MODELING AND ANALYSIS OF UTILIZING FOOD WASTE AND MANURE IN NEW JERSEY

By

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A thesis submitted to the

Graduate School-New Brunswick

Rutgers, the State University of New Jersey

In partial fulfillment of the requirements

For the degree of

Master of Science

Graduate Program in Food & Business Economics

Written under the direction of

Gal Hochman,

And approved by

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New Brunswick, New Jersey

October, 2014
ABSTRACT OF THE THESIS

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Thesis Director:
Gal Hochman

Waste-to-energy (WTE) facilities demonstrate great potential in making maximal use of the increasing amount of waste in modern society. While current researches focus on a certain technology or specific aspects of the technology (e.g., (Bernstad and la Cour Jansen 2011) on life cycle analysis for household food waste; DEFRA (2007) for modern waste incineration in Europe; Whyte et al. (2001) for cost analysis using anaerobic digestion technology; among many more), this study has developed a broader framework to compare the electricity generation capacity, as well as economic benefits and costs of alternative WTE technologies. In the end, we use food waste and manure generation data from New Jersey and apply this integrated program to analyze four theoretical scenarios: Direct Combustion, Landfill-to-Gas, Composting and Anaerobic Digestion.

When calculating productivity, we estimated methane yields and corresponding green electricity generation using a simulation program in Matlab. The results indicate that anaerobic digester with gas collection facilities can generate the largest amount of methane and green electricity generation per unit of waste. In total, WTE facilities can
supply hundreds to thousands of local households with green electricity. In the economic analysis, landfill-to-gas method is proven as the least costly method to consume a unit of waste and has the highest net revenue income stream. In comparison, direct combustion is by far the most costly method.

In summary, composting and landfill-to-gas are the two favorable methods of treating food waste and manure on a large scale. From the aspect of land scarcity and carbon footprint reduction, anaerobic digestion still has great potential to benefit New Jersey municipalities. While discussing the limitations of the simulation analysis, we lay a foundation for further study. Regulatory recommendations are also provided to decision makers in waste management facilities.
ACKNOWLEDGEMENTS

I would like to dedicate my sincere thanks to many individuals and institutions who lent me a hand during my research period. First of all, I want to thank U.S. Department of Agriculture, National Institute of Food and Agriculture (USDA/NIFA) for their financial support on this research topic.

I also would like to express my deep gratitude to Dr. Paul Gottlieb. I could not have completed this work without his guidance and support. I truly appreciate his sincere advice and encouragement since I enrolled in the Food and Business Economics Program. Special thanks to Dr. Serpil Guran and Dr. David Specca from Eco-Complex Institution¹ for providing me invaluable data as reference and giving critical comments on my study.

Also, deepest thanks should be given to Dr. Hochman, my research project advisor, for providing me the great opportunity to conduct this research. He is responsible and patient when introducing renewable energy technologies and explaining differing opinions, which I believe to be the footstone for my early-stage study. His valuable advice and constant assistance are absolutely necessary in keeping my progress on schedule, while his professional guidance and assiduous supervision help me strengthen my research capability.

In addition, I need to thank my committee members, including Dr. Yanhong Jin, for their invaluable time to carefully review my work and to provide critical comments.

¹ Eco-Complex Institution is funded by New Jersey Agriculture Experiment Station and Rutgers University
Undoubtedly, I would not be able to complete my thesis and get this MS degree without the unconditional support from my parents and sincere assistant from my friends. Thank you.
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<tbody>
<tr>
<td>AM</td>
<td>Animal Manure</td>
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<tr>
<td>CH₄</td>
<td>Methane</td>
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<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
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<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
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<tr>
<td>DAFRE</td>
<td>Department of Agriculture, Food and Recourses Economics</td>
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<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
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<tr>
<td>EPA</td>
<td>U.S. Environmental Protection Agency</td>
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<td>FS</td>
<td>Fixed Solids</td>
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<tr>
<td>FW</td>
<td>Food Waste</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
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<tr>
<td>IBA</td>
<td>Incinerator Bottom Ash</td>
</tr>
<tr>
<td>IC</td>
<td>Internal Combustor</td>
</tr>
<tr>
<td>IRR</td>
<td>Internal Rate of Return</td>
</tr>
<tr>
<td>ISWM</td>
<td>Integrated Solid Waste Management</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt-hour</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
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<tr>
<td>LFG</td>
<td>Landfill-to-Gas</td>
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<tr>
<td>MSW</td>
<td>Municipal Solid Waste</td>
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<tr>
<td>NPV</td>
<td>Net Present Value</td>
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<tr>
<td>SWM</td>
<td>Solid Waste Management</td>
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<tr>
<td>TS</td>
<td>Total Solids</td>
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<td>Description</td>
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<tr>
<td>--------------</td>
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<tr>
<td>VS</td>
<td>Volatile Solids</td>
</tr>
<tr>
<td>WTE</td>
<td>Waste-to-Energy</td>
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<td>WHO</td>
<td>World Health Organization</td>
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Chapter 1

Introduction

1.1 Background of the Project

With the fast growth of population and urbanization, the need for sustainable waste management methods has become an urgent demand. Municipalities, especially in heavily populated regions, generate thousands of tons of municipal solid waste that needs to be treated daily. Every year, there are over 1,100 million tons of MSW are generated around the world (Rubio-Romero, Arjona-Jiménez, and López-Arquillos 2013). The average amount of MSW has doubled to 1.2 kilogram per person per day today, compared to 0.64 kilogram a decade ago\(^2\). Food waste has been claimed as the largest single component of total municipal solid waste (MSW), since 100 kilograms of wet food waste can be generated per year by a typical US family with 2.63 people (Diggelman and Ham 2003). Land occupation, GHG leakage and water sources contamination have been raising with the astonishing waste generation rate. Unfortunately, the most efficient way to take care of those MSW with the least negative environmental impacts is still under investigation.

All goods on earth contain a certain amount of energy. Thus, MSW should be considered as a source of energy instead of totally useless trash. If we discard waste without proper recovery or treatment, we will not only lose the chance to get valuable energy and materials, but also expose human beings to severe environmental problem, especially for organic solid waste. Food waste and animal manure constitute a large portion of current

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organic solid wastes stream in traditional landfills. Waste-to-energy technologies offer sustainable solution to exploit the valuable of the combined waste stream in New Jersey. Food waste includes waste from food processing factory, pre- and post-consumption leftovers from both residences and commercial establishments, for example, retail stores, restaurants and school cafeterias. It is characterized to contain a high percentage of rapid degradable components such as protein, carbohydrates, short chain fat and etc. Hall et al. estimated the energy content of food waste by comparing the US food supply data with the calculated food consumed by the US population (Hall et al. 2009). They found that approximately 1400 kilocalories of food were wasted by one person per day, adding up to 150 trillion kcal per year. To produce 1 kcal of food requires 3 kcal of fossil fuel on average. Therefore, the annual food waste accounts for approximately 300 million barrels of oil or about 4% of U.S. oil consumption in 2003 (Hall et al. 2009).

Manure is semi-solid or solid urine and dung that get dried before being collected. Animal excrete more waste than human beings on daily base. According to previous study, a dairy farm with 2500 cattle can produces an equivalent amount of waste as a city with 411,000 people (Manale 2006). At present, the most common method to dispose manure is to disperse it onto farmland as soil amendment. However, the stink odor and groundwater contamination weaken its advantage as a beneficial waste management method. In addition, some experts found that the amount of pathogens in manure may cause human illness and infectious disease. So, from the public health perspective, to dispose manure into environment without specific treatment (e.g. disinfection) is an inferior option for the society.
New Jersey has the densest population (1205.4 persons per square mile) in United States, producing 8.2 million dry tons of biomass annually. It locates at the center of the Northeast megalopolis and adjacent to metropolis like New York and Philadelphia, making it both a great producer and receiver for MSW. The highly dense population are doomed to generate an increasing amount of waste that needs to be disposed in fewer and fewer landfills. There used to be 845 exist in New Jersey, either operating or shutdown. Until 2002, only 13 out of 21 counties in New Jersey own solid waste landfills and five of them have resource recovery facilities. It’s urgent that we find cost-effective method to divert more waste from traditional landfills and make Pareto optimization available to local communities.

The increase in the price of coal, oil and natural gas to produce vehicle fuel and the raise of electricity and fertilizers give us to economic incentive to upgrade traditional landfills into a more effective system to utilize the energy left in waste stream. Four major waste management technologies to dispose food waste and manure have been industrialized in United States. They are direct combustion, landfill-to-gas, composting and anaerobic digestion. Each technology has its own advantages and disadvantages with respect to resource requirement, land use, energy inputs as well as capital and workforce requirements. For instance, wet wastes are more for suitable for anaerobic digestion or composting, while dry wastes are preferred in direct combustion or gasification. We shall carefully examine and weigh their benefits and costs in maximizing the net social welfare of New Jersey municipalities.
1.2 Challenges

WTE progress is considered as a sustainable way to solve the waste management problem around the world. The applicability and social-economic value of potential technology are equally important in the decision making process. The major challenge in this process comes from the lack of an integrated generic system to quantify the technical performance and economic viability for design and optimization purpose.

Previous studies normally focused on one specific WTE technology and normally in the laboratory environment instead of in industrial condition. Investigation on energy potential of food waste and manure is still under research and no solid conclusion about synergetic effect has been confirmed. Meanwhile, we need to make sorts of theoretical assumptions to simulate the plants’ performance and push the results close to the reality based on experience and previous researches.

From the data perspective, it is unlikely to get the accurate waste generation data for New Jersey. With the given data at county or national level, we can get a proportionally efficient estimation, which will introduce bias to the final results.

1.3 Objectives and Outline of the Study

In this study, the overall objective is to compare the energy recovery validity of four different WTE methods in the treatment of food waste and manure. The best waste management method should be able to maximize benefits and minimize costs over a certain designed period. The comparison is primarily based on the net green electricity generation, annual net income and internal rate of return in each technical scenario.

Specifically, the objectives of the present study include:

• To develop a technical analysis framework for WTE technologies
• To integrate simulation models for different WTE process
• To identify the cost components and revenue sources in each WTE scenario
• To compare the economic feasibility of each biotechnology
• To identify the best waste recovery option for municipalities in New Jersey

Generally speaking, we want to provide analytical support for solving environmental problem in modern municipality and reduce environmental risks in the future. In next chapter, previous researches and studies have been reviewed for each WTE technologies with a brief discussion on their feasibility under different conditions.

Chapter Three introduces methodology and models used to develop the integrated system, which analyze the capacity for potential WTE facilities in each scenario. The simulation results will be compared and explained in the later section, followed by an economic sensitivity analysis.

In Chapter Four, the data source for input materials and important parameters in both technical and economic analysis are introduced. The reference of data, how data has been estimated and the rationale behind the choice of parameters are discussed.

Chapter Five presents the economic analysis framework to compare the economic value of each scenario. Cost-benefit analysis is one of the effective and principal decision-making tools to assess the feasibility of waste management processes. The structure of cost and revenue are introduced to analyze the possibility for WTE facilities to earn positive net income.

In the end, conclusion and further research will be summarized. We also provide suggestions for New Jersey residents and legislators in associated departments.
Chapter 2

Literature Review

The waste hierarchy is one of the eleven environmental protection principles advocated in the Environment Protection Act 1970. The integrated solid waste management hierarchy provides us an order of preference and ranks the most commonly used waste management technologies for municipal solid waste. The integrated hierarchy starts with waste prevention and then followed by source minimization, recycling/composting, energy recovery, final treatment and disposal. In the hierarchy, the upper layer is more desirable than the lower layer for less impact on the environment.

As noted above, the waste management legislation and policy in New Jersey should take all of the principals into account and apply the most favorable waste management method based on its specific social conditions.

Figure 2-1 Integrated solid waste management hierarchy

Aimed at generating eco-friendly energy by utilizing two common solid waste, four waste-to-energy methods from the hierarchy will be compared in the study. The corresponding scenarios include direct combustion, landfill-to-gas, composting and anaerobic digestion.

2.1 Direct Combustion

Direct combustion or incineration, is the most straight-forward waste management, during which the conventional thermochemical conversion can release great amount of energy to generate electricity. Meanwhile, direct combustion can significantly reduce the bulk of waste disposed that needs to be disposed in landfills. It is particularly popular in countries where land is a scare resource and the feedstock is not required to be processed before incineration. For instance, combustion combined with energy recovery supplied 4.8% of electricity consumption and 13.7% of total domestic heat consumption in Denmark (Kleis and Dalager 2004). The main stages of the combustion process include drying, degassing, pyrolysis, gasification and oxidation (Bosmans et al. 2013). Waste is combusted at the temperature of 850 °C and transformed to carbon dioxide, vapor and non-combustible incinerator bottom ash (IBA). The plant performance depends on the type of incinerator and the waste composition as well as the recovery capacity, such as metals from the ash for recycling. U.S. Environmental Protection Agency 2011 estimated that about 11.7% of MSW is disposed by direct combustion with energy recovery, making its advantage in reducing the volume of wastes and sterilizing them. Volume reduction from direct combustion can be up to 90% of total waste, which satisfies the second priority of waste management hierarchy.
Direct combustion is normally applied to mechanically-dewatered wastes. It becomes energy-intensive because of the high MC contained in combined waste stream, making it less promising in net electricity generation. During the pretreatment, a significant amount of energy is consumed to dry or dewater the combined waste stream. And the combined gas also costs energy to clean it up before emitted to the air. Therefore, conflict opinions exist about the net energy benefits of combusting FW and AM. Some studies claimed that no energy benefit can be gained due to the high moisture content, where the energy inputs cannot be totally compensated by the energy generated (Michael Centore, Gal Hochman, and Ziberman 2013). Meanwhile, other authors demonstrated that the high evaporation efficiency of dewatering process (up to 80% efficiency) can make the net energy benefits viable (Bernstad and la Cour Jansen 2011). But the energy efficiency of combustion process is not impressively high. The net electrical efficiency of the current advanced incineration plants ranges only between 22 to 26% (Bosmans et al. 2013).

WTE combustion facilities generally require a large cost investment. Construction alone can account for $40.56 in initial cost, and larger plants may require double to triple this amount (DEFRA 2007)\(^4\). Besides, combustion with energy recovery cannot avoid potential environmental problem, especially abundance of dust and ash (about 25-30% by weight of the solid waste input) and the toxicity of the flue gases. In order to meet strict emission standards, waste gas treatment equipment are installed to eliminate those harmful substances. But the cost on those expensive equipment will drive up the total capital cost even further and require long period operation to be viable. Normally, it may

\(^{4}\) Capital cost data comes from Waste Technology Data Centre, [www.environment-agency.gov.uk/wtd](http://www.environment-agency.gov.uk/wtd)
take as long as 30 years to fully realize the economic benefits of MSW combustion. This could hamper the development of future more efficient waste treatment technology\textsuperscript{5}.

Although the low productivity efficiency along with high total cost make direct combustion limited in practice, there are still possible option can maximize its economic benefits. For example, if the gas purification facility has already in place, such as co-incinerated in an existing coal-fired power plant, the cost for combustion will be reduced (Rulkens 2007). And the bottom ashes in incinerator can be collected and sold as the raw material for building material manufacture, such as bricks or cement, at a cost of slightly over $3 per ton\textsuperscript{6}. To conclude, regardless of those problems, direct combustion for organic solid waste is still an available option when employed with energy recovery, control of exhaust and an appropriate disposal method for ash and non-combustion component.

2.2 Landfill-to-Gas

Traditional landfills has a long history to be extensively used for MSW management. Globally, modern managed landfills is the most commonly used method to dispose solid waste, while recovering landfill gas as fuel source become more economically viable (Zhang et al. 2007). Wastes in the landfill sites can be converted into bioenergy through phases including initial adjustment, pyrolysis, liquefaction and gasification. The initial steps are aerobic, but then turn to be anaerobic when oxygen is running out. A mixture gas of methane and carbon dioxide are formed when the organic fractions (such as food and garden waste, paper, wastewater) slowly decompose in landfills.

\textsuperscript{5} Basic Principles and Processes in the Operation of Incineration Technology. \url{http://engineering1.pbworks.com/w/page/32234029/Incineration}
In the United States, 1908 municipal solids waste landfill exist and they are the third-largest source of human-related methane emission, accounting for 16.4% of total emission in 2012 (Lamb 2012, Environmental Protection Agency 2014). The landfills gas (LFG) is a mixture of methane (45-60%), carbon dioxide (40-55%) and a trace amount of other components, which gives landfill gas its characteristic smells. The trace amounts of non-methane organic compounds and volatile organic compounds result from the decomposition of by-products or the evaporation of biodegradable solid wastes. What the literature review revealed is that about 872.3 gigagram(Gg) landfill methane can be produced annually, in equivalent, 4314 gigawatt hours (GWh) of electricity, which accounts for 0.1% of total electricity generation (Bolan et al. 2012). Emission from MSW landfills accounts for about 69% of total solid waste emission and 94% of total landfill emission, with the rest coming from industrial landfills. Although it is reasonable to assume the amount of MSW will increase along with U.S. population, the percentage of being landfilled may decline due to the increase in recycling rate or other WTE technology utilization. A 27% decrease in the net methane emission from landfills has been observed during 1990 to 2011, largely because of the doubled methane recovery facilities and the increase of waste recycling rate—from less than 10 percent in 1980 to over 34 percent in 2011(U.S. Environmental Protection Agency 2011). Landfill gas are collected for a variety of end uses including electricity generation, produce fuels for transportation (bio-diesel), or upgraded biomethane gas. The common treatment is to burn biogas which can give out a significant amount of energy to generate electricity (50.2 GJ/ton waste)\(^7\).

\(^7\) http://www-fa.upc.es/personals/fluids/oriol/ale/eolss.pdf
In practice, the moisture content of waste compound, the temperature inside the landfills, the size of disposed waste, the availability of air circulation can affect the degradation process in landfills. For example, excess water may lead to stagnant saturated zone in the waste, which speeding up the first two steps of biodegradation while limiting the methanogenesis as the result of drop in pH (Hans Oonk, 2010). Operating landfill in aerobic environment have several merits such as increased settlements, decreased metal mobility, lower methane control costs, and reduced environmental liability (Kumar, Chiemchaisri, and Mudhoo 2011).

In addition, every kWh electricity generated from landfill methane, according to Bolan et al. 2012, avoids 0.39649 kg $CO_2$ or 0.215057 kg $CO_2$ produced by power plants using coal or oil\(^8\). Although landfill-to-gas is an economic waste disposal option, its environmental contribution of landfills with gas recovery facility may be minimized, if the not managed properly (Bolan et al. 2012). The major problems include the surface and ground waste contamination, methane leakage during the first a few months and odor emission. Therefore, we suggest that landfills should start to collect LFG shortly after waste disposal and take proper post-treatment for landfill leachates before discharging to the environment.

### 2.3 Composting

Composting or aerobic digestion is a biooxidative process, which has been proven to be a simple and safe bulk treatment for organic waste. During the process, a large portion of the degradable organic carbon is converted into carbon dioxide, water and heat. (Berger et al. 2005). When there is excessive moisture or not enough ventilation, a certain amount

\(^8\) [http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11](http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11)
of methane emission can be detected in composting piles (Thompson, Wagner-Riddle, and Fleming 2004). The methane emission from composting were 74 Gg or 1.5 Tg CO₂ equivalent when the emission of CH₄ have increased approximately 24% from 2000 to 2010 (EPA 2012). Compared to other process, composting produces less odor and a considerable amount of heat, in favor of reducing the concentration of pathogens inside the composter. Measures must be taken to maintain a proper reaction condition, including oxygen supply, moisture and temperature, C/N ratio and pH, in order to inhibit methane generation. Compost, collected at the end of composting, can provide pathogen free source of organic nutrients to enhance soil fertility. The compost contains 8.3 kilograms of nitrogen per dry ton and 2.0 kilograms of phosphorus per dry ton waste (Finnveden, Moberg, et al. 2005). For farmlands that has been depleted through agriculture practice for years, compost with large amount of organic matters is an ideal replacement. Because of the high population in New Jersey, the biggest challenges is the scarcity of enough land space for composting, followed by odor and leachate leakage.

Approximately, 400 composting facilities are in operation across United States (Environmental Protection Agency 2013). Organic solid wastes, such as food waste, yard waste and sludge are commonly treated in composter for its convenience and economically feasibility. The amount of waste composted in the US almost quadrupled from 1990 to 2011, mainly due to the related legislation published in the 1900s to reduce the amount of yard trimming disposed in landfills (Michael Centore, Gal Hochman, and Ziberman 2013). The quantity of food waste generated about 48 million tons per year, but only 0.68 million tons of food waste is composted annually, which represents only 1.4% of the total food waste generated in the United States (P. Ulloa, 2008). Finnveden et al.
discussed the treatment of food waste under composting, digestion, incineration and landfilling situation (Finnveden, Johansson, et al. 2005). Their conclusion pointed out that the advantage of composting FW and AM are limited somehow. In addition, they mentioned that the large scale composting is of limited interest and home composting or small scale composting, in contrast, is a practical alternative. For manure management, the transportation cost is one of the major concerns for farmers. Composting becomes a viable solution to reduce the volume and weight of the manure, during which the liquid manure can be transferred to solid (Kunz, Miele, and Steinmetz 2009). In addition, significant amount of energy (4-8 MJ/kg dry matter) can be generated and reused on the farms.

Two common methods to utilize the energy from composter are self-circulating warm water for heating and burning recaptured methane for electricity generation. Warm water from composting can provide continuous space heating at temperature of 50-55°C, saving investment in boiler installation to store energy. The energy consumption during the composting process, to some extent, diminish the advantage of composting. One study found that the composting process requires about 0.5-0.75 kWh of aeration energy per kg of COD removed (Haandel and Lettinga 1994). About 54.4 megajoules electricity are needed to compost per dry ton of food waste. Thus, the economic benefit to operate a composting plant with full-scale energy recovery facility is not known for sure.

2.4 Anaerobic Digestion

Up to now, extensive amount of research have been done in anaerobic digestion throughout the world. Organic matter is metabolized by microorganisms in an oxygen-free environment and methane production is its major objective. Depending on the type
of electron acceptors, anaerobic process can be classified as either anaerobic fermentation or anaerobic respiration. Factors that affect the layout design and operation performance includes mean treatment time, temperature in reactor, and feedstock characteristics (e.g. moisture content, volatile solids content, biodegradability, etc.).

Among all biological treatments to convert waste to energy, anaerobic digestion is favorable in modern society due to its high energy recovery ability and less negative impact on the environment. In Brazil, the most common disposal strategy for manure management is anaerobic digestion (Kunz, Miele, and Steinmetz 2009). About 0.3 m$^3$/kg TS biogas can be produced during the anaerobic digestion of piggery slurry. The content of methane in biogas from anaerobic digestion can reach 60-70% while the content of carbon dioxide is about 30-40%, along with a trace amount of other gases, like hydrogen sulfide (USDA 2009). The emission of CO$_2$ from anaerobic digestion tends to be 25% to 67% less than that from composting (Mata-Alvarez, Mace, and Llabres 2000). In other words, the greenhouse gas (GHG) reduction from AD is more significant. The gas collection system at the top of the digestion tank transports the methane-rich biogas to be incinerated at the Internal Combustor. The released heat and power can be used to heat a boiler or drive a gas engine to generate electricity, although about 15% of heat is wasted in maintaining digester at proper reaction temperature (Monnet 2003). The methane emission per ton food waste can generate 3,743 MJ energy with 13.2% is used at the plant itself as heat (Finnveden, Moberg, et al. 2005). In this paper, we claim that on average the composition of methane can reach 65% with 23.3 MJ of gross energy per cubic meters.
Based on life cycle analysis from Bernstad et al., we find that AD is more environmental friendly than composting or combusting food waste when the biogas treated as a substitution for vehicle fuel (Bernstad and la Cour Jansen 2011). The high moisture content and abundance of cooking oil makes AD more favorable than composting in treating food waste. The majority of existing food waste digestion projects are co-digesting food waste with either manure or municipal sludge (Bohn 2010). Zhang et al. attempted to calculate the methane yield from different mixtures of food waste and manure based on first-order kinetic model (Zhang and El-Mashad 2010). Two prediction models has been developed, which shown a positive linear relationship between the food waste portion and the final methane yield after 20 and 30 days. They concluded that the food waste portion can make positive contribution on methane production using an anaerobic batch digester at 35(±1)°C. For a digestion time of 20 days, a FW/AM ratio of 1.5 is recommended (El-Mashad and Zhang 2010).

The higher solid removal efficiency of AD can make a larger portion of organic composition of wastes can be converted into inorganic form. The residual organic solids can be upgraded as value-added fertilizer or as the raw material for further composting, which generates additional revenue and drives the operating cost down. However, the digestate from AD contains only about 7.6kg/ton nitrogen and 1.1 kg/ton phosphorus (dry weight9), which are less nutrient compared to compost residues (Finnveden, Johansson, et al. 2005). Beside, anaerobic digestion requires less land occupation than aerobic composting, although the start-up time for AD is quite longer. Commonly, two to four months are required at a mesophilic temperature (35-40° C) and more than a year under thermophilic condition (about 55°C)(Khanal 2008). Therefore, all the pros and cons need

9 Dry weight is 30% of wet weight. (Gal et al. 2013)
to be weighted before a solid conclusion on whether AD is the best WTE technology for local municipalities.
Chapter 3
Methodology

To measure the annual electricity generation using different WTE technology, an integrated system has been built in Matlab environment. A general flow diagram of the system is shown in Figure 3.1. The brown dashed box at the top represents the waste generation and collection process. In real world, the collected waste could be either transported directly to WTE plants, or recycled and disposed in the Waste Transfer Station (WTS) before transporting to the final treatment place. The central red dashed box represents the treatment process of a generic WTE plants with energy inflow and outflow marked as blue solid lines. Depending on the type of WTE technology, the potential final products can include green electricity, CHP and natural biofertilizer.

The key focus of this section is to combine computationally efficient models into an integrated system to estimate the productivity of two final products, green electricity and bio-fertilizer, in five scenarios. The basic scenario introduces one theoretical model which returns the theoretical maximum in production capability and the other four alternative scenarios in order are direct combustion, landfill-to-gas, composting and anaerobic digestion. In following technical analysis, the base unit is chosen to be “MWh generation per ton of combined waste”.
3.1 Major Assumptions

To compare the technical feasibility of WTE plants in simulated scenarios, several assumptions about the inputs and technology have been applied cautiously in this study. The assumptions common in all scenarios are listed as follows:

1. The composition of combined waste are considered to be constant across seasons and geographic locations. But the food waste to manure ratio varies at different plant site, when the combined waste is assumed to be collected from the nearest municipalities.
2. The capacity of WTE plants in each scenario are assumed to be large enough to treat the combined waste throughout the plant’s entire lifespan. It means no further incremental investment is needed in expanding the plants.

3. We assumed that all food waste and animal manure generated in one year are collected and disposed in the WTE plants at constant pace. The combined waste stream is formed by either water content (WC) or total solids (TS). Total solids is the combined by fixed solids (FS) and volatile solids (VS). However, the fixed solids (FS) of the combined waste cannot be decomposed and usually remain unchanged during the WTE process. Food waste contains 10% to 25% TS of which around 80% are VS. For animal manure, it contains about 5% to 30% of TS and 70% to 85% are volatile solids components (Monnet 2003).

4. In landfill and anaerobic digestion scenarios, biogas is assumed as the intermediate product and then burned on-site for power generation. Gross energy (P, kJ/yr.), mainly from the methane of biogas, are calculated based on the volume of methane generation as Equation 3-1. Carbon dioxide and the other trace amount of gases are considered to make no contribution to the total energy generation.

\[ P = V_{CH_4, yr} \times 35,846 \times \theta_p \] 3-1

where \(V_{CH_4, yr}\) is the volume of methane generated from combined waste per year. And the overall system efficiency of power generation (\(\theta_p\)) ranges from 70% to 80%. The net heating energy of methane in biogas (35,846 KJ/m\(^3\)) was obtained from Samir Khanal’s book on anaerobic biotechnology. With 50-60% methane content in biogas, the net thermal value of biogas is approximately 22.4 MJ per cubic meters (Khanal 2008).
5. Based on ideal gas law, 1mol of gas at standard temperature and pressure (STP) has a volume of 22.4 L. The methane concentration in biogas is considered to be stable during any process. In addition, the greenhouse gas emission from during transportation to WTE facilities are neglected. This simplification tends to underestimates the emission from composting and AD scenario, although it may not be significant enough to alter the conclusions.

6. The energy conversion efficiency in waste management varies when the final products are different. Commonly, burning methane gives out lots of energy, during the electricity generation process, but about 65% of energy would be lost as heat and pure losses. Based on the research conducted by Evans et al, the electricity generation efficiency is up to 38% for electricity only, and up to 90% in the case of CHP (Evans 1986). This study assumes that the actual energy conversion efficiency $\theta_e$ for biogas fired internal engine is 35% in those scenarios with electricity as the final product. Therefore, the final electricity generation (kWh) can be expressed as following:

$$\text{Electricity} = P \times \theta_e \times \left(\frac{1}{3,600}\right)$$  \hspace{1cm} 3-2

7. The removal efficiency of VS reveals the technical performance of WTE plants. The higher the removal efficiency is assumed to be related to more electricity generation, more TS conversion to bio-fertilizer or more volume reduction in waste stream.

3.2 Scenario Analysis and Model Selection

3.2.1 Theoretical Energy Potential Scenario

The basic scenario is to calculate energy potential in waste stream by applying the famous Bushwell equation, Equation 3-3 (Buswell and Mueller 1952). The theoretical
yield of methane and carbon dioxide can be estimated from the molecule formula of waste components, assuming all elements are known and all chemical reactions are fully completed.

\[ C_nH_aO_bN_cS_d + \frac{1}{4} (4n - a - 2b + 3c + 2d)H_2O \rightarrow \frac{1}{8} (4n - a + 2b + 3c + 2d)CO_2 + \frac{1}{8} (4n + a - 2b - 3c - 2d)CH_4 + cNH_3 + dH_2S \]

In order to apply Bushwell equation, we need to know the chemical composition of input substrates. The major chemical formula of food waste and animal manure are referred to previous researches conducted by William et al. and Texas Water Resource Institute. (William E. et al. 1997, Engler, Capereda, and Mukhtar 2010, Parry 2013). The molecule formulas of food waste and manure are derived from the ratio of C, H, O N, and S along with their molecular weight, respectively. Table 3-1 is a summary of the chemical composition of food waste and manure and the corresponding molecular weights used in the Bushwell equation.

**AM:** \[ C_{16.58}H_{28.32}O_{13.62}N_{0.71}S_{0.07} \] \[ M_{AM} = 457.38 \text{ (g)} \]

**FW:** \[ C_{21.53}H_{34.21}O_{12.66}N_{1.00}S_{0.07} \] \[ M_{FW} = 511.37 \text{ (g)} \]

In our analysis, the C/N ratio for food waste and manure is quite close, 21.51:1 compared to 23.35:1. However, in some previous studies, Liu et al. found the C/N ratio of manure to be 11:1 which is much lower than what we use in this paper (Liu, Miller, and Safferman 2009). Despite this distinction, the theoretical methane and biogas yield per unit of food waste and manure can be calculated following the law of conservation:

**Food waste:**

1 mol FW~11.484 mol \( CH_4 \)~183.744 g \( CH_4 \)~257.24 L \( CH_4 \)

1 mol FW~10.046 mol \( CO_2 \)~442.024 g \( CO_2 \)~225.0304 L \( CO_2 \)

Equivalently: 1 g FW~0.503 L \( CH_4 \) + 0.44 L \( CO_2 \)
**Manure:**  
1 mol MA~8.141 mol CH$_4$~130.256 g CH$_4$~182.3584 L CH$_4$  
1 mol MA~8.439 mol CO$_2$~371.316 g CO$_2$~189.0336 L CO$_2$  

Equivalently: 1 g MA~0.3987 L CH$_4$ + 0.413 L CO$_2$

The methane potential calculated from this stoichiometric analysis will definitely return the maximum methane yields, because of the assumption that all VS content is converted into methane and carbon dioxide completely. The results show the maximum amount of methane that can be produced, free from any technological limits. It is treated as a performance benchmark as well as the upper limits for methane and electricity generation.

We can compare the theoretical limit with value simulated in WTE process, in order to make a meaningful interpretation. For example, the stoichiometric methane potential calculated by the theoretical model can provide quantitative support on the Potential Methane Generation Capacity ($L_o$) in Landfill-to-Gas scenario.

Table 3-1 The chemical composition of food waste and manure

<table>
<thead>
<tr>
<th>Elements</th>
<th>Food waste</th>
<th>Manure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Atomic weight</td>
<td>Composition (%)</td>
</tr>
<tr>
<td>C</td>
<td>12</td>
<td>50.5</td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>6.72</td>
</tr>
<tr>
<td>O</td>
<td>16</td>
<td>39.6</td>
</tr>
<tr>
<td>N</td>
<td>14</td>
<td>2.74</td>
</tr>
<tr>
<td>S</td>
<td>32</td>
<td>0.44</td>
</tr>
<tr>
<td>C:N</td>
<td>21.53:1</td>
<td></td>
</tr>
<tr>
<td>Molecular weight</td>
<td>511.37</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bushwell equation</td>
<td>Atomic weight</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>CH₄</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>CO₂</td>
<td></td>
<td>44</td>
</tr>
<tr>
<td>NH₃</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>H₂S</td>
<td></td>
<td>34</td>
</tr>
<tr>
<td>CH₄/CO₂</td>
<td></td>
<td>53.3/46.7</td>
</tr>
</tbody>
</table>


### 3.2.1 Direct Combustion Scenario

In the direct combustion scenario, the mixed waste is combusted at high temperature (over 850 °C) in the combustion chamber and the massive heat is assumed to be majorly recovered to boil water which drives the steam turbine to produce electricity. The incinerated bottom ash (IBA), non-combustible part of waste inputs, will be separated as recyclable and non-recyclable group. The chemical composition of IBA depends on the original feedstock and the IBA from direct combustion process is assumed to be sent to landfills. The detailed structure of combustion process is shown in Figure 3-2. The central red dotted box represent the WTE plants with combustor, and electricity is considered as the exclusive final product. Blue solid lines shows the flow of energy, while the black solid lines point out the direction of material flows.
The combustion model is based on the calculation of Higher Heating Value (HHV) and Lower Heating Value (LHV). Equation 3-4 calculates the HHV (MJ/kg) based on dry basis, with an average absolute error of 1.45% and bias error of 0.00% (Channiwala and Parikh 2002). Meanwhile, the net energy released value LHV (MJ/kg) is evaluated by Equation 3-5 after evaporating the water content (Banks 2009).

\[
HHV = 0.3491 \cdot C + 1.1783 \cdot H + 0.1005 \cdot S - 0.1034 \cdot O - 0.0151 \cdot N - 0.0211 \cdot Ash \quad 3-4
\]

\[
LHV = HHV - 2.766 \cdot wt \quad 3-5
\]
where $wt$ represents the moisture content in the inflow waste stream

In Channivalas’s research, the C, H, S, O, N, and Ash represent the mass percentages of carbon, hydrogen, sulphur, oxygen, nitrogen and ash respectively. And the value of each element should satisfy the relevant theoretical interval as follows:

$C \in [0\%,92.25\%], H \in [0.43\%,25.12\%], S \in [0\%,94.08\%], O \in [0\%,50\%], N \in [0\%,5.6\%], Ash \in [0\%,71.4\%]$ 

In addition, we choose the coefficient of heat required to evaporate water to be 2.766.

The model turns to show opposite outcomes on the energy potential of incinerating food waste and manure depending on whether the waste inflows get dewatered in pre-treatment process. With 13% moisture content, the heating value of dairy manure was founded around 15.93 MJ/kg (Engler, Capereda, and Mukhtar 2010). Although food waste and manure have high moisture content, we use the higher amount of electricity generated (HHV) from combustion process in the comparative analysis, assuming that the drying process is completed before being treated in the combustion facilities.

### 3.2.2 Landfill-to-Gas Scenario

Landfilling disposed 64% of MSW generation, followed by recycling (28.5%) and by controlled combustion and generation of electricity (7.4%)(Psomopoulos, Bourka, and Themelis 2009). In this paper, 18 active landfill sites are chosen as candidate WTE plants where the landfill gas is collected and used as an intermediate material to generate electricity. An alternative way to utilize landfill gas is to upgrade it into biomethane as fuel. But biofuel production is out of discussion is this paper. In Landfill-to-gas scenario (LFG), the final products are electricity and biofertilizer upgraded from leachate.
However, in order to maximize the environmental benefit of LFG facility, we should pay enough attention on controlling greenhouse gas leakage and ground contamination. The chart below explains the material and energy flow during landfilling process. The central red dotted box simulated the process happened at LFG plants, and the blue solid line represents the flow of energy during the process.

![Flow diagram of the landfill-to-gas system](image)

Figure 3-3 Flow diagram of the landfill-to-gas system

Various models have been developed by previous researchers to simulate the landfill gas generation process. The most common methods include zero-order, first-order, second-order decay model and more complicated saturation kinetics models. For example, SWANA (1997) conducted study on comparing the prediction efficiency of different modeling methods with methane recovery data from 18 U.S. landfills (Vogt and Augenstein 1997). With the highest regression coefficients ($R^2$), simple first-order decay model was proven to be the most accurate.
In the LFG scenario, we also apply a first-order decay model, modified from the most widely used Landfill Gas Emission Model (LandGEM) and IPCC model. The LandDEG model (v.3.02) was released in 2005 by US EPA as an industry standard model for regulatory and non-regulatory landfill projects in the United States. It calculated the methane generation flow rate ($m^3$/yr) with the following assumptions (EPA 1996).

i. Methane generation from the landfill reach its peak shortly after initial waste placement

ii. Methane generation then decreases exponentially

iii. The default methane content from the landfill gas is 50%

iv. Only the parameter “Potential Methane Capacity “reflect the effect of the composition of input wastes on the real application of the final result.

Our LFG model first calculates the cumulative methane generation over the landfills’ lifespan in Equation 3-6 (EPA 1996). The default lifespan of LFG plant is 25 years. Therefore, the annual landfill gas emission is the average methane generation in each year with approximate 57% of methane. For simplicity, we assume that all parameters of the model are constant and identical for all 18 landfill-to-gas plants. The methane generation potential $L_0$ can be calculated from the degradable components of organic solids in the waste stream as Equation 3-7 (IPCC 2006). DOC, short for degradable organic content, measures the organic portion of waste that can be depredated by microbes in the landfill facilities. Usually, it is reported in unit as % wet weight (w/w). In Equation 3-8, 0.15 and 0.05 count for the degradable organic content for food waste and manure, which defined in EPA’s HH-1 Calculation Spreadsheet\(^\text{10}\).

\(^{10}\) http://www.ccdsupport.com/confluence/display/help/Using+Subpart+HH+Calculation+Spreadsheets#UsingSubpartHHCalculationSpreadsheets-UsingtheEquationHH-1CalculationSpreadsheet
Modified first-order decay model

\[ Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0}^{i-1} \left( \frac{M_i}{10} \right) k L_0 e^{-kt_{ij}} \]

\[ L_0 = \frac{DOC \times DOC_f \times 16}{\rho_{CH_4} \times 12} \]

\[ DOC = 0.15 \cdot fraction_{FW} + 0.05 \cdot fraction_{AM} \]

where:

- \( Q_{CH_4} \) = methane production (ton/yr)
- \( i = 1 \) year time increment
- \( j = 1/10 \) year time increment
- \( n = \) the lift time span of a landfill plant, 25 years as default
- \( M_i = \) the annual mass of wastes accepted (ton/yr)
- \( k = \) methane generation rate (yr\(^{-1}\))
- \( L_0 = \) methane generation potential (kg/ton)
- \( t_{ij} = \) age of the \( j_{th} \) section of waste disposed in the \( i_{th} \) year (demical years)
- \( \rho_{CH_4} = \) density of methane gas, the default value is 0.72 kg/m\(^3\)
- \( DOC = \) the portion of degradable organic waste
- \( DOC_f = \) percentage of DOC being digested under landfill condition, default is 0.5
- \( fraction_{FW} = \) the content of food waste in the combined waste stream
- \( fraction_{AM} = \) the content of animal manure in the combined waste stream

Model Parameters

**Methane Generation Rate Constant (k)**. The methane generation rate constant, \( k \), can be affected by waste composition, moisture content, density, pH and other chemical or environmental parameters. For example, higher moisture content will lead to higher \( k \).
value due to its promotion to waste degradation (Machado et al. 2009). The higher k value, the faster methane is generated at a landfill. High methane generation rate also reduces the post-closure period after the landfills being closed.

The value of k for traditional landfills ranges from 0.04 to 0.13 yr\(^{-1}\) while the \(L_0\) ranges from 56 to 77 m\(^3\) Mg\(^{-1}\) (Amini, Reinhart, and Mackie 2012). In their report, \(L_0 = 67\) m\(^3\)/Mg, \(k = 0.08\) yr\(^{-1}\) were suggested for traditional landfills who do not have available LFG generation data. The parameter k differs in two weather conditions of LandGEM model, 0.02 yr\(^{-1}\) for arid condition and 0.065 yr\(^{-1}\) for wet condition.

Three different k value were introduced in IPCC’s first-order decay model for landfills in different climate regions across United States (Table 3-2). Based on the New Jersey rainfall report, we apply k equal 0.05 in this study for all landfill plants. We should notice that the k values are generally defined for all waste composition, not specified for food waste and manure only. If reliable data source is available in the future, the modified model can be updated with any specific k value.

Table 3-2 Methane generation rate constant (k)

<table>
<thead>
<tr>
<th>Average Rainfall (Inches/Year)</th>
<th>(&lt;20)</th>
<th>20-40</th>
<th>(&gt;40)</th>
</tr>
</thead>
<tbody>
<tr>
<td>k = 0.02</td>
<td>k = 0.038</td>
<td>k = 0.057</td>
<td></td>
</tr>
</tbody>
</table>

Source: Landfill Emission Tool Version 1.2, Tab Methodology\(^{11}\).

Potential Methane Generation Capacity (\(L_0\)).

From Equation 3-7, we find that the higher the organic content of the waste, the higher the value of \(L_0\)\(^{12}\). The theoretical value of \(L_0\) in LandGEM model is between 6.2 to 270

\(^{11}\) California Air Resource Board’s Implementation of IPCC’s Mathematically Exact First-order decay model.

\(^{12}\) LFG Energy Project Development Handbook
cubic meters per metric ton of waste. In the co-landfilling process, since food waste tends to have higher organic content than manure, one of our hypothesis is that plant with higher content of food waste disposed will have more potential methane and electricity generation. Unless a specific $L_0$ is provided, our model will calculate $L_0$ value as Equation 3-7 for each WTE plant.

3.2.3 Composting Scenario

\[
\text{Composting} \quad C_xH_yO_z \xrightarrow{\text{yields}} xCO_2 + \frac{y}{2}H_2O + \text{Heat Energy} \quad 3-9
\]

With lower initial investment and regular operational costs as well as controlled GHP emission, large-scale composting is the most widely accepted organic solids recovery option. Composting manure before land application provides benefits such as reducing odors and lowering the risk to contaminate earth and underground water. The chemical reaction occurred during composting process can be simplified as Equation 3-9(Khanal 2008). Carbon in combined waste is primarily mineralized into CO$_2$ and the total mass can be shrunk by at least 50%. The flow chart below shows how the composting system functions. The central red dotted box represents the large-scale composting plants, where compost and electricity are assumed as the final products. The blue and black solid show how the energy and material flow during the treatment.
Aerobic composting is usually operated at ambient temperature between 5 and 35°C. Most degradable organic matter is bio-oxidized in the composter during the first a few days, when a great amount of heat is produced (de Bertoldi, Vallini, and Pera 1983). The average amount of heat calculated by Guljajew and Szapiro was 961 kJ/kg with compost moisture content to be 52.7% (Guljajew and Szapiro 1962). In 1979, Stainforth did research on composting of wheat straw, and he found that the average heat production was approximately 17.6 MJ/kg (Klejment and Rosiński 2008). Collecting the waste heat through the heat exchanger system was found to be able to provide domestic hot water supply and spatial heating at very competitive price, 0.68 and 0.13$ per kWh, respectively (Irvine, Lamont, and Antizar-Ladislao 2010). However, generating
electricity from the collected heat in composing site was considered as inefficient and uneconomical by many researches and engineers. Their major concern included the low efficiency in the heat-exchange system, increase of fuel price and heat lose in air ventilation.

**Model Composting:**

The composting rate is determined by measuring the amount of volatile solids removed at different time point as below:

\[
\log(1 - VS_d) = -0.0114 \cdot t + 4.368
\]

\[
Heat_C = 17.6 \times 10^3 \cdot (1 - wt) \cdot VS_{dc}
\]

Where:

17.6\times10^3: the quantity of heat produced during carbohydrate oxidation. (kJ/kg)

\( VS_d = the \ volatile \ solids \ destruction \ (%) \)

\( VS_{dc} = the \ carbohydrates \ destruction \ (%) \)

For a “well-managed” compost operation, negligible methane may be generated in the composter when there is not enough oxygen in airflow. In Composting scenario, we assume methane will be oxidized and completely converted to carbon dioxide. The pollutants in exhaust air flow are removed through wet scrubber and biofilter before released to the air. The degradability of organic matter is the major factor to influence the composting efficiency. Therefore, the substrate degradation model play a crucial role in modeling the whole composting process. In 2013, Liming Shao et al. published their study on both aerobic and anaerobic digestion process for the treatment of waste activated sludge in China (Shao et al. 2013). According to their study, a linear relationship exists between the digestion time and logarithmic form of total residual efficiency (Equation 3-10). After 40 days, the rate of dissolved organic carbon were
declined gradually under aerobic digestion. The final degradation efficiency of volatile solids reached 66.1±1.6% after 90 days for sludge (Shao et al. 2013). In 2005, E.Klejment and M. Rosinski provided a critical solution to calculate the amount of heat recovered from a composting process and the thermal conductivity coefficient for compost (Equation 3-11)(Klejment and Rosiński 2008). On average, 37.4% of heat was found to come from total bio-oxidation of organic compounds, which is proportional to degradable volatile organic solids removal rate. However, the efficiency to recover heat from composting process is extremely low. In order to keep composting bacteria alive within the proper temperature range, releasing heat directly through ventilation system or fans instead of circulating it has been commonly applied in current large-scale composting facilities in New Jersey. Therefore, we assume significant amount of electricity can hardly be produced from aerobic composting process.

### 3.2.4 Anaerobic Digestion Scenario

\[ \text{organic solids} \xrightarrow{\text{hydrolysis}} C_x H_y O_z \xrightarrow{\text{fermentation}} \frac{x}{2} CH_3 COOH \xrightarrow{\text{methanogenesis}} \frac{x}{2} CH_4 + \frac{x}{2} CO_2 \]

There are three stages during the AD process, including hydrolysis, fermentation and methanogenesis (Equation 3-12)(Khanal 2008). At the first hydrolysis stage, the degradable organic solids are broken down into fatty acids, amino acids, purines and pyrimides. The product are then converted into short chain acids in the fermentation phase. After that, with the activity of methanogenesis bacteria, methane and carbon dioxide will be produced in oxygen-free environment. Former studies showed that the optimal AD occurs with a pH range of 6.5 to 8.0 and temperature of 25-45 °C (mesospheric), 45-60 °C (thermophilic), less than 20 °C (psychrophilic), and the
carbon/nitrogen/phosphorous (C/N/P) ratio at 100-128/4/1 or C/N of 25-32:1 (Speece 1996).

Anaerobic digester is capable of treating waste stream with different solids composition, from low solids to high solids and from clean organic wastes to grey waste (Verma 2002). Besides, most of degraded energy are stored in the methane molecule, which gives anaerobic digestion an obvious merit in energy recovery. The biogas from anaerobic digester can also be used to heat a boiler or to drive a steam turbine engine to generate electricity. With methane as the intermediate products, it is convenient to control the amount and time to produce electricity. The anaerobic digestion process is plotted in the flow diagram 3-5.
Mathematical models have been built to describe anaerobic digestion process since the 1960s (Karim et al. 2007). In 2002, the International Water Association developed a robust model to simulate the anaerobic digestion process based on interactive, dynamic chemistry. However, this model was too complicated for researches who are not professional in biochemistry to use. Therefore, we are encouraged to generalize the digestion process, especially when their composition or related chemical parameters are unclear.

Although some shortcomings exist, model AD was built on the first-order kinetics model proposed by Zhang et al. (2009). The degradation rates of the feedstock are calculated by Equation 3-13 and 3-14, while the prediction methane yield is assumed to be proportional to the predicted VS destruction as Equation 3-15. Then the volumetric methane production rate can be derived from Contois kinetic model in Equation 3-16 (Hashimoto, A.G., and Y.R. 1981). Ode45 routine is used to solve the first two differentiation equations to get VSFW₁ and VSMA₁. The maximum specific growth rate of microorganisms $\mu_m$ (day⁻¹) is defined as linearly dependent on temperature (T), between 20 and 60 °C, in Equation 3-17 (Hashimoto, A.G., and Y.R. 1981). Parlom and Speeces (1983) also claim that solids retention time (SRT) or microbial generation time is inversely related to growth rate and substrate utilization rate. The kinetic parameter $K_{ds}$ in Equation 3-18 is exponentially related with influent VS concentration TS (%) (Hashimoto 1983).

**Model AD: First-order kinetics model**

$$\frac{dVSFW_t}{dt} = \frac{-k_FW*VSFW_t}{K+VSFW_t}$$  \hspace{1cm} 3-13
\[ \frac{dV_{SMA_t}}{dt} = \frac{-k_{AM}V_{SMA_t}}{K+V_{SMA_t}} \]  

\[ M_{end} = (V_{SFW_0} - V_{SFW_t}) \beta_{FW} + (V_{SMAX} - V_{SMA_t}) \beta_{AM} \]  

\[ M_V = \frac{M_{end}V_{S_{total}}}{SRT} \left[ 1 - \frac{K_{ds}}{SRT \cdot \mu_m - 1 + K_{ds}} \right] \]  

\[ \mu_m = 0.013 \cdot T - 0.129 \quad (20 < T < 60 \, ^\circ C) \]  

\[ K_{ds} = 0.8 + 0.0016 \cdot e^{0.06 \cdot T_{S_{total}}} \]  

where:

\( t = \text{digestion time (days)} \)  

\( k = \text{first order rate constant (day}^{-1}) \)  

\( k_{fw}, k_{am} = \text{biodegradation kinetics constant for food waste and animal manure, respectively} \)  

\( K = \text{saturation constant (kg/m}^3) \)  

\( K_{ds} = \text{kinetic parameter, dimensionless} \)  

\( M_{end} = \text{ultimate methane yield (m}^3) \)  

\( M_V = \text{volumetric methane production rate per day (m}^3/\text{day}) \)  

\( SRT = \text{solids retention time (days)} \)  

\( \beta_{FW} = \text{substrate utilization rate for food waste} \)  

\( \beta_{AM} = \text{substrate utilization rate for animal manure} \)  

The kinetic coefficients (\( K_{ds} \)) for cow manure under anaerobic condition is  \( 0.324 \pm 0.0073 \text{kg/m}^3 \cdot \text{day} \) for readily degradable fraction and  \( 0.082 \pm 0.0001 \) for slowly biodegradable fraction (Buendía et al. 2008). The biodegradation kinetics constants for food waste and manure remain the same as those in Zhang’s model, 0.118 and 0.05 kg/m\(^3\) \cdot \text{day}, respectively.

The average specific biogas production was found to be 0.74 m\(^3\) per kg VS destroyed, which is within the range of 0.6 to 1 m\(^3\)/kg \( V_{S_{destroyed}} \) for conventional anaerobic
mesophilic waste activated sludge digestion (Tomei, Rita, and Mininni 2011). The value is evaluated in sequential anaerobic-aerobic digestion, which may be upward deviated from pure anaerobic digestion process. For anaerobic bio-refinery, $\beta_{FW}$ is assumed to be in the range of 0.353 to $0.5 \text{m}^3/kg VS_{destroyed}$ while $\beta_{AM}$ is in the range of 0.356 to $0.41 \text{m}^3/kg VS_{destroyed}$ (Zhang and El-Mashad 2010).

3.3 Model Limitations

There are a few factors can affect the accuracy of the simulation system.

First, chemical composition data are not available for New Jersey waste stream. So the simulation system with generic waste composition causes inaccuracy in modelling and deviation from plant’s real performance. Those strict assumptions about constant waste generation, transportation method, production efficiency also add prediction error in our simulation system.

Second, the generalization of the simulation models makes it hard to prove the synergistic effect of co-digesting food waste and manure. The difference in plant’s generation capabilities in the same scenario majorly depend on the amount of disposal waste, instead of the waste composition. If more parameters are available in operation, the simulation models can be updated in the future to calculate the optimal feedstock ratio for the co-digestion process.

Third, electricity is taken as the primary energy product in direct combustion, LFG and AD scenario. Although we do assume a proportion of heat can be recycled and used onsite, the current simulation system does not calculate the value of CHP, which is possibly more feasible to be utilized by WTE plants, including large-scale composting.
Chapter 4

Data

4.1 WTE plants

The simulation models are sensitive to input parameters, and the prediction accuracy can be improved if accurate model parameters for specific WTE facilities are available, especially in Landfill-to-gas and Anaerobic digestion scenarios. Eighteen operating commercial sanitary landfills are chosen as candidates for our integrated simulation system. The information of those candidate plants is summarized from a variety of databases. The primary source of data comes from EPA’s LMOP database, which provided comprehensive information about landfills with LFG projects. However, the accuracy of these data is limited due to the voluntary data submission process. Therefore, we also double checked all candidate plants with supplementary information from FRS Facility Detail Report (EPA), New Jersey Landfill Database (NJDEP) and landfill list provided by Eco-Complex. In the future work, we can expand our integrated system to include more potential plants and compare the performance of smaller decentralized remote plants to larger centralized plants. The figure below locates all candidate WTE plants on the New Jersey map. Meanwhile, the detailed information about those eighteen plants can be viewed in Appendix 1.
In the past decades, New Jersey had more than 400 landfills, most of which are small, privately operated sites. Municipal solid waste is the most common type of waste disposed in landfills. In 2010, New Jersey generated over 22 million tons of solids waste and the total MSW reached about 9.8 million tons (Rutgers and EcoComplex 2007). An increasing trend of solid waste generation per person has been observed in New Jersey from middle 80s\textsuperscript{13}. The largest component of MSW generation and recovery are organic materials, in which food waste is the largest proportion of discards after MSW recovery (Environmental Protection Agency 2014). Figure 4.2 shows the breakdown of MSW generated and discarded, by material in 2012.

\textsuperscript{13} http://www.nj.gov/dep/dsr/trends/pdfs/solidwaste.pdf
New Jersey also used to receive large amounts of waste from neighbor states, mostly from Pennsylvania and New York. Up until early 1980s, an average amount of 12 million tons of waste were treated in New Jersey per year, while in present, 37% of solid waste are transported out of state for disposal. In our analysis, we assume that there was no import or export of waste from or to the outside of New Jersey. All food waste and manure are collected from source origins and transported to the nearest WTE plants.

4.2 Food Waste

Food waste (FW) includes waste from food processing factory, pre- and post-consumption leftovers from both residences and commercial establishments, for example, retail stores, hospitals, restaurants and school cafeterias. Since 2008, New Jersey began to generate more food waste than combined glass containers, aluminum cans and
newspapers per year, and only 2.5% are diverted from landfills. EcoComplex did survey study on food waste generation in Mercer County, which expanded the report Assessment of Biomass Energy Potential in New Jersey in the 2007 (Arnold G. Mercer and P.E. 2013). They claimed that the ratio of total Food waste to MSW is 13.9%, slightly different from EPA’s national estimate (12.7%). On average, six million tons of MSW are generated in New Jersey per year, therefore, approximately 0.78 million tons belongs to food waste.

According to the US Census Bureau’s FactFinder, we can get the population and land area of all municipalities in New Jersey. Based on the population and county-level MSW data from EcoComplex survey, we calculate the average food waste density in each county. Multiplying by the municipal-level population, it gives us a rough measure on the food waste produced in each municipality (Equation 4-1).

\[
FW_{municipality_i} = \frac{FW_{county_i}}{Pop_{county_i}} \times Pop_{municipality_i}
\]

\[
Pop_{county_i} = Population \ in \ the \ ith \ county
\]

\[
Pop_{municipality_i} = Population \ in \ the \ ith \ municipality
\]

\[
FW_{county_i} = Food \ waste \ generation \ in \ the \ ith \ county
\]

\[
FW_{municipality_i} = Food \ waste \ generation \ in \ the \ ith \ municipality
\]

However, there may be some sources of error in our food generation estimation. First, the percentage of food waste in total MSW is possibly underestimated. Food waste can makes up more than 20%-30% of total wastes disposed in some waste treatment facility. Second, the amount of food waste used in the integrated system may be overestimated or underestimated. On one hand, food waste as inputs could be higher than current estimates.

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14 Solid Waste Management Hierarchy-State of New Jersey
because food waste generation from residential category was not included in EcoComplex assessment. The residential category of waste generator produce over 40% of food waste in United States (Arnold G. Mercer and P.E. 2013). On the other hand, a portion of food waste are discarded or sold to animal farmers before being collected and treated in WTE plants. The higher recycling rate and discarding rate of food waste, the lower amount of food waste goes to the final treatment place. Third, the general assumption on constant proportion of food waste and annual MSW generated would become progressively worse over time. Between 2007 and 2020, NJ’s population is expected to grow by 10%, adding about 1,000,000 more people. Along with the increase in population, MSW is about to increase by 10.55% by 2020 (Rutgers and EcoComplex 2007). A feasible solution is to assume the annual population growth rate as 5.12 %15, which indicates an additional 0.42 million tons of food waste would be generated by 0.44 million more local residents in 2020.

4.3 Animal Manure

Animal manure (AM) or manure is a widely used as nutrient-packed fertilizer for crops, providing a low-cost disposal method for stock farmers. 1.1 billion tons of manure are generated by 2.2 billion livestock in the U.S in 2007 (Cuéllar and Webber 2008). Without proper management, the nutrients can reach water sources and cause waters rich or other organisms’ extinction. Manure management is responsible for 9% of methane emission in the United States, and other pollutant gaseous nitrogen (NO, N₂O or N₂)(Environmental Protection Agency 2013). New Jersey State have enacted regulations as Nutrient Management Plants and Concentrated Animal Feeding Operations to limit the amount of

---

manure that can be spread on farmlands. Hence, farmers have to find other methods to dispose manure off the farm. Manure-to-Energy technology is an attractive option. It can not only remove pathogens in slurry and reduce the total volume of manure, but also provide considerable amount of energy back to the farmers. The energy from animal waste could also help New Jersey to meet its goal of producing 20% renewable energy by 2020.

Figure 4-3 The sources of methane emission in United States


The number of all cattle and calves in New Jersey dropped to 31,000 heads in January 2012 (New Jersey Department of Agriculture 2013). The average annual volatile solids manure production is 3,341.09 pounds for a cattle while 1,165.05 pounds for a pig or hog. And total cattle and calves are responsible for nearly 90.8% of livestock manure generation. Through rough estimation, 114.06 million tons of animal manure need New Jersey farmers to dispose in 2012. Refer to Table 4-1 below for livestock and poultry
population and manure generation. The total volatile solids produced by livestock in each county are obtained from the Equation 4-2, modified from equation in EPA State Workbook 7\textsuperscript{16}.

\[
MA_{\text{county}_i} = \left( \sum_j \text{Livestock Number}_{j,\text{county}_i} \times \text{Animal Mass}_{\text{type}_j} \times VS_j \right) / VS_{\text{MA}} 
\]

\[
MA_{\text{municipality}_i} = \frac{MA_{\text{county}_i}}{Pop_{\text{county}_i}} \times Pop_{\text{municipality}_i} 
\]

Where

\( MA_{\text{county}_i} = \text{total amount of manure produced from livestock population in county } i \text{ (ton/yr)} \)

\( \text{Livestock Number}_{j,\text{county}_i} = \text{Population of type } j \text{ animal in county } i \text{ (head)} \)

\( \text{Animal Mass}_{\text{type}_j} = \text{Typical animal mass for animal type } j \text{ (ton/head)} \)

\( VS_j = \text{Average annual volatile solid production per unit of animal mass of animal type } j \)

\( VS_{\text{MA}} = \text{the average volatile solid content in average animal manure} \)

Table 4-1 Number of livestock on farms and manure generation in New Jersey, 2012.

<table>
<thead>
<tr>
<th>Animal Type</th>
<th>Number of Population (head)</th>
<th>Average annual VS waste production (pound/yr)</th>
<th>Manure generation (pound/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All cattle and calves</td>
<td>31,000</td>
<td>3341.091</td>
<td>103,573,825</td>
</tr>
<tr>
<td>Beef cows</td>
<td>8,000</td>
<td>2,865.2</td>
<td>22,921,600</td>
</tr>
<tr>
<td>Milk cows</td>
<td>7,500</td>
<td>4,909.25</td>
<td>36,819,375</td>
</tr>
<tr>
<td>Steers</td>
<td>4,500</td>
<td>2,064.4</td>
<td>9,289,800</td>
</tr>
<tr>
<td>Bull</td>
<td>3,500</td>
<td>4,126.2</td>
<td>14,441,700</td>
</tr>
<tr>
<td>Heifers</td>
<td>7,500</td>
<td>2,680.18</td>
<td>20,101,350</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Animal Type</th>
<th>Quantity</th>
<th>TS (kg/acre)</th>
<th>Total (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Hogs and pigs</td>
<td>9,000</td>
<td>1,165.051</td>
<td>10,485,440</td>
</tr>
<tr>
<td>Breeding</td>
<td>700</td>
<td>313.1</td>
<td>219,170</td>
</tr>
<tr>
<td>Marketing</td>
<td>8,300</td>
<td>1,236.9</td>
<td>10,266,270</td>
</tr>
<tr>
<td>Total livestock</td>
<td>40,000</td>
<td>2,851.481</td>
<td>114,059,265</td>
</tr>
</tbody>
</table>


Commonly, animal manure are mixed with other organic waste, such as wood chips and stored for a period before being transported to centralized biogas plants in the form of slurry. The state-level estimate for manure generation per farmland acre is 257.39 kg/acre in New Jersey. To measure the municipal-level manure generation, we can estimate animal manure per municipality as the product of average manure collection per person and the city population (Equation 4-3). Limited by the detailed information about animal type, we choose to simplify our estimation by calculating the mean value of manure generation for each municipality.

### 4.4 Chemical Perspectives of Feedstock

The total solids (TS) and volatile solids (VS) of the FW and AM are measured according to standard methods (Awwa 1998). The solids composition and chemical analysis of food waste and manure are shown in Table 4-2, along with references to previous researches. In this study, TS value for food is 25 %, higher than animal manure (15%) on the dry matter basis. The amount of water affects not only the size of reactor in the composting and anaerobic scenarios, but also the energy consumption during the pre-combustion process. Volatile Solids content, especially the degradable VS, is considered as the main source for methane emission from combined waste stream. Thus, the estimation of $CH_4$...
in return, is related to the reduction in degradable VS concentration. The higher VS content of food waste compared to animal manure makes it more desirable for energy production. It can be seen from Table 4.2 that the VS/TS ratio are 93% and 85% for food waste and manure, respectively. The biodegradable COD concentration of food waste is approximately 238 $kg/m^3$ when the density is chosen to be 750 $kg/m^3$. In comparison, the biodegradable COD concentration for manure is less (130.8$kg/m^3$), with density to be 650 $kg/m^3$. 
Table 4-2 Chemical properties of food waste and manure.

<table>
<thead>
<tr>
<th></th>
<th>Food Waste</th>
<th>Animal Manure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Reference</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS (%)</td>
<td>30.90±0.1</td>
<td>Zhang et al.(2007)</td>
</tr>
<tr>
<td>VS/TS ratio</td>
<td>0.853</td>
<td>Zhang et al.(2007)</td>
</tr>
<tr>
<td>COD (kg/m³)</td>
<td>238.5±3.8</td>
<td>Zhang et al.(2010)</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>496.57</td>
<td>Parry (2013)</td>
</tr>
<tr>
<td>Moisture content (w/w %)</td>
<td>50-80</td>
<td>Tchbanoglous (1993)</td>
</tr>
<tr>
<td>Biogas yields (m³/kg VS)</td>
<td>0.5</td>
<td>Gebrezgabher (2009)</td>
</tr>
<tr>
<td>Heat Content (MJ/kg)</td>
<td>21-25</td>
<td>EIA (2005)</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------</td>
<td>------------</td>
</tr>
</tbody>
</table>

## 4.5 Model Parameters of Cost-benefit Analysis

In our analysis, costs are divided into initial capital investment, as well as operation and management costs. Because of the lack of data, the calculation of costs and revenues are simplified and assumptions on parameters are derived from published data in previous researches and industrial reports.

Direct combustion plants require a large initial capital investment and depend on factors such as waste quality, size, and location. According to Waste Technology Data center, a combustion plants dealing with 50,000 tons of MSW per year costs about 25 million as initial investment, equivalently, $500 per throughout ton (DEFRA 2007). The average annual capital cost for direct combustion is obtained from Dominic Hogg’s study on costs for municipal waste management in Europe, which ranges from €34.58 to €37.08 per ton (Hogg 2001). The initial capital cost is around 3.76 million for a 15-year LFG project with 3 MW power generation capability, defined by EPA LMOP’s LFGcost-Web V2.0.\(^\text{17}\)

In this study annual capital cost is chosen to be €17.81 per ton per year or $1100-1300 per kW annually generated (Hogg 2001). After currency conversion, the annualized cost of combustion is $49.01/ton, twice the amount cost by landfill, $24.36/ton on dry basis. According to Renkow and Rubin (1998), total net cost for MSW composting ranges from $43 and $54 per ton of MSW processed (Renkow and Rubin 1998). Composting Council of Canada published the cost ranges of large-scale composting plants, assuming a

minimum of 50,000 throughout tons per year. For Enclosed Windrowing composting plant, the initial capital cost is between $100 and $150 per throughout ton. Meanwhile, the initial capital cost for In-vessel aerobic composting ranges from $300 to $500 per throughout ton\(^{18}\). In this study, the annual capital cost is chosen to be $10.2/ton, using data from Steutevillie’s study (Steuteville 1996). In order to make fair comparison with other technologies, we converted the value to $13.6/ton on 2010’s currency base. It should be noted that anaerobic digestion may not be quite appealing, with an approximate initial cost up to $561, or even $600 per annual ton of capacity\(^{19}\) (Moriarty 2013). The annualized capital cost is set to be $54/ton using current anaerobic digestion technologies (EIA 2010a, Rapport et al. 2008). Economic scale may be achieved for large-scale anaerobic digestion, which is still under research and development. Table 4-3 shows the average annual capital cost in each scenario.

Table 4-3 Average annual capital costs for WTE facilities

<table>
<thead>
<tr>
<th>Technology of WTE facility</th>
<th>Capital Cost ($/ton)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Combustion</td>
<td>49.01</td>
<td>Rob van Haaren (2010)</td>
</tr>
<tr>
<td>Landfill</td>
<td>24.36</td>
<td>Rob van Haaren (2010)</td>
</tr>
<tr>
<td>Composting</td>
<td>13.6</td>
<td>Steuteville (1996)</td>
</tr>
<tr>
<td>Anaerobic Digesting</td>
<td>54</td>
<td>Rapport et al. 2008</td>
</tr>
</tbody>
</table>

The ranges of O&M cost are referred to Salman Zafar’s study about eight different WTE technologies, including pyrolysis, gasification and etc. However, we believe Salman’s estimate for O&M is too high of AD is too high, so we choose the value to be $48/ton for anaerobic digestion (Rapport et al. 2008, Whyte and Perry 2001, Moriarty 2013). Table 4-4 shows that range of O&M costs for the four scenarios. In the following

\(^{18}\) http://www.compost.org/pdf/compost_proc_tech_eng.pdf
\(^{19}\) Biogas%20AD%20Market%20Report%20March%202013.pdf
economic analysis, we take the mean value of each cost range as the unit cost, except for the AD facilities.

Table 4-4 Average annual O&M costs for WTE facilities

<table>
<thead>
<tr>
<th>Technology of WTE facility</th>
<th>O&amp;M Cost ($/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Combustion</td>
<td>80-120</td>
</tr>
<tr>
<td>Landfill</td>
<td>10-30</td>
</tr>
<tr>
<td>Composting</td>
<td>30-60</td>
</tr>
<tr>
<td>Anaerobic Digesting</td>
<td>60-100</td>
</tr>
</tbody>
</table>


The most important source of income for waste management facilities is the price they charge to dispose waste from customers. It is mainly used to cover the hauling and treating waste at a disposal facility and commonly known as the tipping fee. Due to the relatively lower tipping fee charge, New Jersey has kept importing and disposing waste from adjacent states. According to the waste management industry, the average tipping fee in New Jersey is $76.52 per ton, ranging from $59.5/ton to $99.5/ton (Table 4-5). In Comparison, New York and Pennsylvania’s tipping fees, average $ 86.3 per ton and $75.96 per ton.

At the same time, we should notice that different tipping fees may exist at a facility for distinct types of waste material. In our analysis, tipping fee use the average fee charged by New Jersey landfills to dispose Type 10 waste, defined as the municipal waste collected from residents, businesses and institutions\(^\text{20}\). To make the tipping fee revenue comparable for each WTE technology, we assume that the unified tipping fee is $50/ton for all plants in four technical scenarios.

### Table 4-5 Tipping fee for WTE Facilities in New Jersey

<table>
<thead>
<tr>
<th>County</th>
<th>Tipping Fee ($/ton)</th>
<th>Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic</td>
<td>66.09</td>
<td>ACUA</td>
</tr>
<tr>
<td>Burlington</td>
<td>75.06</td>
<td>Burlington County SLF I, II, III</td>
</tr>
<tr>
<td>Cape May</td>
<td>67.25</td>
<td>Cape May County SLF</td>
</tr>
<tr>
<td>Cumberland</td>
<td>59.54</td>
<td>Cumberland County SLF</td>
</tr>
<tr>
<td>Middlesex</td>
<td>69.00</td>
<td>Edison Township SLF, Middlesex County SLF, Industrial Land Reclaiming</td>
</tr>
<tr>
<td>Gloucester</td>
<td>84.34</td>
<td>Kinsley’s LF</td>
</tr>
<tr>
<td>Sussex</td>
<td>96.00</td>
<td>Hamm’s LF, Sussex County SLF 1-E</td>
</tr>
<tr>
<td>Monmouth</td>
<td>73.85</td>
<td>Monmouth County SLF</td>
</tr>
<tr>
<td>Ocean</td>
<td>71.21</td>
<td>Ocean County LF</td>
</tr>
<tr>
<td>Camden</td>
<td>99.50</td>
<td>Pennsauken LF</td>
</tr>
<tr>
<td>Salem</td>
<td>59.5</td>
<td>Salem County SLF</td>
</tr>
<tr>
<td>Warren</td>
<td>96.00</td>
<td>Warren County LF</td>
</tr>
<tr>
<td>Bergen</td>
<td>76.00*</td>
<td>NJMC 1-E</td>
</tr>
</tbody>
</table>

Source: Atlantic County Utilities Authority, New Jersey (2013)

* indicates that the value is average value

Another important revenue source of waste-to-energy technology comes from the resale of upgraded solid leftover as bio-fertilizer. However, no valuable leftover is assumed to be collected from the direct combustion process. Except incineration scenario, the average price of compost and digestate from composting, landfills and AD scenarios was estimated based on the national fertilizer price. The unit price of compost and digestate in our analysis are significantly higher than previous studies. For example, Hoornweg, D. et al. stated that the price of final compost is between $40/ton to $50/ton in India (Hoornweg, Thomas, and Otten 1999). Rob van Haaren claimed the price for selling compost ranged from $10 per ton to $31 per ton in US (van Haaren, Themelis, and Barlaz 2010). We assume that the residue solids (compost or digestate) have a resale value of $ 80/ ton based on the average mixed fertilizer retailing price in northeast United State.
However, we still believe the resale value of digestate were underestimated because the price of fertilizer has always been increasing in recent years.

The third source of income comes from the supply of environmental-friendly electricity to local communities. New Jersey Renewable Portfolio Standard requires that 22.5% of electricity sold in the state come from renewable energy sources by 2021, with 5 percent coming from biomass (Wiser 2008). According to U.S. Department of Energy, the average site energy consumption by New Jersey homes reached 127 million Btu per year\(^{21}\). A typical New Jersey household consumes about 8,902 kWh electricity per year, with an average family size of 2.73 persons. With a higher demand for heating, New Jersey homes need to pay about $3,065 per year as annual energy expenditure, which is 33.96% higher than the national average (RECS 2009)\(^ {22}\). Our study assumed that WTE facilities in New Jersey could earn $0.15/kWh from the sale of electricity to the local grid and pay $0.0998/kWh if purchase electricity from the local power utilities (EIA 2010b).

\(^{21}\) http://www.eia.gov/state/print.cfm?sid=NJ

Chapter 5
Economic Analysis

This section introduces cost-benefit analysis to evaluate the economic value of different waste-to-energy management processes. Generally, the cost of green electricity generation from waste can be impacted by technical performance, feedstock quality, regional location, tax reduction, size of the plant and etc. Because of the lack of detailed data, costs are simplified as combination of initial capital investment cost and operating and maintenance (O&M) cost. Economic benefits are measured as the sum of the tipping fee revenue, along with sales revenue from net electricity generation and final digestate as bio-fertilizer.

To construct the cost-benefit analysis, several general assumption are made as follows:
1. The design specifications are identical for plants in one scenario regardless of the location, except the capability. In addition, the unit cost and income value only differ across different scenarios.

2. All cost and benefit are scaled on a one-year basis, reducing the impact of market inflation and money value across plant’s life-span. The unit cost and sale price are referred to the actual market information and former studies as discussed in Section 4.5.

3. There is no difference in transportation cost among all four scenarios. Without enough data to estimate the cost of maintaining transportation vehicles and the salary paid to truck drivers, the total transportation cost is only calculated as a portion of O&M cost.

The annualized capital cost, O&M and revenues are evaluated in the following subsections in order to assess the economic feasibility of each WTE technology. Net
Income is used as the standard for comparison and the final comparison is in the unit of $/metric ton of combined waste.

5.1 Capital Costs

Capital cost is defined as the initial capital expenditure invested in establishing any project. Normally, it is one of the major costs and depends on such factors as equipment costs, interest rates, and cost-recovery periods (EIA 2010a). WTE technologies are more capital-intensive than traditional electricity generation technologies using non-renewable fuels. The levelized cost of the conventional coal-based plant is about $50/MWh while the levelized cost associated with biogas power is projected to be $70/MWh\(^2\).

The average capital costs for each WTE technology are introduced in Table 4-3, summarized from several previous researches. The values presented in the Table should be treated as the annualized capital cost, from which the initial capital investment could be derived. Based on the table, composting has the lowest total initial capital cost among four WTE technologies. However, it may lost this advantage when comparing capital cost based on the amount of electricity generation or waste treated. The initial investment for a waste combustion facility is close to the highest cost of an anaerobic digestion plant. Municipalities with limited space availability and low environmental regulations may still find combustion is a logistically feasible option.

In our analysis, total capital cost is computed as the product of average annualized capital cost per ton and the amount of combined waste disposed in one WTE plant (Equation 5-1). The annualization factor is calculated based on a discounted cash flow analysis, which takes the value of money into consideration (Equation 5-2). The typical WTE facility has

\(^2\) http://en.openei.org/apps/TCDB/
default 25 years operation period and 10% discount rate. Given the annual throughput and annualized ratio, the initial capital cost for the same facility varies across different scenarios (Equation 5-3). Meanwhile, we can also calculate the dollars per ton for the initial capital investment divided by the total tonnage processes in the plant’s lifetime. The hypothesis about enough treatment capacity indicates no incremental investment for candidate WTE facilities throughout their lifespans. However, it is unlikely that the increasing demand for waste disposal would not result in any additional cost for infrastructure reconstruction in the real world.

\[
Total \ Capital \ Costs_{WTE_i} = Average \ Annualized \ Capital \ Cost_{WTE_i} \times Weight_{combined \ wastes} \tag{5-1}
\]

\[
Annualization \ Factor = \frac{r(r+1)^{PL}}{(r+1)^{PL}-1} \tag{5-2}
\]

where \( r = annual \ interest \ or \ discount \ rate \ paid \ over \ the \ lifetime \ of \ the \ plant; \)

\[
PL = the \ lifetime \ of \ the \ WTE \ plant
\]

\[
Initial \ Capital \ Cost_{WTE_i} = \frac{Annualized \ Capital \ Costs_{WTE_i}}{Annualization \ Factor} \tag{5-3}
\]

5.2 Operating and Maintenance Costs

Operating and Maintenance costs represent the continuous expenditure to operate and maintain a facility until the end of its lifetime. WTE facility cannot function well unless all O&M cost are considered. Usually, Operating and Maintenance costs are divided into fixed and variable costs. Fixed O&M cost is constant with plants’ capabilities and includes labor salary, equipment maintenance and materials, overhead, tax, etc. Variable O&M cost, in comparison, depends on the amount of waste that is disposed. Energy consumption during the process, repair and other maintenance expense on haulers are treated as variable O&M cost.
Transportation makes up one of the important expenditures and direct energy outputs in the whole waste management process. Therefore, transportation distance and fuel consumption are key factors in determining the economic feasibility of a WTE project. In this study, transportation distances are measured as the minimal geographic distances, with assumption that wastes in each municipality are transported to their nearest WTE plant. To make the corresponding fuel consumption costs comparable, transportation distances remain the same across different process scenarios. With a fixed average distance to biorefinery plants and constant waste generation rate, transportation costs vary only due to the fuel price fluctuation. However, fuel consumption in transportation represents only a minor source of transportation costs. There are vehicle maintenance fee, salary for drivers, administration fee and taxes that affect the total transportation cost. For the lack of real cost parameters, transportation cost will not be calculated as an independent cost source in the later cost-benefit analysis. Instead, it is treated as one component of Operating and Maintenance Cost. The average transportation distance and carbon dioxide generation during the transportation are listed in Appendix 2, along with the average geographic distance from their nearest municipalities.

According to Table 4.5, the O&M cost of direct combustion plant is the highest, majorly due to utility expense on pre-processing steps and air control system. In contrast, landfill plant pays least on regular operation. According to EIA’s report, O&M cost in landfills is approximately $28 per ton of waste processing. The O&M cost of the full-scale AD plant is proposed to be $60-100/ton, which is the second highest among different scenarios. Utilities consumption for keeping reactor at a required temperature is one of the major reasons for driving the O&M cost high for anaerobic digestion. We assume that lower
O&M can be achieved if a larger portion of the biogas and CHP are able to be recycled to heat the digester instead of purchasing fossil fuel from outside. For large-scale composting, labor and land lease are the biggest contributors to its O&M expenditure, 55% and 23%, respectively (van Haaren, Themelis, and Barlaz 2010)

With the average O&M cost derived from Salman Zafar’s study in 2011, the annual O&M expense in each WTE scenario can be computed using Equation 5-4. A linear relationship is assumed between the total O&M costs and the amount of combined wastes treated at a given plant site. Unlike capital cost, O&M costs cannot be annualized through the facility’s entire lifetime, making it much higher than the capital cost at the one-year period.

\[
O&M\ Cost = Average\ O&M_{WTE_i} \times Weight_{combined\ wastes}
\]

5.3 Tipping fee

The shortage of landfill space is also contributing to the escalation in tipping fee. The range of tipping fee for landfills to dispose a ton of MSW in North East is between $45 and $85, which are much higher than the other regions of United States (Abbott, 2008). For WTE plants, tipping fee is one of their primary income sources, especially when their electrical sales revenue is not significantly high. This also provide an explanation why WTE plants were reported to have higher tipping fees than traditional landfills.

Despite the variation of tipping fee charged by WTE plants, we assumed that the total tipping fee revenue is positive related to the amount of total waste transported to each plants and the unit tipping fee charged in each county. The calculation is expressed in Equation 5-5.

\[
Tipping\ Fee\ Revenue = Tipping\ Fee_{WTE_i} \times Weight_{Combined\ wastes}
\]
5.4 Revenue from Digestate Resale

WTE technologies is efficient in reducing the volume of solid waste. Our study found that total waste volume can be reduced by 50-90% and VS removal are typically in the range of 50-70% of original input waste. The liquid digestate, one by-product from WTE process, can be resold as bio-fertilizer while the solid digestate is either composted or used as bedding material. The solid waste leftover is the combination of both the remaining volatile solids and the non-degradable components in the input waste (Equation 5-7). The total revenue from selling digestate as bio-fertilizer equals average price times the amount of residual solids after WTE process, shown in Equation 5-6.

\[
Revenue_{\text{resale of residue solids}} = Price_{\text{fertilizer}} \times Weight_{\text{residue solids}} \quad 5-6
\]

\[
Weight_{\text{residue solids}} = (VS_{\text{remain}} + VS_{\text{non-degradable}}) \times Weight_{\text{combined wastes}}
\]

\[
= \left[ (1 - VS_{\text{removal}}) \times \frac{VS}{TS} \times TS + (1 - \frac{VS}{TS}) \times TS \right] \times Weight_{\text{combined wastes}} \quad 5-7
\]

5.5 Revenue from Green Electricity Sales

From European landfill statistics, we can find that 1.7-2.5 million m³ of collected methane is expected to be generated from 1 million dry tons of MSW, enough to fuel a gas engine producing 6500 to 10,000 MWh of electricity per year\(^{24}\). With 1.8 million wet tons of food waste and manure estimates, the potential energy recovery calculated is at least 7,727.94 MWh annually, replacing 647.23 ton of fossil fuel consumption. Revenue from selling electricity can bring millions of dollars to WTE plants, especially for anaerobic digester. The revenue from selling green electricity can be calculated as the

\(^{24}\) http://www.clarke-energy.com/gas-type/landfill-gas/
electricity generation from WTE process times the retail price of electricity in New Jersey (Equation 5-8).

\[
\text{Green Electricity Sales} = \text{Electricity Generation}_{WTE} \times \text{Average Retail Price}_{\text{green electricity}}
\]

5.6 Results

5.6.1 Net Income Value

Generation capability and economic value are two important factors that can influence the choice of waste management methods. Capital investment, environmental impact, potential output, and logistics of transportation also needs to be considered in order to optimize overall social benefits. With the estimation of cost and benefit components, we can investigate the financial feasibility for each WTE technology. Net income, the difference between benefits and costs, is chosen as the decision criteria (Equation 5-9). Positive net income indicates that the revenue earned by WTE plants can cover the amount of expense in both construction and operation processes. Negative net income, to some extent, will weaken the social benefits of converting waste into energy supply source.

\[
\text{Net Income} = \text{Total Revenue} - \text{Total Costs} = (\text{Tipping Fee} + \text{Digestate Resale} + \text{Electricity Sales}) - (\text{Capital Cost} - \text{O&M Cost})
\]

Figure 5.1 shows the net income for dealing food waste and manure in different types of WTE plants. The final comparison is calculated as $/ ton of feedstock. The landfill-to-gas method is proven to be the most prevalent and cost-effective method to utilize food waste and manure. Further, it also has the lowest operating and maintenance requirement. In the contrary, direct Combustion is the most expensive method to operate. Because of the high moisture content in combined wastes, a significant amount of fossil fuels are needed in
the pre-dewatering process and maintain a high burn temperature. Therefore, a more efficient alternative option is to incinerate food waste and manure together with other solid wastes containing low moisture content, such as paper, yard waste. Composting and reselling compost should be encouraged as the other cost-effective way to treat and reutilize organic wastes in New Jersey. However, anaerobic digestion, with the highest electricity generation, ranks the third place when consider primarily about net income per ton. The significant capital investment and utility expense can explain why benefit from tipping fee and electricity sales cannot cover the total costs. Considering the increase of land scarcity and the benefits from reducing global warming, anaerobic digestion is still feasible in urban regions.

![Figure 5-1: Net income for potential WTE plants in New Jersey](image)

**Figure 5-1** Net income for potential WTE facilities in New Jersey

### 5.6.2 Cost and Revenue Structure

The structure of total costs and revenues provides a way to understand their impact on net income. The component of total cost are displayed and compared in Figure 5.2, where we
can see that O&M cost is the dominant part of total cost for the four WTE technologies. In the first year, the total install cost will definitely bring huge amount of negative cash outflow from all WTE facility. After annualized over the plant’s lifespan, 25 years as default, the huge expenses on constructing WTE facilities become less important, compared to the daily expense on regular operation. From Equation 5-2, we know that longer plant life and the lower discount rate tend to drive the impact of capital cost down even further. With the assumption that operation costs decrease as the annual disposal capacity of the facility increases, we believe large-scale of WTE facility has more advantage when economics of scale could be achieved.

Based on the comparison of revenue composition in Figure 5-3, we found the sales of green electricity is far from being able to cover the total cost. The tipping fee revenue is the largest source of income, normally over 60% of total revenue for all four WTE technologies. For waste incineration and large-scale composting, tipping fee is almost their exclusive income source. Revenue from selling upgraded compost or digestate as fertilizer also brings significant amount of income. The higher average retail price, the larger part of the total revenue will be contributed by bio-fertilizer resale. For example, if the price increased from $80/ton to $239/ton, it will take 35% of total revenue and anaerobic digestion will become more profitable.
Figure 5-2 Components of total costs for WTE facilities.

The trade-offs between costs and benefits has not been well defined on case by case basis. Therefore, the best system for particular community or region must also takes the regulatory environment, market specification and growth in waste stream into consideration. According to SWANA’s Applied Research Foundation, investment spent
on WTE facilities could remain within the communities and WTE technology is a great option for communities seeking the sustainable way to manage waste. Although many questions remained with regard to the high total cost, anaerobic digestion appears to be the most practical, economical way to treat food waste and manure and provide energy in New Jersey. We will seek to answer the possible methods to driven down the average costs in the forthcoming research.

5.6.3 Internal Rate of Return (IRR)

Besides the Net Income, from the investor perspective, the efficiency and financial performance of WTE plants can also be reflected by the Internal Rate of Return (IRR). IRR is defined as the discount rate at which the Net Present Value (NPV) of an investment asset is zero (Equation 5-10) (Van Passel et al. 2013). IRR can reflect the actual ROI without requiring assumptions about discount rate. The calculation of IRR is expressed as Equation 5-10.

\[ \sum_{t=1}^{PL} \frac{CF_t}{(1+IRR)^{t-1}} = NPV = 0 \]

where \( CF_t \) is the cash flow of each WTE in year t, simply represented by the Net Income value at year t. The default plant life of WTE facilities are 25 years and we assume no incremental investment is required after in operation.

If the IRR value is larger than an established minimum acceptable rate of return, the investment of WTE projects would be considered as profitable. WTE project becomes more attractive with higher IRR value, 32.06% on average. In the Direct Combustion Scenario, it’s not meaningful to calculate IRR with Net Present Value of WTE facilities
to be always negative during the plants’ lifespan. Figure 5-4 below shows the IRR value in Landfill-to-Gas, Composting and Anaerobic Digestion scenarios.

![Internal Rate of Return for WTE plants in New Jersey](image)

**Figure 5-4 Internal rate of return (IRR) for WTE facilities**

From Figure 5-4, we can see that composting becomes the most attractive WTE project to utilize food waste and manure from the private investors’ perspective. It provides us another way to understand WTE plant’s profitability compared to the Net Income analysis. Among all WTE technology with positive yields, anaerobic digestion has the lowest average IRR value, similar to the Net Income analysis. Especially, for Edison Township SLF, implementing anaerobic digestion leads to negative Internal Rate of Return (-5.69%), which is quite undesirable for investors. Based on IRR value, Landfill-to-Gas still shows significant advantage, considering about its lowest cost requirement and strong earning power. Generally, with investment in WTE projects, private or public investors are likely to gain access to reliable long-term returns at low risk.

**5.6.3 Electricity supply**
New Jersey consumed 79,179,000 Megawatt-hours (MWh) of electricity in 2010, but nearly one third of its electricity was supplied by generators in other states. Nuclear and natural gas-fired represent over 90% of net electricity generation. About 816,317 MWh were generated from biogenic municipal solid waste, landfill gas, sludge waste, agricultural byproducts, other biomass liquid or gases. As indicated by Table 5.1, the number of household can be supplied is positively related to total electricity generation and revenue from selling green electricity. Although the total number of household can be supplied represent only less than 1% of New Jersey population, the amount of electricity generation can reach 10% of total electricity generation from biomass resources.

We also believe the total electricity generation and sales revenue are underestimated, since the food waste data used in this study haven’t taken food waste from food industry into account yet. If all of the food waste and animal manure generated in New Jersey was anaerobically digested, enough electricity would be generated to power over 15,000 local family for one year.

Table 5-1 Summary of electricity sales revenue in WTE facilities.

<table>
<thead>
<tr>
<th>WTE Technology</th>
<th>Total electricity Generation (MWh)</th>
<th>Total electricity Sales Revenue (million $)</th>
<th>Number of Household Supplied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Combustion</td>
<td>7,719.41</td>
<td>1.157</td>
<td>867</td>
</tr>
<tr>
<td>Landfill</td>
<td>12,764.26</td>
<td>1.914</td>
<td>1435</td>
</tr>
</tbody>
</table>

25 http://www.eia.gov/state/print.cfm?sid=NJ
Hurricane Sandy landed New Jersey on Oct 29th, 2012 and caused catastrophic damage and power outage for over 2.6 million people. The peak number of total customers out of service reached about 2,052,724, account for 51% of population (Sullivan and Uccellini 2012). It took 10 days to restore power to 95% of affected customers and Sandy caused more than $ 68 billion dollars damage. The demand for electricity fell about 18% after Hurricane Sandy made landfall. It was mainly due to extensive retail and residential customers’ outages. Table 5-2 shows that retail supply of electricity in New Jersey has dropped significantly in October 2012, compared to the former years. Therefore, it sounds promising for WTE facility to supply local residents under extreme weather conditions when traditional power companies out of business. During natural disaster, the demand for electricity to maintain daily life is sure to be lower than during normal days. If we assume that electricity consumption by household decrease by 50%, then with all eighteen WTE plants operating, over 50,000 people would not have to experience power outage after Sandy landed.

Table 5-2 Retail sales of electricity in New Jersey, by End-Use Sector, Million Kilowatt-hours (2009-2012)

<table>
<thead>
<tr>
<th>End-Use Sector</th>
<th>October, 2009</th>
<th>October, 2010</th>
<th>October, 2011</th>
<th>October 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Sector</td>
<td>5,711.81332</td>
<td>5,810.15976</td>
<td>5,645.66915</td>
<td>5,498.35182</td>
</tr>
<tr>
<td>Residential</td>
<td>1,891.46646</td>
<td>1,905.1548</td>
<td>1,880.0746</td>
<td>1,847.4817</td>
</tr>
</tbody>
</table>
5.7 Sensitivity Analysis

Cost-benefit analysis (CBA) is preferred by economists to choose sustainable projects and relocate resources within society. But, it is hard to draw conclusions with uncertainty in input data and assumptions in methodology. Therefore, it is necessary to evaluate the effect of changes in those factors on the measure of final results. In this subsection, we studied the effects of changes in the following factors:

- Changes in the Interest Rate and Amortization Period
- Changes in the Price of Bio-fertilizer
- Changes in the Tipping fee

5.7.1 Changes in the Interest Rate and Plant’s Lifetime

The structure of WTE facilities shows that annualized capital costs have a strong impact on the sign of final net income. Interest Rate/discount rate \( r \) and the plant’s Lifetime (PL) affect the annualized capital costs, thereby having potential to change the profitability of each WTE alternative. Without published transaction record, there is little data to quantify interest rate for renewable energy debt in New Jersey. We assume interest rate for debt on waste-to-energy projects could fluctuate with the change of financing environment in local commercial market, from 5% to 15%. The results are presented in Figure 5-5.
Given certain plants’ lifetime, the net income proportionally decrease in all WTE scenarios along with the increase in interest rate. It seems not quite appealing when calculated in the unit of dollars per ton, but for one plant with thousands of combined wastes to dispose, the change in interest rate by 5% can lead to hundreds of dollars difference in annual net income.

In the previous CBA analysis, the amortization period is treated as the plant’s lifetime, which is 25 years as default. However, the lifetime of landfill-to-gas and combustion facilities could be as long as 30 years in current industry. And the amortization periods of debt financing may be shorter or longer than the plant’s lifetime, depending on the regulatory support and initial investment option. Therefore, we assume that the amortization period for WTE plants range from 10 to 30 years. A non-proportional increasing trend in net income is observed in Figure 5-6. With a constant interest rate, such as 10% as default, net income will continue increase along with the raise of amortization period for all WTE facilities. Although the net income for direct combustion
is always negative with any amortization period, the longer amortization period still have larger impact on the change of Net Income. From the lower two trend lines, we can also find that the slop of the trend decrease when the interest payment add to the cost in long run.

Figure 5-6 Net Income of WTE technology with different amortization periods

Since both interest rate and amortization period has influence on the net benefit performance of WTE plants, the changes in both factors are more effective in changing the net income than each individual factor. We can predict that WTE plants could get higher annual profit when the interest rate for debt is lower and the amortization period is longer.

5.7.2 Changes in the price of bio-fertilizer

In scenario Landfill-to-Gas, composting and anaerobic digestion, one important final product is the upgraded solid leftover as bio-fertilizer. And from previous subsections, we already know that higher price of bio-fertilizer is linear with the increase in digestate
sales revenue. The higher amount of digestate generated as final byproducts, the higher the annual net income. One dollar increase in bio-fertilizer price could lead to net income increase in composting, Landfill-to-Gas, anaerobic digestion scenario, as $0.27, $0.24, $0.37 per ton respectively. Figure 5-7 explains that how the annual net income changes with the price of bio-fertilizer.

![Net Income with different price of bio-fertilizer](image)

Figure 5-7 Net Income of WTE technology with different bio-fertilizer prices

In direct combustion scenario, net income has no change in value with the fluctuation of bio-fertilizer’s price. The assumption in direct combustion is that IBA cannot be sold as bio-fertilizer, therefore, it has no market price. National Agricultural Statistics Service (USDA) provide historical U.S. farm prices of selected fertilizer from 1960 to 2013. A significant growing trend exist for all selected fertilizer, and at least 26% increase in fertilizer’s price has been observed from the last four years. In our study, the maximum bio-fertilizer price is still lower than most chemical fertilizer, which means they have competitive power in local markets. Although the marketability of promoting bio-
fertilizer is yet uncertain, if we assume the same trend occurs in the sales of bio-fertilizer, WTE faculties still could take the advantage of upgrading the valuable byproducts.

5.7.3 Changes in tipping fee

In previous CBA method, tipping fee revenue is assumed to be the product of currently unit tipping fee, differs by counties located, and the amount of combined waste to dispose. With constant tipping fee in all scenarios, the total revenue for eighteen plants is $144.67 million. From Figure 5-3, we can see that tipping revenue is the most important income source for WTE facilities. Therefore, a growth or drop in average tipping fee will have a significant impact on the profitability of WTE candidates. Figure 5-8 shows the effect of changes in unit tipping fee on the net income in four scenarios, given the amount of waste disposal remain constant.

![Net Income with different tipping fee](image)

**Figure 5-8 Net Income of WTE technology with different unit tipping fees**

Although the net income for direct combustion is still negative with 10% increase in tipping fee, its average net income has increased by 27%. It proves possibility of making
positive profit for direct combustion facility as long as they can charge much higher unit tipping fee than current landfill companies.

In addition, some researchers pointed out that tipping fee for WTE facilities usually higher than traditional landfill facilities, partly due to the higher O&M expenditure and regulatory support. The average tipping fee at waste incinerator was reported to be $85.66 per ton, while it was about $57.32 per ton for landfills.\textsuperscript{26} Survey conducted by ILSR found that tipping fee to cover capital and operational costs of AD projects using food waste is around $60/ton (The Institute for Local Self-Reliance 2010). In this study, we use a unit tipping fee of $44.27 per ton for composting facilities plants, which is close to that reported by Core plant at Cedar Grove (Core Trip Note 2009). With the referred unit tipping fee for different WTE scenarios (Table 5.3), we can find a small change in their revenue structure, as plotted in Figure 5-9.

Table 5-3 Tipping fee for different WTE facilities

<table>
<thead>
<tr>
<th>Technology of WTE facility</th>
<th>Tipping Fee ($/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Combustion</td>
<td>85.66</td>
</tr>
<tr>
<td>Landfill</td>
<td>57.32</td>
</tr>
<tr>
<td>Composting</td>
<td>44.27</td>
</tr>
<tr>
<td>Anaerobic Digesting</td>
<td>60</td>
</tr>
</tbody>
</table>

Figure 5-9 Revenue Structure for WTE facilities with different tipping fee

With an estimated 2.4% annual population growth, New Jersey could have to deal with additional thousands of tons of waste in the coming decades. WTE facilities has the ability to increase tipping fee as the city continue to expand and to compensate the incremental increase in annual expense.
Chapter 6
Conclusion and Future Perspectives

NJ Solid Waste Management Plan, released in 2006, affirmed that an increasing amount of food waste has been generated than the combined wastes of old newspapers, glass containers and aluminum cans in New Jersey. Further research on waste energy recovery is crucial for system building and authority supervision in New Jersey municipalities in both short and long runs. The productivity analysis outlined different options to reduce waste volume and utilize potential energy storage of food waste and manure. While the economic analysis provided convincing proof for local authority to consider about updating existing conventional landfills into more economically and environmentally friendly waste-to-energy plants. Based on this research, the New Jersey municipality is recommended to promote WTE project to reduce environmental footprint while having economic benefits for local communities.

6.1 Conclusions

Based on the analysis in the previous sections, we have gained a brief understanding about the WTE technology in converting food waste and manure into energy and bio-products that can be reused in our society. Based on different criteria, a WTE technology may be superior to others. Some of the overall conclusions are presented as follows:

1. Anaerobic digestion is generally favorable over composting according to our study with regard to total and net energy generation. Less net income value, on the other hand, shows the opposite result. But there are some income has not been discussed in our
framework, which may discredit our current conclusion. For example, the grant support and tax reduction for anaerobic digestion plants from government agencies.

2. Neither directly combustion nor composting, in general, seems to be an attractive methods if the main subjective is to generate green electricity and reduce toxic gas emission. However, landfill-to-gas has great advantage in operation with the lowest investment and operation cost needed in the upgrades. Meanwhile, the least preferred technology to generate electricity from FW and AM is the direct combustion.

3. O&M cost, instead of total capital cost, is proven to be the most important factor that prevent WTE facilities from generating positive revenue. The expenditure of regular operation are majorly affected by the amount of waste in stream instead of distance. Similar relation applies on the capital cost, either. What’s more, according to our analysis, the transportation costs on fuel consumption only account for a small portion of total O&M cost, which means that the location of WTE plants is not our first concern. But it would be beneficial to avoid recruiting extra full-time works when volunteer and part-time employees are available.

6.2 Limitations and Future Research

From the integrated system, we can get a comprehensive understanding of costs versus benefits in converting food waste and manure into energy. However, the calculations have been made for simulated situation instead of realistic situation with many critical assumptions. Many further research needs to be conducted, such as collecting input data and crucial parameters from the real world.

1. Cost-benefit analysis might not be easily comparable across countries since the cost structure and environment concerns can be very different internationally. Therefore, our
results are slightly dependent on local economic structure and the availability of facilities. Site-specified assessments should also be tried in order to grasp more information about the impacts in each WTE scenario.

2. The models in the integrated system do not depend on waste fraction, except the theoretical model and combustion model. So, we cannot prove the synergic effect of mixing food waste with animal manure.

3. It is also important to notice that more robust results can be reached if exact input data is available. In our study, we only compared WTE technologies in independent scenarios. It is also interesting to analyze the combination of different technologies, such as landfilling with composting or anaerobic digestion with landfilling. Those potential combinations are receiving growing attention and can be the subjective of our further studies. What’s more, our study just focus on two fractions of MSW, food waste and animal manure. It is also reasonable to expect that the methodologies applied can be used to study other waste fractions, such as agriculture residues and forest residues.

4. Some social benefits, such as job creation function, have not been considered. Because it is hard to quantify its money value in order to be included in our economic analysis. From EPA’s reports, 1 job will be created per 10,000 tons of waste to be disposed in landfills or incinerators. And we expected even more jobs can be made in composting and anaerobic digestion facilities.

5. Beside the electricity generation capability and cost-benefit effects, the environmental soundness should also be measured in long term perspective. Global warming, acidification and ozone layer depletion are important effects that WTE technologies need
to be aware of. By quantifying the environmental effect, we may also come to different conclusions about the most preferable methods to treat waste in New Jersey.

6. Potential revenue from carbon credit sales are not included in the cost-benefit analysis. Although it provides an additional revenue source to drive down the operating cost of WTE facilities, the market value of carbon reduction has not been clearly defined in United States.

6.3 Recommendations

Despite the significant capital and O&M costs, WTE facility, with the ability to generate electricity, recover heat and resell bio-fertilizer, is proven to be a profitable method in disposing food waste and manure. Given the economic benefits presented by this study, the author suggests that upgrading conventional landfills would achieve both environmental and economic benefits for residents in New Jersey. In order to make WTE facility more beneficial, it would be recommended to consider the following:

1. Increase of tipping fee for disposing organic solid wastes to improve the ability for WTE plants to make positive net income. It would also drive the market demand for consuming environmental-friendly energy in New Jersey municipalities. In addition, advantages and disadvantages about the WTE technology should be promoted to the public. Therefore, the local communities could be involved in the decision of waste management methods.

2. Government support has decisive effect on the promotion of waste-to-energy technology in New Jersey. More regulatory acts, like NJ Energy Master Plant, should be issued to support further utilization of solid waste as an energy source. In addition,
related incentive plans should also be put into effect, which can partially offset the cost of research and pre-evaluation.

3. No matter which biotechnology is implemented to update traditional landfills, odor control system should be installed, especially for an urban plant sites. It would be better for the WTE facility to recovery higher content of biogas or CHP, especially when viewed on a much larger scale. Besides, a further analysis of the environmental impact is encouraged, which can provide more valuable information for public selection.
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<th>Location</th>
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<td>65432</td>
<td>456 Broadway</td>
</tr>
</tbody>
</table>

Note: This table lists the names and addresses of various locations within the Appendix. The addresses are not the actual addresses but are placeholders for demonstration purposes.
## Appendix 2

<table>
<thead>
<tr>
<th>Facility Name</th>
<th>Number of Municipality Covered</th>
<th>Average distance to the plant (km)</th>
<th>Total transportation distance</th>
<th>Total CO₂ generation from Transportation (pounds)</th>
<th>mpg=5.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACUA</td>
<td>2</td>
<td>12.58</td>
<td>18,531.30</td>
<td>44,817.79</td>
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<tr>
<td>Burlington County SLF I</td>
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<td>114,214.17</td>
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<td>154,254.42</td>
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<td>15.79</td>
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<td>222,974.02</td>
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