtu)	20066	heat (mmbtu)	14,326			
yard waste	*diesel (liter)	1356	*electricity from grid (kwh)	143594							
	***Output (kg)**		****Output (kg)**		***Carbon storage**		***Avoidance (kg)**		total		GWP
	CO2	7112	CO2	1,282,923	(733400)		CO2	(1073538)	CO2	(1561720)	1
							Biogenic CO2	(1044817)			
	CH4	7660	CH4	135856			CH4	(6958)	CH4	136559	21
	N2O	0.1088	N2O	18			N2O	(2)	N2O	16	310
									***MT CO2 e**	1311	

*Input: energy and fuel inputs for process

*diesel (liter) = annual tralvel distance(km)/ vehicle efficiency (km/liter)

**diesel (liter)= facility diesel use (liter/tonne)* waste generation(tonne)

*electricity from grid (kwh): additional electricity use from the grid

carbon storage = the amount of organic waste carbon storage factors

*Output (kg) = diesel (liter)*emission factor(kg/liter) +electricity(kwh)*emission factor(kg/kwh)

**Output (kg) : emissions from diesel use, electricity use from grid, and biogas combustion

*Avoidance (saving): environmental benefits by avoiding natural gas extraction and combustion

*CO2 total : biogenic CO2 from AD is not counted.

*Total Emissions:

emissiosns (collection+diesel consumption at AD facility+Biogas combustion+electricity from grid) -avoided emissions (of natural gas extraction & combustion)-Biogenic CO2- carbon storage

*MT CO2 equi. = (CO2(kg)*1+CH4(kg)*21+N2O(kg)*310)/1000

Scenario6. AD + CNG

Alternative	*Ordinary*	*Savings*
Renewable CNG	CNG	NG extraction & electricity from grid

Generation	*Collection*		*AD*								
	***Input**		***Input**		Value added products		Net Revenue				
food waste	*diesel (liter)	1356	**diesel (liter)	48082	Heating value of biogas (mmbtu)	20066	Renewable CNG (mmbtu)	11968			
yard waste	*diesel (liter)	1356	Biogas combusted for electricity generation (MMBTU)	1345	*electricity from biogas (micro CHT, kwh)	110,374	electricity from biogas (kwh)	10,376			
	***Output (kg)**		***Output (kg)**		***Carbon Storage**		***Avoidance**		*Total Emissions		GWP
	CO2	7112.0	CO2	199720		(733400)	CO2	(65770)	*CO2	(662372)	1
							Biogenic CO2	(70035)			
	CH4	7660.3	CH4	135794			CH4	(6939)	CH4	136516	21
	N2O	0.1	N2O	4			N2O	(1)	N2O	3	310
									***MT CO2 equiv.**	2205	

*Input: energy and fuel inputs for process
*diesel (liter) = annual tralvel distance(km)/ vehicle efficiency (km/liter)
**diesel (liter)= facility diesel use (liter/tonne)* waste generation(tonne)
carbon storage = the amount of organic waste carbon storage factors
*electricity from biogas (kwh): initial electricity generation before parasitic load (kwh)
*output (kg) = diesel (liter)*emission factor(kg/liter) +electricity(kwh)*emission factor(kg/kwh)
*Avoidance (saving): environmental benefits from avoid natural gas extraction and electricity generation from fossil fuel
*CO2 total : biogenic CO2 from AD is not counted.
*Total Emissions:
emissiosns (collection+diesel consumption at AD facility+Biogas combustion) -avoided emissions (of natural gas extraction+electricity generation)-Biogenic CO2- carbon storage
*MT CO2 equi. = (CO2(kg)*1+CH4(kg)*21+N2O(kg)*310)/1000

Vita

Hei-Young Kim was born in Seoul, South Korea. She entered Konkuk University in Seoul, South Korea, in March 1994 to study Industrial Chemistry. In February 1999, she was awarded the Bachelor of Science degree in Engineering. She worked as a process engineer in Lam Research Cooperation after graduation. She married to Ok-Youn Yu in 2001 and moved to the United States in 2003 for her husband's Ph.D. degree at Texas A&M University. She moved to Boone, North Carolina, with her husband and two children when Ok-Youn started teaching at Appalachian State University in 2010. In the fall of 2012, she began to study renewable energy engineering toward a Master of Science degree at Appalachian State University.