Modeling and Design of a Food Waste to Energy System for an Urban Building

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A Thesis

in

The Department

of

Electrical and Computer Engineering

Presented in Partial Fulfillment of the Requirements

for the Degree of Master of Applied Science at

Concordia University

Montréal, Québec, Canada

August 2010

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

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Entitled: "Modeling and Design of a Food Waste to Energy System for an Urban Building"

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

Modeling and Design of a Food Waste to Energy System for an Urban Building

Nathan Curry

Urban sustainability is a subject of recent focus in North America, and Canada specifically. As our urban areas continue to grow and consume large quantities of energy and produce massive amounts of waste, we are faced with the challenge of how to manage this situation in a way which is both responsible and sustainable. One feasible urban waste-to-energy technology is anaerobic digestion. Anaerobic digestion (AD) has been a usable energy source for over 100 years and is currently being employed in countries around the world in rural settings to generate electricity and heat, but it has yet to make a large migration to the urban environment though it is a viable and mature process.

Applied to the organic waste produced in urban environments, anaerobic digestion could provide a critical solution to growing garbage problems while simultaneously reducing external energy requirements. The cost of transporting waste outside of cities to landfills will continue to rise and if a substantial portion of this waste could be retained, digested, reduced, and converted into useable energy in the urban environment, then this is something to be seriously considered. The goal of this thesis is to investigate the feasibility of power and energy generation through the use of anaerobic digestion of food waste in the urban environment, suggest a novel modeling technique using the International Water Association's *Anaerobic Digestion Model #1*, and provide a case study from the downtown campus of Concordia University in Montreal, Canada.

ACKNOWLEDGMENTS

The author would like to offer his sincerest gratitude to his supervisor, Dr. Pragasen Pillay, for diligent oversight, outstanding patience, and continuous financial support through the course of the Master's Program.

The author would also like to express warm regards and thanks to all of the other researchers and professors involved in the P.E.E.R. Group for their consistent support and insightful discussions in the P.D. Ziogas Power Electronics Laboratory.

In addition, support for this thesis came from many different sources that also deserve high regard and thanks: Sustainable Concordia for their meticulous records and general knowledge, Claude Laflamme at Hydro Quebec for providing a wealth of information and insights into the anaerobic digestion process, the engineers at Electrigaz for providing support and information in a timely and professional manner.

Lastly, the author would like to express gratitude to his family and his girlfriend, Zoë Mowat. Their support kept him grounded.

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Chapter 1

Introduction

Section 1.1 The Growing Problem with Urban Waste

Urban waste generation and disposal has become a major global issue. As the world's population continues to grow toward the 7 billion mark and more people move to urban areas, the amount of waste generated therein will soon become unmanageable. In 1900, only 10% of the global population lived in an urban environment. Just over 100 years later, in 2008, the number of people living in cities surpassed those living in rural areas and it has been estimated that by 2030, 5 billion people will be living in cities - compared with 3.5 billion living in cities now. Global population has more than doubled since 1960 and in the next 20 years will have tripled. Projections from the United Nations show that the rapid depletion of essential human resources will only speed up as the population continues to grow at exponential levels [1]. As a result, there is conceptual push by public intellectuals for the growth of "ecopolis" or sustainable cities [2]. This is a special form of urbanization in which cities are "greened" by employing current and future technologies to minimize energy requirements, water and food requirements, waste outputs, air pollution, greenhouse gases, and water pollution. This projected eco-city should be able to sustain itself with minimal reliance on the surrounding areas for energy input and it should get most if not all of its power from renewable sources, including waste-to-energy technologies. This is a noble goal, and one that should be pursued as urban waste production quickly comes into focus as one of the major global issues.

Section 1.2 The Problem with Landfills

The waste generated by this increased urbanization of humans and their industries will have to be sorted and processed in some way. The most common and widespread solution is landfilling, but therein lies a problem: landfills around the world are running out of space to put all of the waste. The last landfill in the greater New York City area closed in 2001 and now waste is currently being transported out of the state by truck and train. London, UK, sends its annual waste to 18 different landfills. In Montreal, Quebec, the closest landfill accepting waste is 40 km away with permits that were set to expire but have been extended only to 2012. In 2006, nearly a million tons of the waste generated in Toronto, Ontario, was trucked to landfills across the U.S. border into Michigan. As a solution, Toronto has purchased a landfill site that is over 200 km away from the downtown area scheduled to open sometime in 2010. Mexico City produces 12,500 tons of trash per day and it is sent to sprawling, polluted landfills that are quickly running out of space. As of 2007, two-thirds of China's cities were overrun with garbage.

Cairo, one of the largest cities in the world, faces a dire garbage problem as well and it serves as a prime example of exactly how bad the urban waste problem has become. The population of Cairo has doubled since 1960 and now 6.8 million inhabitants call it home with an additional 10 million people living in the surrounding suburban areas. An estimated 10,000 tons of waste is generated each day in Cairo and 4,000 tons of it is not processed or sorted in any way and it is often just burned, posing serious health and environmental hazards. In essence, the outskirts of Cairo and many of the streets have become bastions of garbage and the city itself is transforming into a landfill. Since the turn of the 20th Century, a group of migrants and poor farmers known as the Zabbaleen or "garbage people" have been taking the garbage out of the city and have ended up settling into abandoned slums which have become known as the Manshiyat Naser or "Garbage City" as seen below.

Image 1. "Garbage City" located outside Cairo, Egypt (L), Zabbaleen family (R)

Until the 1980s, Cairo didn't have any municipal collection at all and any garbage collection, sorting, and reuse of waste was done by the Zaballeen. In this sprawling wasteland they sort, stack, reuse and recycle anything that is available and feed any organic waste they find to pigs that they raise. The Zabbaleen have been largely ignored by the government and the media and are looked down upon due to their religious beliefs and the fact that they raise pigs in a predominantly Muslim city. During the Swine Flu epidemic of 2009, the Egyptian government decided to exterminate all pigs living in this area and as of now, no organic waste is being treated or collected. The Zaballeen have lost a large source of food and income, and organic waste is rotting in the streets of Cairo. In addition to this garbage pollution, Cairo also suffers from air pollution due to the large number of older vehicles on the road (most more than 20 years old without catalytic converters), smelting factories, lack of rain, and water pollution from overflowing, failed sewers. This human environmental crisis serves as an example and a warning of what can happen to an urban area that grows too quickly without proper planning. Sustainable, renewable, environmental solutions are needed now more than ever. As can be seen from the example of Cairo and those mentioned earlier, increased and extended landfilling is not the best option.

In addition to the problem of not having enough space to process the increasing urbanization of humans, landfills also generate the largest amount of anthropological greenhouse gases. According to estimates by The Environmental Protection Agency of the United States of America, more than 50 percent of total global methane emissions are due to human-related activities and landfilling is second on that list (the remaining 50 percent of methane production comes from natural sources which include wetlands, gas hydrates, permafrost, oceans, freshwater bodies, non-wetland soils, and wildfires.) [3]. The government of Canada has not released the same information, but it can be assumed that the results would be similar as both economies are intertwined and lifestyles are similar across North America. The list of top methane producers is summarized below.

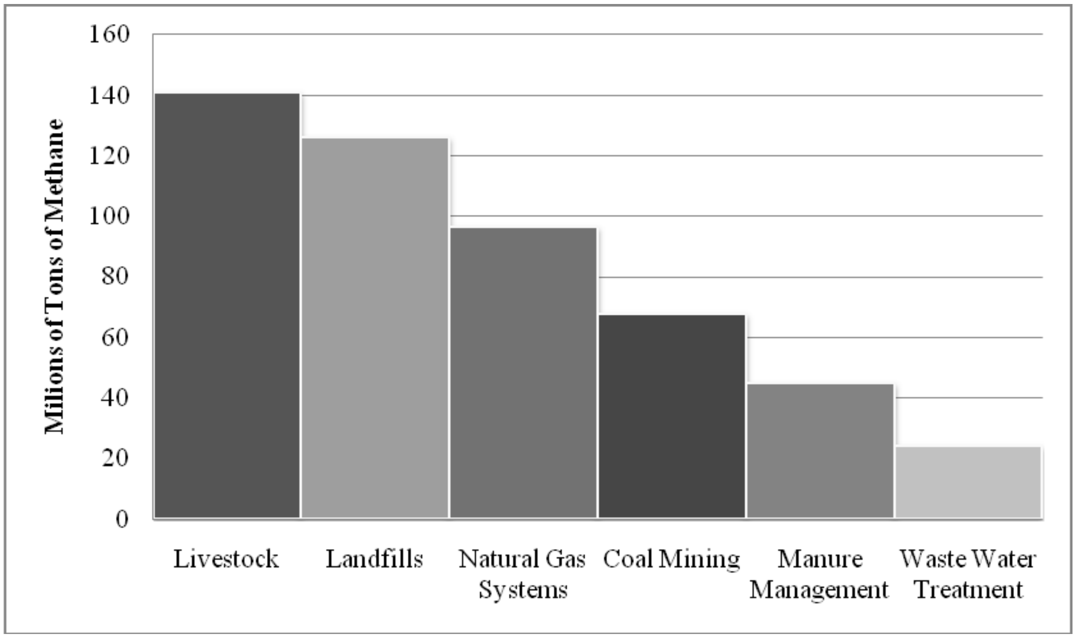


Figure 1. Largest annual Anthropogenic producers of Methane in 2008 [3].

To gain some perspective, there are presently about six thousand landfills in operation in the United States producing an estimated 450-650 billion cubic feet of methane which directly contributes to global warming as methane is over 20 times worse as a greenhouse gas than carbon dioxide is by volume. The graphic below from the National Renewable Energy Laboratory shows how widespread landfilling is in the US and exactly where the methane is produced [4].

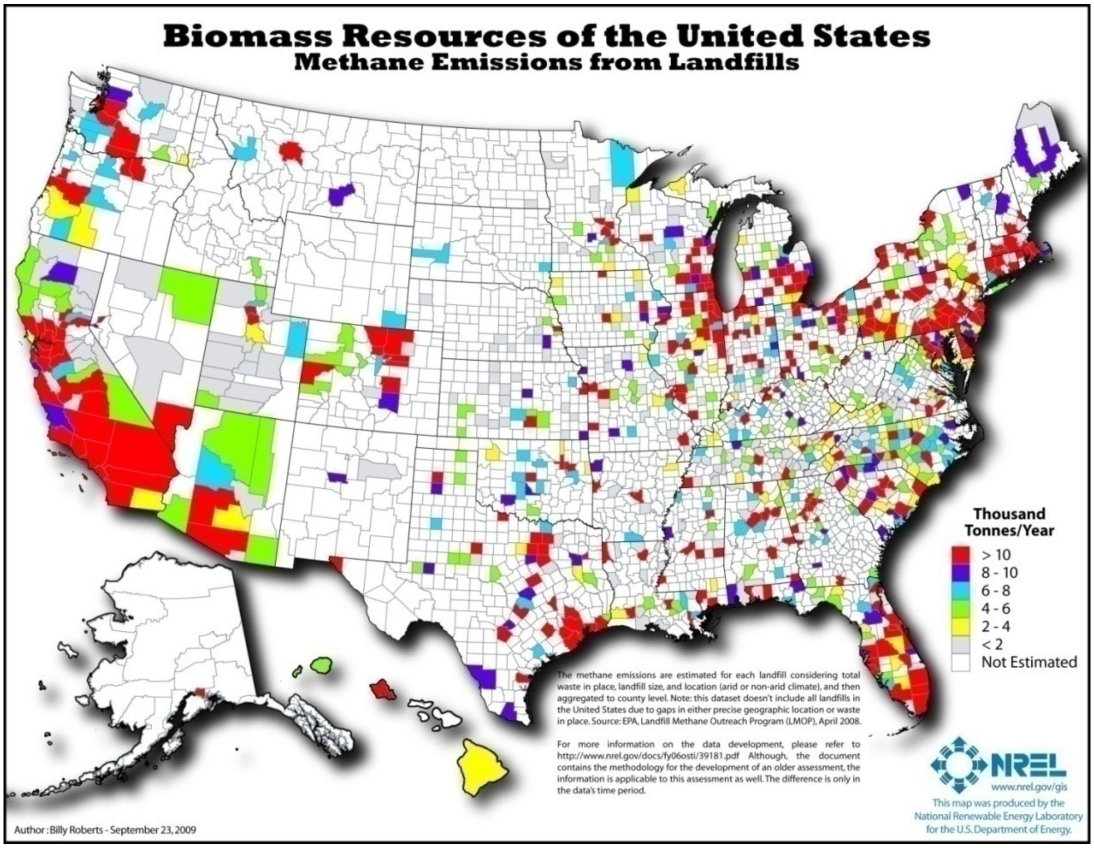


Figure 2. Methane production from landfills across the United States [4].

It can be inferred from the above graph that most of the landfills receiving more than 10 thousand tons of garbage per year surround the largest cities in the country – NY, LA, D.C., Boston, Detroit, Seattle, San Francisco, Dallas, etc.

Landfilling is one of the largest contributors to global warming, however, the largest production of methane in North America is due to the enteric fermentation of the livestock that are raised for consumption. It has been estimated that in the past 50 years, global meat consumption has increased by at least 500 percent and is still on the rise [5]. Additionally, a third of the earth's entire landmass is presently used to raise animals for food and this represents about 70% of land that could be used for agriculture and a third of the cereals grown on the remaining arable land are used to feed the aforementioned livestock [6]. The fifth largest contributor to annual methane production is the manure waste from these and other animals raised for human consumption.

These two large waste problems can be solved with the same waste-to-energy solution: anaerobic digestion. Farm waste and food waste are two of the most common biodegradable wastes in North America and instead of sending them to landfill or just piling the waste in giant lagoons, they could be digested, creating an energy-rich biogas that could be burned to produce combined heat and power. The research presented in this thesis deals with the anaerobic digestion of food waste produced in the urban environment and it is inspired by the research being done on the digestion of farm waste in the rural environment. As this technology doesn't yet exist in a realized form in the urban environment, a feasibility, modeling, and case study approach to its implementation is presented.

Section 1.3 North American Waste

To grasp the big picture in North America, in 2008, the United States generated 250 million tons of municipal solid waste (MSW) comprised mainly of food scraps, yard waste, plastic packaging, furniture, tires, appliances, paper, and cardboard. This discarded MSW came from two main sources: Residential (55-65%) and Commercial / Institutional (35-45%) with construction and hazardous wastes not considered in the grouping. Nearly half of this waste was recycled or reclaimed but 135 million tons (54%) was still sent to landfill [7].

In Canada, the total amount of waste sent to landfill in 2006 was 27.2 million tons, which roughly scales to the population difference (Canada 30 million, US 300 million).

Due to the lack of a comprehensive waste analysis report for the whole of Canada, it is assumed that the composition of MSW is similar for the US and Canada and the waste breakdown from the U.S. Environmental Protection Agency is used. This assumption can be verified by checking the waste reports of individual provinces in Canada (Ontario, British Colombia) to verify the waste percentages [8]. The USA Environmental Protection Agency predicts that 12.7% of the total waste disposed of is food waste.

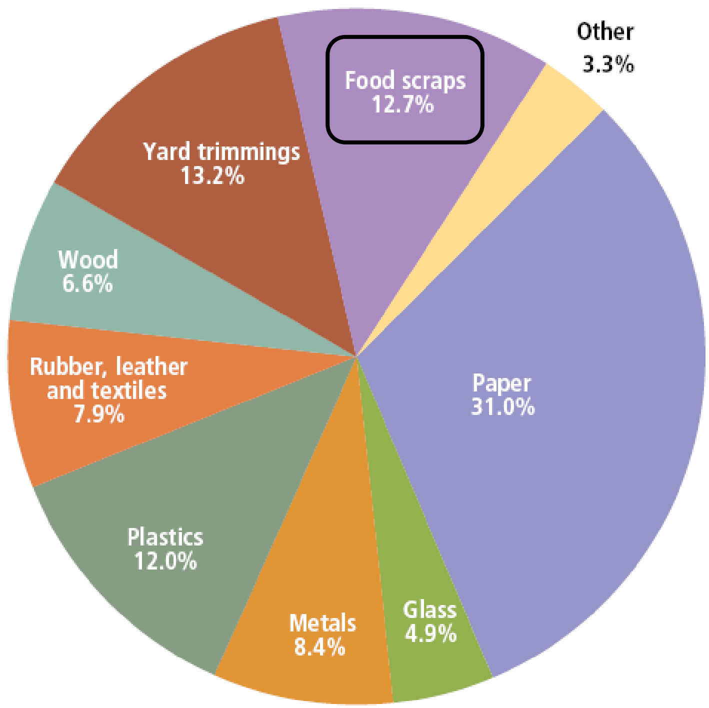


Figure 3. Annual MSW Composition in United States [7]

Using this figure, 3.5 million tons of food waste are available for energy reclamation. This means 2,400 GWh/year of thermal energy or 853 GWh/year of electrical energy is available through the use of biogas produced by anaerobic digestion (these results are based on biogas yields and energy content of biogas from the research detailed in this thesis – 367 m^3/ton VS and 6.25 kWh_t / m^3 biogas – *2.3MWh /ton VS*). This is a substantial amount of available unclaimed energy that is currently going straight to the landfill. It is obvious that there is no simple solution to the global waste crisis. New consumption paradigms as well as waste management solutions are needed.

Section 1.4 Waste Management and Energy Solutions

Landfilling may be the most common waste management solution, but it is not the only. There are several additional waste processing technologies that are currently employed around the world that fall under the *incineration* and *biological processing* headings. This section will show that among these, anaerobic digestion is the most promising and the most benign technology.

Incineration

Incineration is a waste disposal method that involves combustion of waste material at high temperatures and is often referred to as ‘thermal treatment.” Incinerators convert waste materials into heat, gas, steam, and ash and in the process reduce the volume of the original MSW by up to 85%. The heat and steam produced can be used to power a turbine to generate electricity and thereby qualifies incineration as a “waste-to-energy” technology.

The drawbacks of incineration are the toxicity of the flue gases and the fly ash and bottom ash produced during the process. The flue gases need to be scrubbed of particulates, acids, and dioxin and furan content as they post serious environmental and health hazards. Additionally, the fly ash left over from the incineration process is toxic as it contains significantly high concentrations of heavy metals such as lead, cadmium, copper, and zinc. This ash needs to be buried in a designated toxic area and many communities are not comfortable with toxic materials being located nearby. Incinerators remain a contentious environmental and social issue but are still employed around the world in places like Japan and Denmark that are short on space. Denmark and Sweden have been using this waste disposal technology for more than a century and often have district heating schemes that run exclusively off the heat produced by the process. In 2005, Denmark produced 14% of its domestic heating and almost 5% of its electricity through waste incineration [9].

Pyrolysis/Gasification

Pyrolysis/Gasification is another waste-to-energy treatment that is related to incineration but it occurs at higher temperatures and produces different byproducts due to the fact that it is done without oxygen. Pyrolysis is the chemical decomposition of organic materials at temperatures above 430°C and it produces two main byproducts: a syngas made of carbon monoxide and hydrogen that can be burned for energy and a biochar ash which is rich in carbon and can be used as a fertilizer. Instead of the carbon in the organic materials bonding with oxygen and forming CO_2, as occurs in incineration and decomposition, the carbon is essentially "stored" in the biochar. As a result, Pyrolysis is considered a "carbon negative" process because it breaks the natural occurring carbon cycle by sequestering the carbon. Storing carbon in biochar has received interest recently as a possible tool to use against global warming patterns. The syngas produced by the process can be can used as a fuel and has about half the energy content of natural gas. Data on pyrolysis of MSW is scarce although it is a promising technology. Not much is known about emissions and cost analysis as there are currently no large-scale pyrolysis plants operating in North America.

Plasma Arc Incineration

Although technically falling under the label of "incineration," plasma arc technology is a different entity than the other forms of incineration though it is often confused or lumped in with the rest. Plasma exists as a fourth state of matter in the physical world and occurs when a gas is heated to the point where it becomes ionized. Lightning is a natural example of plasma and the phenomenon has been turned into a technology with the plasma torch. When used in a lab or with an industrial purpose, plasma torch technologies can reach temperatures of around 7,000-14,000 degrees Celsius. In the case of plasma incineration of MSW, the electrical arc formed in a vacuum chamber can vaporize organic materials into syngas and inorganic materials into an inert solid rock-like material. The rock-like aggregate can be used for building, ceramic tiles, bricks, or gravel to make roads. The syngas produced can be used as fuel for gas turbines, boilers, and low BTU reciprocating generators and can be further processed to produce various hydrocarbon fuels such as gasoline, diesel, ethanol, and methanol which are usually refined from fossil fuels. This makes plasma gasification a renewable energy technology and an attractive candidate for waste to energy technology. Unfortunately, at this time, there exist few environmental or engineering standards for the technology as a waste-to-energy candidate and there are currently no examples of large-scale treatment plants in North America.

Biological Processing

There are two main forms of biological processing used to treat the organic fraction of municipal solid waste: *composting* and *anaerobic digestion*. Although they both employ the use of microbes and bacteria to convert organic material into gas and fertilizer, only anaerobic digestion produces a fuel that can be burned to generate electrical power.

Composting

As a process, composting can be described as the decomposition of organic materials that occurs anywhere in nature where oxygen is available (aerobic). Organic constituents are converted into carbon dioxide, heat, and a stable fertilizer by microorganisms – mostly bacteria. As a technology, composting dates to the early Roman Empire and is mentioned specifically as far back as 60AD in the writings of Pliny the Elder as a way to organize and process organic wastes. Many different organic substrates can be composted but the ratio of carbon to nitrogen remains the most important factor. Carbon-heavy inputs that are dry and brown often called "browns" (leaves, paper, straw, branches) must outweigh the nitrogen-heavy inputs (fruits, vegetables, grass, coffee grinds), or "greens," by a 30:1 ratio in order for the process to occur most efficiently. Greens have a much higher moisture content (60-80%) and decompose quickly while the browns are dryer and decompose more slowly providing a buffer for the faster breakdown of the greens. Cooked meats, fats, greases, and oils are not ideal composting candidates as they attract flies and rodents and release terrible odors as they putrefy. Composting releases the carbon dioxide originally sequestered by the organic material from the atmosphere and as such is considered a "carbon-neutral" process. No energy is available from this process.

Anaerobic Digestion

Anaerobic Digestion is a naturally-occurring digestive process in which microbes convert organic materials into biogas and neutral digestate sludge in the absence of oxygen. It is considered a renewable waste-to-energy technology because the methane-rich biogas produced (often 55-70% methane) can be burned as a fuel and offset the need for fossil fuels. Most of the methane is produced within 30 days of adding the organic material to the digestion process whereas in composting, a full year is often required for neutralization. Unlike incineration technologies, there are no toxic byproducts and the digestate that comes from this process can be spread directly as a fertilizer. This process can reduce the volume of the input material from 50% up to 80%.

The advantage of using anaerobic digestion in an urban environment to treat organic waste as opposed to composting it is that anaerobic digestion produces biogas with a high percentage of methane which can be used as fuel whereas composting produces mostly carbon dioxide which can't be burned as fuel. Importantly, AD also prefers cooked and oily food waste to be digested where composting does not. In fact, the AD process produces more biogas when used cooking oil and cooked meats are added. AD could be applied to the organic fraction of MSW either "en situ" or directly at the landfills if it is presorted by the producers. The following chapter will discuss the anaerobic digestion process in detail.

This thesis is organized as follows: Chapter 2 includes a detailed description and design of an anaerobic digestion system with food waste as input substrate. Chapter 3 deals with the modeling of the anaerobic digestion process - specifically the Anaerobic Digestion Model #1 (ADM1). Chapter 4 discusses a transformer recently developed to interface ADM1 with commonly measured and reported substrate parameters and a novel implementation technique for energy calculations. Chapter 5 presents a case study of food waste digestion on the downtown campus of Concordia University including a proposed system design. Chapter 6 summarizes the conclusions and contributions of this research as well as recommendations for future work on this subject.

The main contributions and intentions of this research are to qualify the food waste produced in the urban environment as a valid candidate for anaerobic digestion and to propose using small-scale digestion as a way to deal with the organic fraction of waste currently sent to landfills and in the process generate biogas which can be used for energy production. A novel modeling technique is suggested which provides a bridge between the biochemical research and energy research being done on waste-to-energy technologies. A case study at Concordia University is presented as an example of how this technology could be immediately implemented in the urban environment.

The following papers have been published or are under preparation regarding this research:

Curry, N., "Converting Food Waste to Usable Energy in the Urban Environment Through Anaerobic Digestion," paper was presented and accepted to be published at The Electrical Power and Energy Conference (EPEC) organized and sponsored by

IEEE Canada, IEEE Power & Energy Society, IEEE Montreal Section, Montreal, 23 Oct. 2009.

A. Gharakhani Siraki, N. Curry, P. Pillay. S.S. Williamson, "Power Electronics Intensive Solutions for Integrated Urban Building Renewable Energy Systems," was accepted to be published in the 35th Conference of the IEEE Industrial Electronics Society, IECON 09, Portugal, Nov. 2009. *Personal contribution to this co-authored paper was how to integrate an Anaerobic Digestion system to produce energy from the food waste generated in an urban building.

Curry, N., "Potential for Biomass Waste-to-Energy Systems in the Urban Environment," paper submitted to World Energy Conference, Montreal 2010.

Curry, N., "Estimating the Energy Content of Food Waste for CHP Applications in Urban Environment," under preparation for IEEE Renewable Energy Journal, 2010.

Chapter 2

Anaerobic Digestion as Waste-to-Energy Candidate for the Urban Environment

Section 2.1 Introduction

It can be argued that anaerobic digestion is one of the oldest known chemical conversion processes on the planet. The first documented forms of life on earth are single-celled microorganisms called archaea that lack a nucleus and produce methane as a byproduct of their metabolic processes. They show up in the fossil record approximately 3.5 billion years ago, almost a billion years before aerobic photosynthesis evolved, a billion years after the earth formed and cooled [10]. There are now over 50 known species of archaea, classified as methanogens, converting organic materials into methane. They can be found in swamps, the intestines of ruminant animals and humans, and in more extreme places such as hydrothermal vents and hot springs. These microorganisms drive the process we call anaerobic digestion.

It has been speculated that humans first started using anaerobic digestion to convert organic waste to energy in 1859 at a leper colony in Bombay, India, although it's likely that the phenomenon was observed and harnessed in much earlier centuries. Since the turn of the 20^{th} century, it has become a widely used technology and can be found everywhere from small farms in Africa to villages in India to integrated networks of farms in Germany and Denmark to giant MW farm installations in the US.

In recent years, anaerobic digestion technology has seen rapid growth. Biogas plants around the world have experienced a 20 to 30 percent increase each year with the most experienced and well-developed markets being in Germany, Denmark, and Austria. As of 2007, Germany has 3,700 biogas plants in operation [11], Denmark has 20 centralized plants and 35 farm scale plants in operation [9], and Austria has 323 plants with an electrical capacity of 81MW[12].

In other parts of the world, AD technology also flourishes as a waste-to-energy solution but on a smaller scale and in a decentralized manner. In 2007, China had an estimated 18 million biogas digesters and in India there are currently over 5 million small-scale biogas plants in operation. The volumes of the digesters range from $2m^3$ to $20m^3$ and they are usually fed household and agricultural wastes. The biogas is predominantly used for personal cooking and lighting purposes [11].

Despite all of these advances, anaerobic digestion has yet to make a large migration to the urban environment. Historically, landfilling has been a cheaper option for urban development but as landfills continue to run out of space and move farther from the cities, the cost of landfilling will continue to rise, both monetarily and environmentally. If the organic waste produced in the cities was source-separated from the recyclable materials and digested on-site in small-scale anaerobic reactors, it could provide a critical solution to growing garbage problems while simultaneously reducing external energy requirements and greenhouse gas emissions. The biogas could be burned to produce heat and electricity using internal combustion engines, microturbines, or water boilers in a cogeneration arrangements. The electricity and waste heat generated could be used to warm the digesters or to heat buildings. This chapter discusses the biochemical process of anaerobic digestion in detail, summarizes the operation parameters and system design considerations, and provides a history of the modeling techniques used to predict biogas output.

Section 2.2 Description of Process

Anaerobic digestion is a complicated biochemical process. Based on temperature and input substrate, different strains of bacteria digest complex chains of carbohydrates, fats, and proteins into their component parts, then again into intermediate, simpler molecules, and eventually into a biogas which is rich in methane and can be burned as fuel in the place of natural gas. Leading experts on the process claim that we might not ever be able to fully understand all aspects of the biochemical processes involved, but current understanding does provide us with a trustworthy guide to navigate and predict the microorganism interactions and their products to a high level of accuracy.

Anaerobic digestion occurs in four separate phases: Hydrolysis, Acidogenesis, Acetogenesis, and Methanogenesis. The last stage of the process, Methanogenesis, is where the biogas is produced and it contains 50-70% methane which can then be used for heat and power applications. These stages can be seen in a simplified version below:

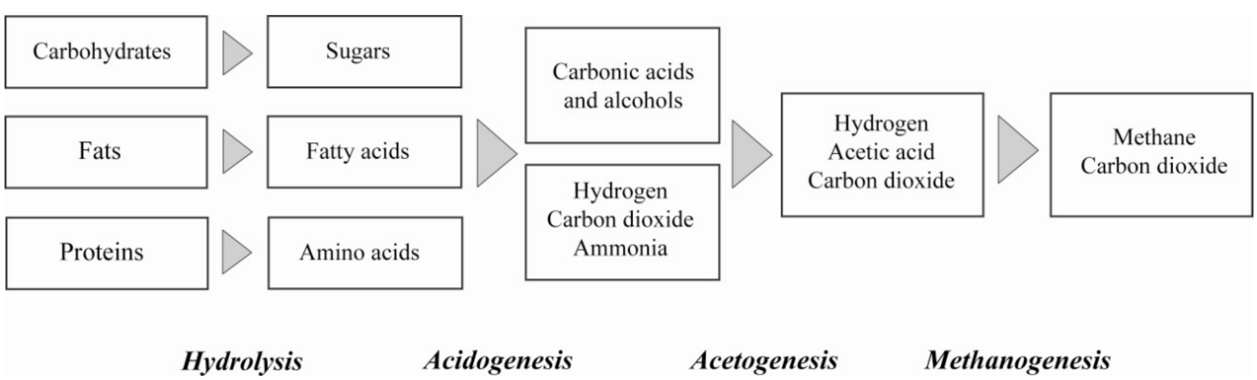


Figure 4. Anaerobic Digestion Process

In actuality, the process is much more complicated and intermediate products are used for future steps and future products are used for intermediate steps in a feedback loop of molecules and microorganisms as seen in *Figure 5*. The individual stages of the anaerobic digestion process can be explained as follows:

1. *Disintegration*

   In this step, food waste is broken down into its constituent elements being: carbohydrates, proteins, and fats/lipids. This step is aided by the grinding or chopping of the input substrate into small (5mm or less) pieces so that the microorganisms can act on the substrate. The smaller the pieces, the more easily the substrate can be broken down and the more biogas is produced in the final steps of the process.

2. *Hydrolysis*

   The hydrolysis stage of the AD process often includes the disintegration process and is referred to as the first stage. The complex organic compounds produced by disintegration of input material – carbohydrates, proteins, and fats - are broken down into simpler organic constituents – sugars, amino acids, and long-chain fatty acids, respectively. Hydrolytic bacteria secrete enzymes which breakdown the long chain compounds into soluble compounds and in the process generate Hydrogen and CO_2. For complex wastes like food wastes that are very highly biodegradable, it is advisable to separate the hydrolysis phase from the rest of process as it is often the most volatile and the acids produced can dramatically affect the pH and the stability of the process.

3. *Acidogenesis*

In this step, the hydrolysis products are metabolized by acidogenic bacteria and converted mostly into volatile fatty acids (acetate, propionate, butyrate, valerate) and alcohols (ethanol, methanol). Additionally, some CO_2, ammonia, and hydrogen are produced which, along with acetate, can be directly consumed by the methanogenic bacteria if the system is already in steady state.

4. *Acetogenesis*

The remaining VFAs and alcohols with chains longer than acetate are further broken down by acetogenic bacteria into acetic acid, CO_2, and hydrogen so that the methanogenic bacteria can metabolize them.

5. *Methanogenesis*

In the final step of the anaerobic digestion process, methane and carbon dioxide are produced from the three remaining products of the acetogenic phase. On average, 70% of the methane generated comes from the acetate and 30% comes from the metabolizing of CO_2 and hydrogen. The methanogenic reactions are seen below:

$CH_3COOH \leftrightarrow CH_4 + CO_2$ (70% of methane generation from acetate) *(1)*

$CO_2 + H_2 \leftrightarrow CH_4 + 2H_2O$ (30% of methane generation) *(2)*

Methanogenesis is the slowest of the phases of AD and is the most sensitive to operating conditions such as input composition, organic loading rate, pH, and temperature. Any remaining substrate which can't be digested by the methanogenic bacteria plus the bacteria that die during the process make up the digestate.

A graphical representation of the above descriptions with intermediate paths is show below:

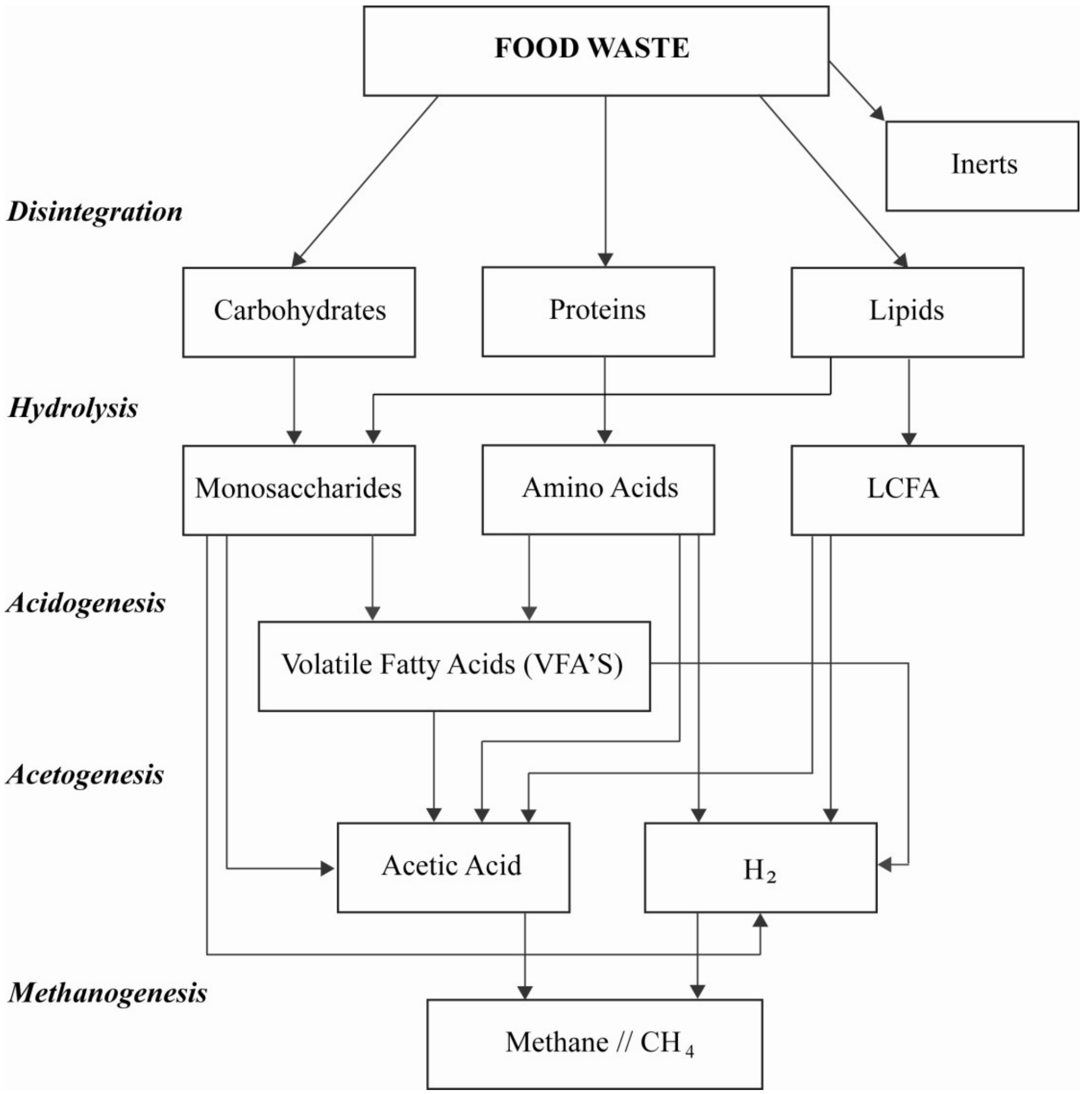


Figure 5. Overview of the Anaerobic Digestion Process with Biochemical Pathways

There are 3 main temperature ranges where anaerobic digestion can occur and each has its own set of advantages and limitations:

1. *Thermophilic (50°C–60°C)*

Thermophilic digestion systems operate at the highest temperature range. The desirable aspect of this system is the fact that the micro-organisms rapidly break down the organic material and produce largest volumes of biogas. This results in smaller digestion tanks and shorter retention times – often as short as 5-10 days. The drawbacks are that more insulation is necessary to maintain the temperature range, and more energy is needed for heating the system. Additionally because the process occurs so fast, it is the most unstable and most sensitive to small changes in the input material. It may be more practical in areas that are warm year round and have a consistent waste input. It is possible to do thermophilic digestion of food waste.

2. *Mesophilic (35°C–40°C)*

Mesophilic is the most common range of digestion due to the robust and stable nature of the bacteria involved. A longer retention time (at least 15–20 days) is needed to break down the organic matter and produce biogas then in a thermophilic system. This range is most common for farming and agriculture-food systems. Regarding food waste, several studies have shown that using mesophilic digestion can yield similar amounts of biogas under similar retention times as thermophilic systems while being more stable [21] [22].

3. *Psycrophilic (15°C–25°C)*

Psychrophilic digestion occurs at around ambient/room temperature and is a more recent development as an anaerobic producer of methane. Researchers in colder climates in Canada – more specifically in Manitoba and Quebec – are working to digest manure waste and produce methane at a steady rate. The drawback to this technology is that it takes much longer for the methane to be produced which is fine if you have a long term "storage pit" or lagoon set up and doesn't require much heating at all.

For the urban environment, the most promising candidate to digest food waste is mesophilic digestion due to the low retention times, high organic loading and methane production rates, and overall stability. Several studies have shown that at larger scales, and smaller scales, mesophilic digestion seems to be the best candidate [13][14][15]. Thermophilic digestion allows for faster methane extraction and therefore has a lower substrate retention time and can be considered in situations where size is a restriction [13].

The literature on the anaerobic digestion of solid wastes is difficult to summarize and is often very confusing due to the "black box" aspect of the process. Not everything is fully understood about how all the different species of bacteria interact and further, how each particular strain of each bacteria interact with each other. At some points there can be 8 different methanogenic bacterias converting acetic acid into methane. Any attempt at standardizing or modeling an AD system will be based on a particular waste with a particular experimental set up. The almost endless variability of waste compositions, reactor designs, and operational parameters leads to different conclusions. For complicated wastes such as food waste, the problems are multiplied as the biochemical pathways involved in the digestion are estimations at best and require a case-by-case interaction to run efficiently. In addition, the lens that the researcher applies to the experiment greatly affects the outcome data. It's especially rare to find experiments done from an energy engineering perspective as the focus of the research is often on the stability and completion of biochemical reactions and not on optimum biogas production and high methane content. The same can be said for environmental and economical concerns.

Section 2.2 Anaerobic Digestion Reactor Operating Parameters

There are several important parameters for proper design and operation of an anaerobic digestion system. A description of these parameters can be summarized from *The Biomethanization of the Organic Fraction of Municipal Solid Waste* [15]:

1. *Total Solids (TS)* – residue or dry material left over after drying the substrate for 48 hours at 105°C. It is a raw estimation of the amount of organic and inorganic material in the substrate.

2. *Total Volatile Solids (TVS)* – an approximation of the "organic" fraction of the total solids. Determined by heating TS to 550°C for 24 hours. Leftover material is inert or mineral fraction (inorganic).

3. *Chemical Oxygen Demand (COD)* – a measure of the oxygen equivalent of organic material in a substrate. Determined by adding a strong chemical oxidizing agent to the substrate in an acidic medium. It gives an accurate estimate of the amount of organic (degradable) material in a sample.

A corollary and equivalent way to determine the amount of organic material in a substrate is Calculated Oxygen Demand (COD') if the empirical formula for the substrate is known or determined by Ultimate Analysis [25].

$$COD' = C_nH_aO_bN_c + \left(n + \frac{a}{4} - \frac{b}{2} - \frac{3}{4}c\right) O_2 \leftrightarrow nCO_2 + \left(\frac{a}{2} - \frac{3}{2}c\right) H_2O + cNH_3 \tag{3}$$

There is no direct analogue between the commonly reported and measured Volatile Solids (VS) in kg/m^3 and the COD in kg/m^3 that is used for more advanced modeling of anaerobic digestion for wastewater applications (advanced modeling discussed in Chapter 3). However, there is a "rule of thumb" that can be gleaned from literature. [15] gives a list COD'/weight (TS) measurements for various substrates with Lowest, Median, and Highest being 1.16, 1.39, and 1.99 respectively. Additionally, the year-long study on anaerobic digestion of food waste done by East Bay Municipal District outside of San Francisco, California [16], reports a ratio of 1.96 when measuring both COD and VS for the mixed food waste input. This is valuable for calculating total COD (CODt) for a substrate with known volatile solids content.

4. *Hydraulic Retention Time* (HRT) [days] – the amount of time that the substrate spends in a reactor under ideal conditions

$$HRT = \frac{V}{Q} \tag{4}$$

Where V: Reactor Volume [m^3]

Q: Flow Rate [m^3/day]

5. *Organic Loading Rate (OLR)* – The amount of organic material added to the reactor in a given amount of time; usually a per day flow rate

$$OLR = \frac{Q*S}{V} \tag{5}$$

Where:

OLR: Organic Loading Rate [kg substrate / m^3 / day]

Q: Flow rate of input [m^3/day]

S: Concentration of VS in the input [kg/m^3]

V: Reactor Volume [m^3]

6. *Specific Gas Production (SGP)* – This aspect of the AD process relates the amount of biogas produced in cubic meters to the amount of volatile solids being digested on a per unit basis (often m^3/kg or ton). When compared with other substrates, it can be used as a guide to biodegradability (higher SGP = higher degradability).

$$SGP = \frac{Q_{biogas}}{Q*S} \tag{6}$$

Where:

SGP: Specific gas production [m^3 biogas / kg substrate]
Qbiogas: biogas flow rate [m^3/day]
Q: input flow rate [m^3/day]
S: VS concentration of input [kg / m^3]

Section 2.3 Designing an Anaerobic Digestion Reactor System with Food Waste as Substrate

There are several important factors to consider when discussing the feasibility of designing an anaerobic digestion to operate with food waste as the predominant input substrate. Food waste is considered a desirable input substrate but it is also prone to over-acidification and lower pH levels due to the amount of fatty acids produced. A literature review of important considerations for digesting food waste follows.

1) *Amount of waste available*

An estimation of the total tonnage of input substrate is a very important first step in the design process. Often this amount is not directly known and needs to be estimated through a waste audit. A total amount of waste can be estimated from a weekly, monthly, or annual audit.

2) *Dryness of Input*

One of the more important parameters for AD systems is the dryness of the input material. Before an accurate size of the digestion tank or a prediction of biogas content is able to be made, the amount of dry solids present in the input substrate is necessary. In agricultural manure waste, there is only a 2-12% solids content meaning the input slurry is mostly water. The potential biogas comes from the solids content, so accordingly manure has a very low biogas yield per ton. According to a literature review of waste taken from cafeterias, restaurants, and markets, food waste is approximately 30% dry material[14][15][16][17][18][19].

As the substrate moves away from being mostly water, the density of the substrate decreases. This is an important factor to note when converting from tons of input material to a volumetric measurement of meters cubed.

The relationship between dryness and volume can be determined by the following set of inequalities:

$$D = 1 \; for \; b \leq 0.15 \tag{7}$$

$$D = 1 - \; e^{\left(\frac{-0.3}{b-0.1}\right)} \; for \; b > 0.15 \tag{8}$$

Where: D = Density in dry tons/m^3

b = Dryness (%)

A graphical representation of these equations can be seen below. As dry material in a substrate increases, density decreases. In the case of food waste, density is 0.78 tons / m^3.

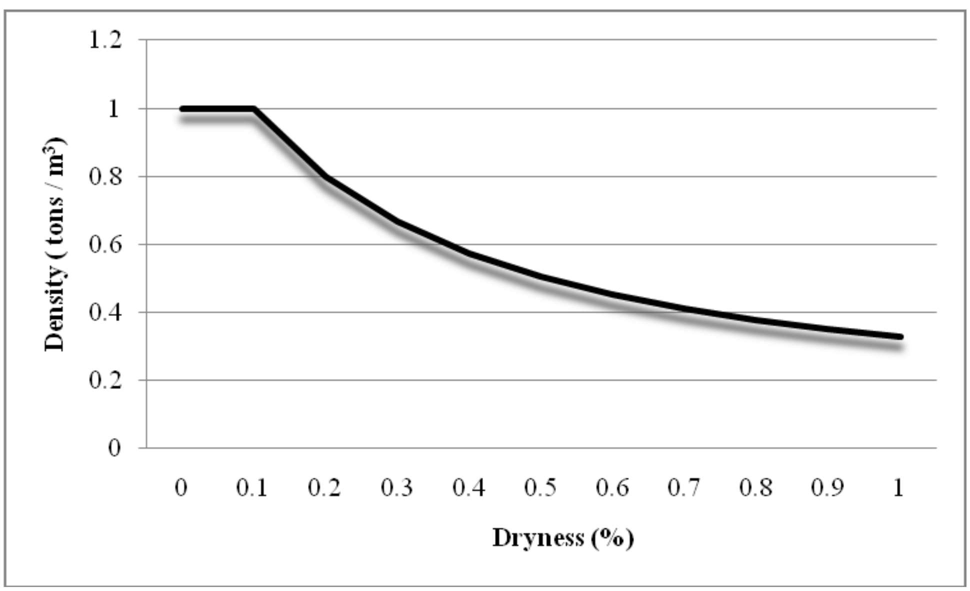


Figure 6. Dryness vs. Density for Organic Materials

3) Sizing Considerations

In order to figure out the size of the tank needed to digest the waste, several related parameters are needed: Input Flow Rate, Dryness, Total Solids, Volatile Solids, Organic Loading Rate, and Hydraulic Retention Time. The size of the reactor can be calculated by a modified version of the organic loading rate equation:

$$Volume\ (m^3) = \frac{Flow\ Rate\ \left(\frac{m^3}{day}\right) * Volatile\ Solids\ Concentration\ \left(\frac{kg}{m^3}\right)}{Organic\ Loading\ Rate\ \left(\frac{kg}{m^3}/day\right)} \qquad 9)$$

From the estimate annual tonnage, the amount of dry material can be calculated. Once the amount of dry material is known and the density, then a flow rate can be calculated after the tonnage is converted to cubic meters and divided by the number of days in a year.

Next, the amount of volatile solids (VS) needs to be measured or taken from literature. This can be done in a laboratory by taking a sample, weighing it, drying it in an oven at 550°C until it maintains a stable weight (24hrs.) and then comparing the two weights. In the case of food waste, literature shows volatile solids are usually 90-95% of the total solids (dry material) or 28-29% of the substrate's wet weight [16][17][19]. Once the VS percentage is known, the concentration of organic material in kg/m^3 can be obtained by multiplying VS by the weight of the substrate per cubic meter (derived by knowing density).

From here, it becomes necessary to have a desired organic loading rate for the substrate. Studies of the mesophilic digestion of food waste show that the organic loading rate can be much higher than typical wastewater treatment or farm waste systems while remaining stable. For wastewater treatment and farm waste, OLRs can range from 1-5 kgVS/m^3 [20][21]. The Environmental Protection Agency's year-long study of food waste AD in California ran successfully at an OLR of 7 kgVS/m^3 [16]. Other studies have shown that the OLR for food waste can go as high as 10 kgVS/m^3 while remaining stable and producing biogas [13][14][19].

Once flow rate, concentration, and possible OLR ranges have been determined, a design choice becomes necessary: because OLR and HRT depend on each other and can both be used to size the system, one or the other must be fixed in order to determine the appropriate reactor size. This process should leave an amount of eligible play for the parameter that has been fixed once the system has been sized. Once in operation, changing HRT and OLR have different effects on the system and the possible consequences need to be considered before sizing occurs. If the concentration of VS is increased by increasing the OLR while keeping the HRT constant, then the viscosity of the slurry changes and subsequently the pumpability of the substrate changes. There is a usually an upper limit of 15% on pumps used to transport the slurry, so the system could experience mechanical failure if the OLR was already close to the upper limit [11]. In contrast to this, if the OLR is kept the same and the HRT is changed, then the system could experience undesirable biochemical effects as the expected organic matter disintegrates and subsequent methane production would both decrease accordingly. Using the OLR as a prominent design criterion does not appear much in the literature, more often the HRT of a system is varied.

4. *Biogas Yield*

Once the system has been properly sized, hydraulic retention time and organic loading rate have definite values, then the biogas production and specific methane production can be calculated.

A comparison of typical reported biogas yields from literature are seen below [11][16][22]. As becomes immediately evident, food waste has the highest yield of biogas per dry ton than most substrates. Comparing food waste yields with cow manure for example shows that food waste yields 15 times more biogas per ton than farm waste. This is intuitive because the manure has already been digested by a living creature and therefore large amounts of the energy have already been removed.

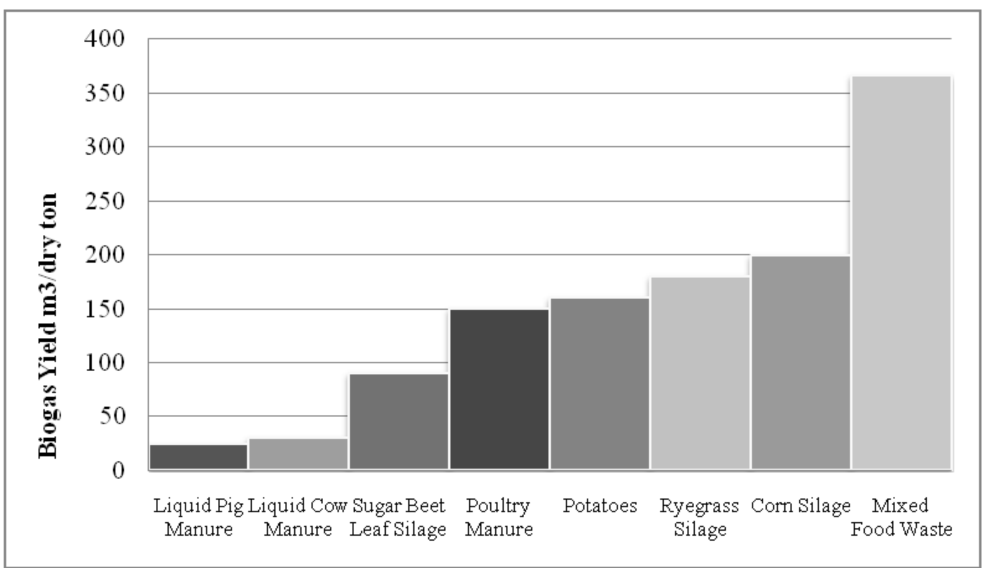


Figure 7. Biogas yields of various substrates in m^3/ ton VS

A flow chart of the biogas design process with important equations can be seen below:

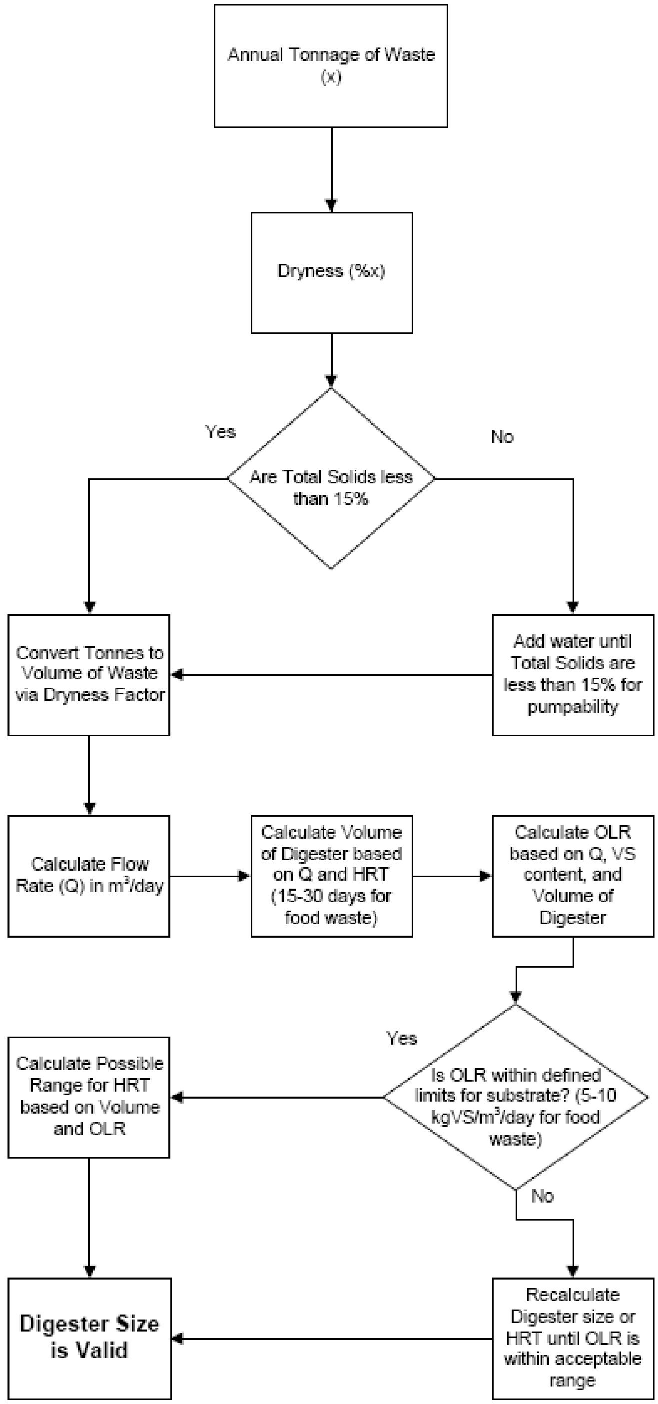


Figure 8: Digester Sizing Process Flowchart

Section 2.4 Modeling of Anaerobic Digestion

Once it was understood that methane could be reliably produced from the anaerobic digestion process at the turn of the 20th century, it became necessary to have a model to predict how much methane was available from a given substrate so that an economical value could be equated and the technology could be standardized. The first model of the anaerobic digestion process came from Arthur Buswell in 1930 while under the employ of the "Illinois Division of State Survey[23]." Buswell's equation calculates the moles of methane and carbon dioxide produced from a mole of an organic molecule (CHON) assuming the full elemental composition is known ahead of time.

Buswell's Equation

Proximate/Ultimate Analysis

In order to perform Buswell's analysis, you need to know the input substrate's elemental composition or ultimate analysis. This can be determined by Standard Methods or gained from literature. An example calculation is performed below:

From literature, an example of food waste elemental composition in carbon, hydrogen, oxygen, and nitrogen (CHONS) assuming 150 kg annually [23]:

	Kg/mol
C	5.45
H	0.46
O	7.26
N	6.35
S	14.55

	%
C	48
H	6.4
O	37.6
N	2.6
S	0.4

If 1 mole of N is selected as the value for "d", then $C_{22}H_{38}0_{13}N$ is the Chemical Formula for 150 kg Food Waste (VS) based on percentages above.

Using Buswell's Equation:

$$C_aH_bO_cN_d + \left(\frac{4a-b-2c+3d}{4}\right)H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right)CH_4 + \left(\frac{4a-b+2c+3d}{8}\right)CO_2 + dNH_3 \qquad (10)$$

Yields:

$$C_{22}H_{38}O_{13}N + 6.75H_2O \rightarrow 12.13CH_4 + 9.88CO_2 + 1NH_3 \qquad (11)$$

as the balanced equation.

From this, the theoretical methane and biogas yields can be calculated:

CH_4 yield: 55.7 tons @ 25 degrees C (0.668 kg/m^3) = 83,383 m^3 CH_4

CO_2 yield: 124.2 tons @ 25 degrees C (1.842 kg/m^3) = 67,318 m^3 CO_2

Total biogas yield = 1,005 m^3 biogas /ton VS @ 55% methane

This value needs to be compared with a realized value for digested food waste biogas yield in order to make a meaningful comparison. From experimental food waste digestion results, the average steady state biogas yield was 367 m^3/ton VS [16]. This procedure over predicts biogas yield compared with experimental results by almost 300%. This over-prediction is due to the assumption that 100% of the biodegradable material is converted to methane and can be tempered by introducing a biodegradability factor.

Nutritional Value Biogas Yield

Another biogas estimation technique was developed in the course of this research. It is not a formal technique but provides a better estimate than Buswell's equation of biogas due to the fact that it tries to be more accurate with the original description of the waste. If general formulas are assigned to the amounts of carbohydrates, proteins, and fats in a substrate and their percentages are known – which is often the case with food waste – then the biogas output can be directly computed by the following set of equalities given in [24].

$$\textit{Fat} \text{ (based on } C_{57}H_{104}O_6) = 1014 \text{ m}^3 \text{ } CH_4 \text{ / ton VS} \quad (11)$$

$$\textit{Protein} \text{ (based on } C_5H_7O_2N) = 496 \text{ m}^3 \text{ } CH_4 \text{ / ton VS} \quad (12)$$

$$\textit{Carbohydrate} \text{ (based on } (C_6H_{10}O_5)n = 415 \text{ m}^3 \text{ } CH_4 \text{ / ton VS} \quad (13)$$

The USDA has an archive of nutritional information for thousands of different foods and if the food waste being digested is simple enough in its constitution than a fairly accurate prediction of biogas is possible. For a mixed waste, there can sometimes been specific information about the three main components found in literature. For example, if estimated from the values presented in Zaher [25] for a “mixed kitchen waste” the carbohydrate, protein, and lipid concentration of the sampled food waste are 59%, 33%, and 8% respectively. Using these values coupled with a standard biogas yield for each category based on molecular formulas above, a value for the biogas content of the mixed food waste can be calculated as follows:

Carbohydrates : 59% @ 415Nm^3/ton VS

Proteins : 33% @ 496Nm^3/ton VS

Lipids : 8% @ 1014Nm^3/ton VS

Yield : 487 m^3/ton VS

This is a 33% over prediction compared with experimental results (367 m^3/ton VS) and a large improvement in accuracy over the Buswell equation.The biggest problem with this method is that the percentages of carbohydrates, proteins, and lipids are often not readily available for a mixed substrate and difficult to measure. In this case, the result happens to be much closer to an experimentally verified biogas yield compared with the proximate analysis but that might not hold true for other mixed wastes due to unknown composition. This method works better for a homogeneous substrate where the carbohydrate, proteins, and lipid values are obtainable from USDA or similar archives.

Since Buswell's time, there have been several phases of model development for the biochemical anaerobic digestion process, but the real swell of innovation didn't happen until computer processors became fast enough to model all of the complex simultaneous differential equations involved. In 1987, The International Association on Water Pollution Research and Control (IAWPRC) released a model called the Activated Sludge Model #1 (ASM1) which presented a guideline for the characterization of wastewater sludges and provided a set of default parameters that would yield realistic model results. More importantly, it standardized a "language" for anaerobic digestion researchers to share and allowed their understanding to deepen. This model was widely used through the nineties and as the general biochemical knowledge of the process grew, so did the model complexities: ASM2 was released in 1995, ASM2d in 1999 and ASM3 in 2000 [26].

The ASM family of models paved the way for the International Water Association to collaborate on a new model of the AD process in 2002 which would improve the modeling to include the advances of computer technology and the increased understanding of the AD process in general. This model is called Anaerobic Digestion Model #1 and is the focus of the next chapter.

Section 2.6 Comparison of AD Efficiency with Other Renewable Sources

Anaerobic Digestion is often referred to as the “constant renewable energy source” because biogas is produced at a constant rate compared with the intermittent nature of solar and wind power. In order to provide a brief overview of the technologies, a comparison of the energy extraction versus energy potential of renewable technologies (solar panels, wind turbines, and anaerobic digestion of biomass) is investigated in the *Table 2* below.

For solar panels, there is approximately 1kWH/m^2 of sunlight available for an estimated of 3.5-6 hours per day in North America.. Of this solar energy, currently technology allows a 14% conversion into electrical energy through the use of solar panels. Further considering the wiring, battery, and inverter losses brings the practical efficiency of this technology down to 11% or about 110 Wh/m^2 overall efficiency. For wind turbines, the amount of available energy depends on the speed and direction of the wind. A theoretical energy extraction of 59% is available but in practice, a maximum extraction of 45-50% is possible but only at a specific wind speed. Considering mechanical conversion (gear box) and electrical conversion yields a maximum practical efficiency at a specific speed of 35%. For biomass, the energy potential lies in the Specific Gas Yield for a specific substrate. It is proportional to the amount of organic material present. Maximum gas potentials can be over 1000 m^3 of Biogas for 1 ton of VS. Practically, only about 35% of the potential energy available in the organic material is extracted for energy purposes. This percentage considers only the amount of energy available from burning the resulting biogas in a water boiler or similar high-efficiency technology. For electrical conversion without heat recovery, this percentage drops to 10% overall efficiency.

	Energy Input	Availability	Energy Available	Theoretical Efficiency	Practical Efficiency
Solar	Sun	Seasonal/Intermittent	$1kWh/m^2$	14%	11.00%
Wind	Wind	Intermittent	Depends on Velocity	59%	35%
Biomass	Organic Materials	Continuous	Organic % of Substrate	100% degradation of all VS	35%

Table 2: Efficiency Comparison of Renewable Technologies

Chapter 3

Anaerobic Digestion Model #1 (ADM1)

Section 3.1 Description and Literature Review

The most advanced and accurate predictor of biogas produced from anaerobic digestion comes from the Anaerobic Digestion Model 1 (ADM1). ADM1 was developed by the International Water Association in 2002 with the objective of building a mathematical model of anaerobic digestion based on the interactive, dynamic chemistry of anaerobic reactors. Currently, it is the research tool which most completely models the process in which a complex substrate is broken down by microorganisms in the absence of oxygen. For those not trained in biochemistry and familiar with the wastewater engineering field, ADM1 is extremely complicated to use and requires extensive knowledge of the biochemistry involved in the anaerobic process as well as a complete chemical breakdown of the input substrate. This is unfortunate for power engineers as the output of this model can be very useful for energy calculations. A solution is sought that will bridge the gap between commonly understood and measured parameters and ADM1.

The first step of the ADM1 model converts solids into carbohydrates, lipids, proteins and inert material (soluble and particulate inert). The second step is the hydrolysis process which disintegrates the products of the first step into sugars, amino acids and long chain fatty acids (LCFA). Next, the amino acids and sugars are fermented to produce volatile fatty acids (VFA), hydrogen, and carbon dioxide (acidogenesis). Then the organic acids (LCFA, propionic acid, butyric acid and valeric acid) are anaerobically oxidized into acetate, carbon dioxide and hydrogen (acetogenesis). In the last step, this carbon dioxide and hydrogen is turned into methane by methanogenic bacteria (methanogenesis).

For wastewater applications, the ADM1 input parameters are estimated from experimental data as well as expert knowledge about expected characteristics. For the Differential and Algebraic Equation version of the ADM1 model (DAE) developed in 2006 there are 26 dynamic state concentration variables, 19 biochemical kinetic processes, 3 gas/liquid transfer kinetic processes and 8 implicit algebraic variables represented with varying sensitivities. The 26 DAE state variables are calculated at each time (t) by solving a set of differential equations made up of ADM1 process rates, configuration, inputs, and initial conditions so at any time t, the digestion process can be defined by its set of 26 variables [20]. In order to use this model with complex substrates, the practical characteristics of solid wastes need to be interpolated into their carbohydrate, protein and lipid constituents because complex particulate waste is assumed to be homogeneous and already disintegrated down to that point. The hydrolysis step represented by first-order kinetics as a summary of all the biological processes occurring. This step is one of the most important for the digestion of food waste. The next section will deal with the most important parameters that should be verified when modeling with ADM1.

Section 3.2 The most important parameters

For heterogeneous complex food waste substrates, among the most important parameters are the hydrolysis constants for proteins, lipids, and carbohydrates. Batstone's original text on ADM1 lists the disintegration constant (k_{dis}(d^{-1}), hydrolysis constant for carbohydrates (k_{hyd_ch}(d^{-1})), hydrolysis constant for proteins (k_{hyd_PR}(d^{-1})), hydrolysis constant for lipids (k_{hyd_LI}(d-1)), and the residence time ($t_{res,X}$ (d)) as the parameters with the highest sensitivity when dealing with high-rate mesophilic digestion of solids. It is stated that the variability of k_{dis} and k_{hyd_LI} are variable within a factor of 300% while k_{hyd_CH} , k_{hyd_PR}, and t_{res} are all variable within a factor of 100%. This provides a bounded starting point for the modeling of food waste [20].

Since t_{res} is listed as one of the most important parameters in the model, it is important to note that it doesn't actually appear as an input to the ADM1 model, rather, it is inferred from the daily flow rate and the volume of the digester. A daily flow rate Q in tons is provided to the input along with a volume of in m^3 of the digester itself. The residence time is obtained by multiplying these two numbers. So in order to change the residence time, it is possible to change one input or the other, or both at the same time.

The hydrolysis kinetics listed above are given as generic values in the original ADM1 literature, but a year later a book was published on ADM1 that deals more with the organic fraction of municipal solid wastes [15]. In that book it gives a range for the hydrolysis constants for organic food waste and they are at least a factor of ten smaller than the rate constants given in the original literature. They are as follows:

Carbohydrates	$k = 0.5 - 2\ (d^{-1})$
Lipids	$k = 0.1 – 0.7\ (d^{-1})$
Proteins	$k = 0.25 – 0.8\ (d^{-1})$

In 2009, [25] listed that the default hydrolysis rates from the original ADM1 model are now considered to be too slow by a factor of 10. Experimental data yielded the following values for the hydrolysis rates:

Carbohydrates	$k = 5.22\ (d^{-1})$
Lipids	$k = 1.24\ (d^{-1})$
Proteins	$k = 1.86\ (d^{-1})$

Plugging these values into ADM1 and leaving all of the rest of the inputs as the standard values gave biogas predictions that were sometimes a factor of 6 too large compared with experimental values.

Section 3.3 Limitations for Energy Calculation

Although ADM1 is the most robust and complex tool for modeling the anaerobic digestion process itself, it's also extremely complicated and takes years of background expertise to understand how it works and even more expertise to confidently make changes to all or many of the inputs. If you don't have a biochemistry background, there is little chance of being able to use ADM1 as a research tool for a non-standard substrate, which is unfortunate because there is a lot of potential for collaborative efforts with renewable energy engineering projects.

In order to make more accurate predictions of biogas outputs, another modeling technique was needed. This was found in an input transformer released in 2009.

Chapter 4

Using a Transformer to Calculate Inputs to ADM1

Section 4.1 Description and Implementation

Acknowledging ADM1's complicated nature and the difficulty involved in implementing non-standard wastes into the model, a transformer was developed to interpolate ADM1 inputs from 11 commonly available measurements that show up in literature. In order to use this model with complex substrates, the practical characteristics of solid wastes need to be expressed by their carbohydrate, protein and lipid constituents. In 2009, a transformer was developed which improves on the Continuity Based Interfacing Model (CBIM) developed in 2005 [28][25][27]. The CBIM balances the macronutrient (CHNOP) elemental continuity with respect to Chemical Oxygen Demand (COD) balance and charge balance. The CBIM assumes the input feedstock to have a constant composition which does not allow for dynamic simulation. The transformer in [25] takes this process a step further by attempting to maintain the mass balance, COD balance, and charge balance according to a predefined, ordered, maximization procedure. This transformer allows ADM1 to be more accurately employed as a biogas estimation tool.

The transformer allows the 32 required inputs for ADM1 to be estimated for complex substrates through the input of 11 parameters. This development helps to strengthen the link between ADM1 and commonly measured characteristics of solid wastes. The transformer was programmed in C and incorporated into a General Integrated Solid Waste Co-Digestion model (GISCOD) that runs in Matlab-Simulink [25].

The transformer developed by Zaher is much more useful for prediction of biogas for energy calculations as it originates in Microsoft Excel and is straightforward to use. Previously the only way to manipulate input parameters to ADM1 was to change the long, involved initialization m-file that accompanies the ADM1 model. This m-file (depending on version) has 102 inputs – 41 stoichiometric, 36 biochemical, 23 physiochemical, and 2 physical parameters. The inputs required in the excel worksheet can be seen below:

time	CODp	DODs-VFA	VFA	TOC	Norg	TAN	TP-orthoP	orthoP	TIC	Scat	FS	flow
(d)	(gCOD m^{-3})	(gCOD m^{-3})	(g COD m^{-3})	(gC m^{-3})	(gN m^{-3})	(gN m^{-3})	(gP m^{-3})	(gP m^{-3})	(mol HCO_3^- m^{-3})	(equ m^{-3})	(g m^{-3})	(m^{-3}/d)
0	386,400	3500	8747	139280	14000	1300	720	886	40	25	31000.00	0.27
1000	386,400	3500	8747	139280	14000	1300	720	886	40	25	31000.00	0.27

Table 1. 11 Required inputs to transformer.

One of the most common measurements of wastes used for anaerobic digestion is chemical oxygen demand. The four main kinds of COD can be broken down as below:

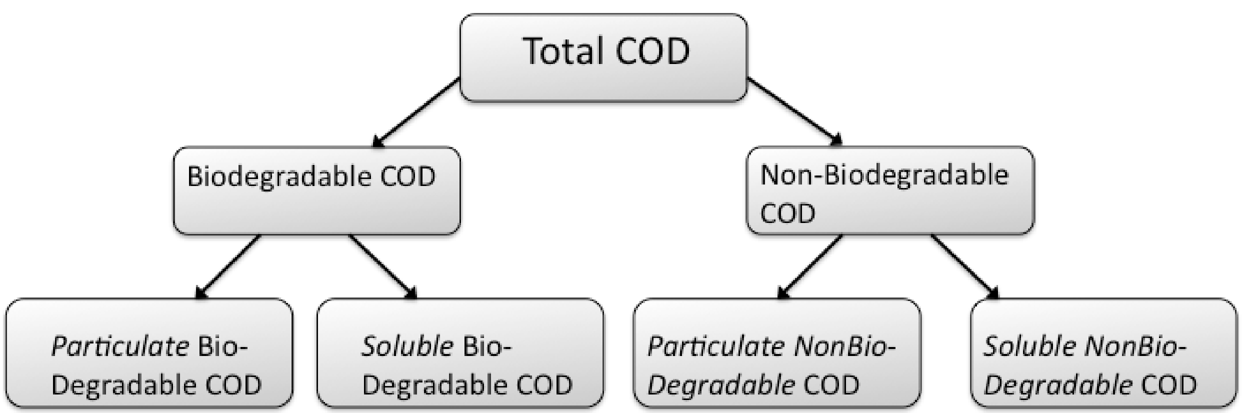


Figure 8. COD breakdown in AD process

For the transformer method of solid waste digestion, the following practical characteristics are considered available: total COD (CODt), particulate COD (CODp), soluble COD (CODs), VFA, total carbon (TC), total organic carbon (TOC), total inorganic carbon (TIC), TKN, TAN, total phosphorous, orthophosphate (orthoP), total alkalinity (Scat), total solids (TS), and total volatile solids (TVS). From these characteristics, the 11 inputs to the transformer can be determined as follows:

1. *Particulate COD (CODp) in gCOD/m^3*

   This value is calculated as total COD minus soluble COD (CODt – CODs) where soluble COD is split into soluble substrate minus COD of VFAs (CODs – COD of VFAs) and VFAs. (In literature, particulate COD for food waste is approximately 97% of total COD as a very small percentage of a mixed food waste has become soluble [16][25]).

2. Soluble COD without VFA COD (CODs – VFA) in gCOD/m^3

   This value doesn't show up often in literature or common measurements but it can be obtained by subtracting the chemical oxygen demand of the VFA in the next step from the particulate COD obtained from the total COD above.

3. Volatile Fatty Acids (VFA) in gCOD/m^3

   This value is likely to be found in literature. In the case of food waste, the VFAs are formed later in the process and there aren't many in the initial state of the waste. A literature review shows COD of VFAs to be 2% of the total COD as a marker.

4. Total Organic Carbon (TOC) in gC/m^3

Total Organic Carbon is a measurement of decaying organic material, bacterial growth, and the metabolic activities of the microorganisms contained in the substrate. A total carbon (TC) measurement often shows up in literature and the TOC can be determined by subtracting the total amount of inorganic carbon (TIC) from the TC.

5. Total Organic Nitrogen (Norg) in gN/m^3

Typically the amount of organic nitrogen is calculated by subtracting the amount of inorganic nitrogen from the value of total nitrogen measured. The mass fraction for the transformer comes from the assumption that only the proteins in the substrate contain nitrogen. The estimated protein formula is: $C_6H_{12}0_3N_2$.

6. Total Ammonia Nitrogen (TAN) in gN/m^3

Calculation of this parameter is based on the stoichiometric formula for ammonium – NH_4^+ - and can be calculated directly from a measured concentration or a value from literature. TAN can also be calculated by subtracting Norg from Total Kheldal Nitrogen.

7. Organic Phosphorous (TP-OrthoP) in gP/m^3

Organic Phosphorous is measured by subtracting the inorganic orthophosphates from the total measurable phosphorous in the substrate. Phosphorous is classified as a macronutrient and is extremely important in the metabolism of microorganisms. Inside the cells, it allows for the transfer of energy from one reaction to the next.

8. Ortho-Phosphate (orthoP) in gP/m^3

OrthoP is considered inorganic phosphorous and it is calculated by measuring the amount of PO_4^- in the substrate. Orthophosphates are produced when microorganisms breakdown organic phosphorous.

9. Total Inorganic Carbon (TIC) in mol HCO_3^-/m^3

   TIC is calculated by measuring the moles of bicarbonate in the substrate and using the stoichiometric formula to directly compute elemental mass fractions.

10. Total Alkalininty (Scat) equ $/m^3$

   This parameter is measured directly and is an estimate of the alkalinity of the substrate. Alkalinity can be used as a sort of "manual buffer" for the system if the VFA levels are peaking and the pH drops too low. It can be seen as a manual addition of bicarbonate to the system if the value is arbitrarily increased.

11. Fixed Solids (FS) in g/m^3

   Fixed solids are the measure of inert solids in the input substrate. It is calculated by subtracting the amount of volatile solids from the amount of total solids.

Once all of the parameters have been determined and input to the Excel file, a Matlab script reads them from Excel and places them in the Matlab workspace.

From the workspace, practical characteristics and flows of the waste are placed in the transformer nodes and a set of algebraic equations maps the influxes to vectors where the stoichiometry matrix – a two dimensional array – is loaded into the workspace. A maximization procedure then occurs based on the original CBIM but maximized by Zaher in [25] to conceal and correct any possible errors in the practical measurements and retain overall mass balance during all of the conversion steps. A predefined order maximizes the conversion steps of the AD process. The output of the process after the desired HRT shows up in the Matlab workspace and can be pasted back into Excel and saved with the input parameters.

Section 4.2 Transformer Benchmarking

In the case of not being able to measure all of these parameters directly, the engineer can use literature and specialized archives (USDA, etc.) to determine the necessary input parameters to the transformer. In order to verify this process, a benchmark test was done with data not included in Zaher's [25][27] papers on the transformer.

Using a white, medium sized potato as the desired substrate for digestion and the USDA food databases [29], and a literature review [30][31][32], the transformer was used to model potato waste in ADM1 and the results were compared with the results from experimentally determined of biogas yields.

ADM1 transformer inputs:

1. CODp = 206,200
2. CODs – VFA = 37,000 – 19,000 = 18000

3. VFA = 19,000

4. TOC = 76,000

5. Norg = 4225 (18:1 C:N ratio)

6. TAN = 144

7. OrthoP = 570g

8. OrthoP = 180g

9. TIC = 16

10. Scat = 25

11. FS = 9500

Biogas Yield of Potato Waste based on 3 Techniques

1. Proximate Analysis of Carbs/Starch = **614 m^3/ton** VS (175% error)
2. Nutritional Breakdown (USDA) = **423 m^3/ton VS (**88% error)
3. ADM1 + Transformer + Estimated parameters from Literature = **244 m^3/ton VS** (9% error)

   Experimental = **224 m^3/ton VS** [22].

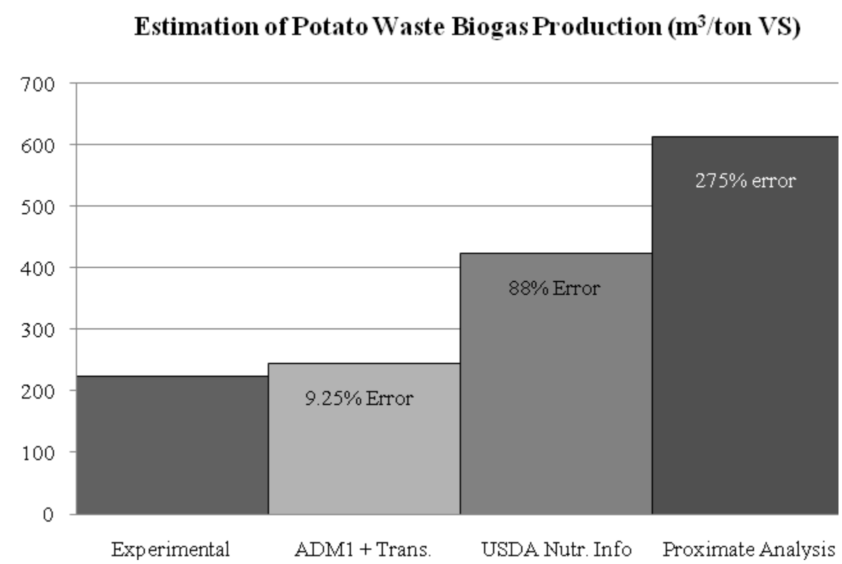


Figure 9. Biogas estimation techniques for medium white potato waste

Similarly, ADM1 was used to predict biogas output from food waste by using transformer inputs for kitchen waste and experimental hydrolysis rates (5.22, 1.86, and 1.24 d^{-1} for carbohydrates, proteins, and lipids respectively) found in [25]. The disintegration constant k_{dis} was set at 0.5 for solid waste according to [15].

The inputs to the transformer are seen below:

1. CODp = 368,400
2. CODs – VFA = 3,500
3. VFA = 8,747
4. TOC = 139,280
5. Norg = 14,000
6. TAN = 1,300
7. OrthoP = 720
8. OrthoP = 886
9. TIC = 40
10. Scat = 25
11. FS = 31,000

Biogas Yield: **316 m^3/ton VS** = 14% error compared with experimental yield of 367 m^3/ton VS.

Summary of three techniques as follows:

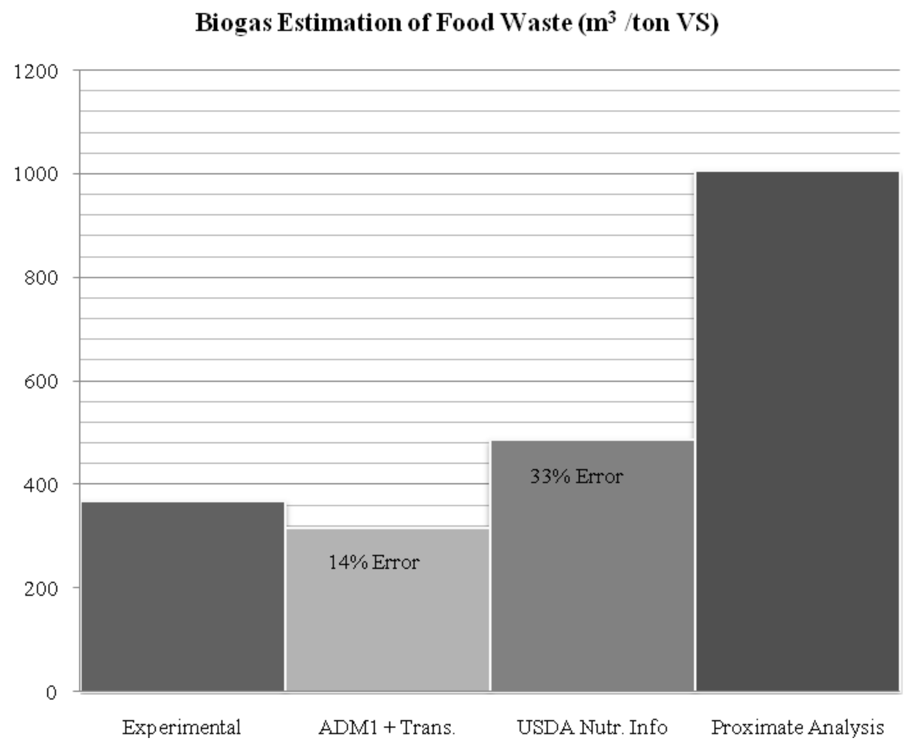


Figure 10. Biogas Estimation Methods for Food Waste

Chapter 5

Case Study of Food Waste to Energy at Concordia University

Section 5.1 Introduction

Concordia University is a prime candidate for urban waste-to-energy technology as it already has a very active sustainable ethos and community. A student-driven initiative entitled "Sustainable Concordia" was formed in 2002 to work toward making the downtown and suburban campuses of Concordia more sustainable in practical ways. On their website, the organization claims to be "…a nexus that engages students, staff, faculty and administrators to work together in non-hierarchical consensus based decision-making processes to address issues of sustainable development on campus. [34]" In the past eight years Sustainable Concordia has established sustainable transport, recycling, assessment, composting, vermi-composting and greenhouse programs. Interested in furthering the vision of a renewable, sustainable future, they have agreed to offer any information they have and even funding to help build a waste-to-energy system on campus. The proposed site is the top floor of the Hall building, a 14-story building in the center of downtown Montreal - home to two cafeterias and several small coffee and food shops.

There already exists a greenhouse on the roof on the Hall building that is host to student research projects and a vermi-composting system that digests 10 tons of organic waste per year (mainly coffee grinds and vegetables) and the resulting fertilizer is used in the greenhouse for the plants. There has been a proposal submitted to the Canadian Foundation for Innovation to renovate this greenhouse and turn it into an integrated urban

Renewable Energy Laboratory which would have PV panels, a wind turbine, and an anaerobic digestion waste-to-energy system. It would be the first of its kind in North America.

This proposed lab would be used for studying the integration of renewable energy sources in the urban environment at full scale. The goal would be full functionality as a standalone entity that could provide enough energy to supply all of its loads. Excess heat and energy could be tied into existing building heating and electrical systems and provide a unique example of what can be done with urban rooftops. This greenhouse could also serve as example of how to build a grid-tied or standalone renewable energy system in different settings. A waste-to-energy system that can digest up to 165 tons of food waste per year has been included in the proposal. A photo of the proposed anaerobic digestion system location in the greenhouse and a model of the proposed greenhouse are seen below.

Figure 11. Location of proposed renewable energy greenhouse lab and anaerobic digestion system

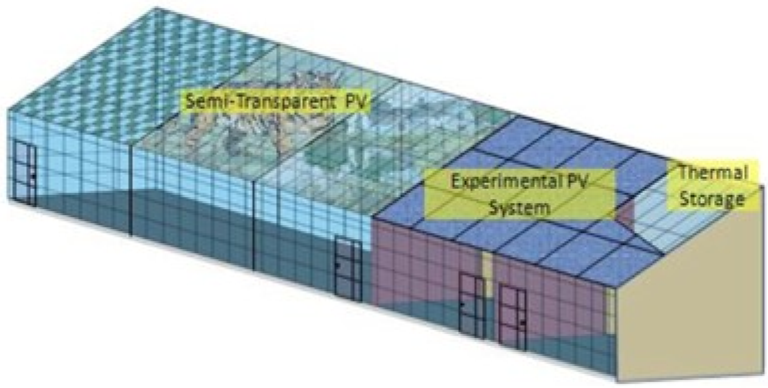


Figure 12. Proposed Greenhouse with solar paneling

Section 5.2 Waste Analysis

Waste Analysis is one of the most important steps in the AD process. Knowing the general composition of the substrate (input material) to the system is essential for calculating the amount and composition of the biogas produced as well as the amount of energy contained in the biogas. The focus of this research is on a general mixed food waste that is found in most large kitchens and cafeterias in urban high-rise buildings.

If organic waste is not source separated, it is necessary to do a waste audit to accurately determine the percentage of the total waste that is biodegradable. At Concordia University, a Sustainable Concordia does a yearly month-long waste audit to estimate the average composition of the waste that is sent to the landfill. The waste is collected daily from selected locations across both campuses to try to give the most accurate picture as possible of the weekly composition. The results from the most recent waste audit in 2007 can be simplified into the following waste breakdown:

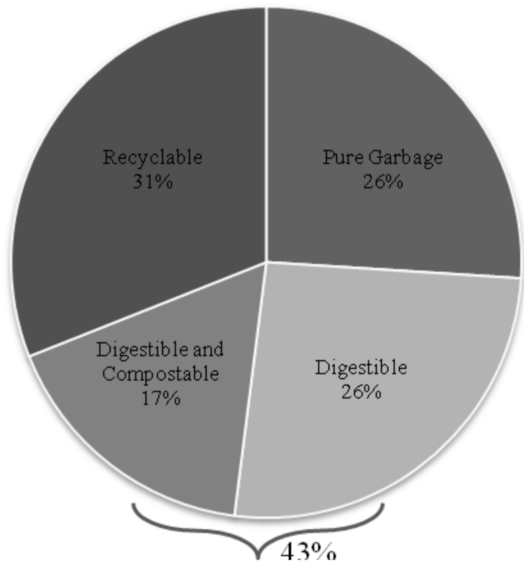


Figure 13. Waste Breakdown for the Downtown Campus (2007).

According to the audit from 2007, the average amount of digestible waste is 43% of the total waste. From the records of the waste sent to the landfill, a total tonnage of waste can be calculated as well as a reasonable estimate of how many tons of waste per year are theoretically available for anaerobic digestion. From the landfill records, it's also possible to determine how much waste comes from individual buildings and then estimate the amount of organic waste located therein.

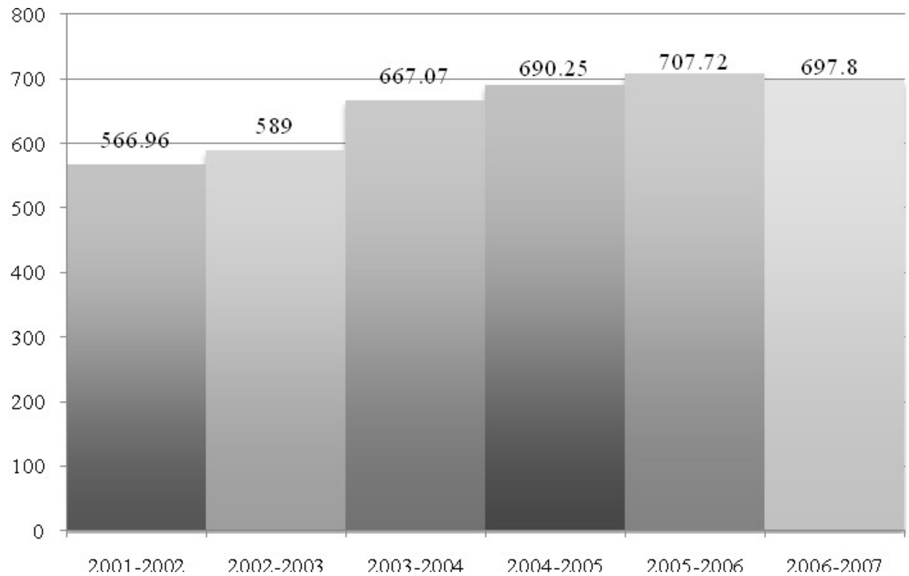


Figure 14. Total Tons of Waste Sent to Landfill Annually

It can be noticed from the above graph of the total amount of waste sent to the landfill over the last few years that the total waste produced in 2006-2007 was actually less than the waste produced the year before. This is due to increased recycling and general awareness of the sustainability effort on campus. In spite of this seemingly positive advance, the cost of waste disposal has risen by 14% each year and will most likely continue to rise in the coming years as the price of petroleum based fuels rise.

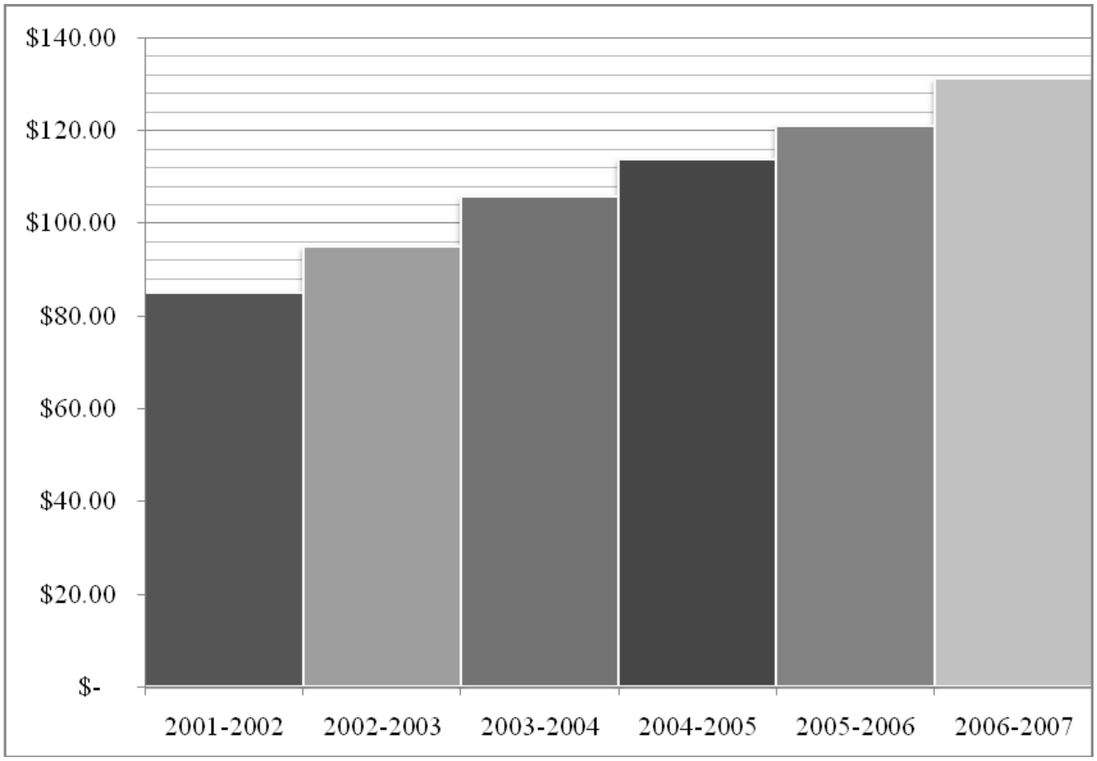


Figure 15. Cost of Waste Disposal (Landfilling) Per Ton in Montreal, QC

Taking the most recent year's data as an example, Concordia sent 698 metric tons of waste to landfill at a cost of $131.28 per ton for a total cost of $91,608 (further cost analysis will be presented in Chapter). Consulting the landfill records for the entire university and then selecting the buildings located in the downtown campus, it can be shown that 55% of Concordia's waste was produced on the downtown campus totaling 385 metric tons. Taking into account the fact that approximately 43% of this waste is biodegradable and could be used for composting or anaerobic digestion, 165 tons of food waste is available. The amount of waste per month fluctuates with the season and as a result, the biogas output would not be constant unless the waste is first stored and fed at a constant controlled rate.

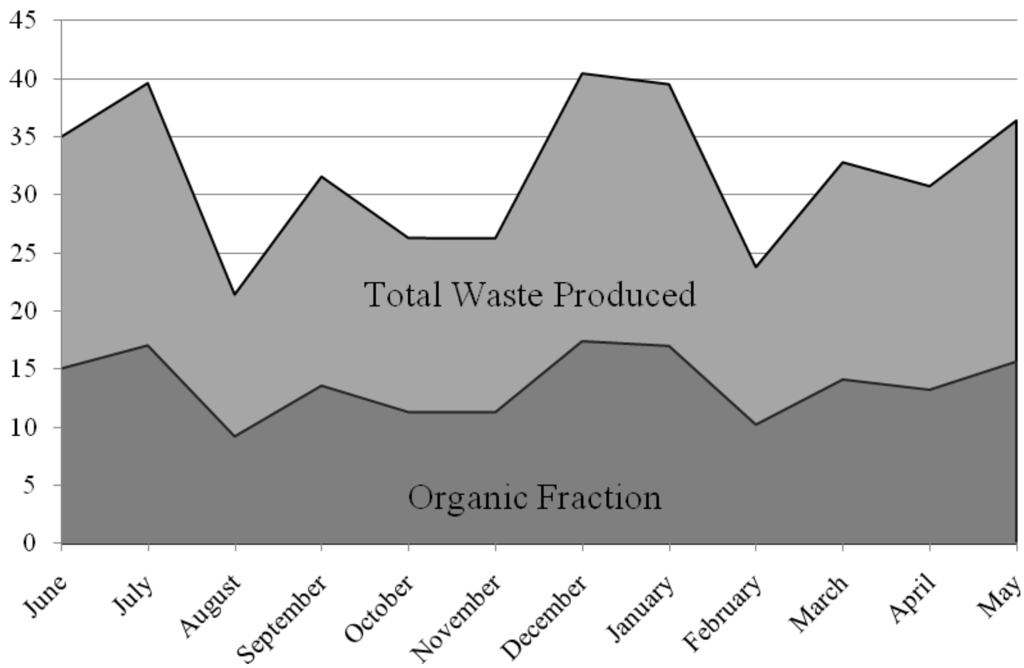


Figure 16. Downtown Waste Fluctuations Over the Course of a Year (tons)

Section 5.3 Energy Production

In order to estimate the amount of energy in the biogas it is necessary to know the average biogas yield per ton of food waste input. Each substrate is different and studies have been performed to determine appropriate values. For mixed food waste, a year-long study (released March 2008) performed by the Environmental Protection Agency in East Bay, California, fed 100 tons of mixed food waste daily into a mesophilic digester and yielded an average of 367 m^3 of biogas per ton of food added to the digester [16]. For 165 tons of food waste produced on the Concordia downtown campus, there would be annual yield of 18,350 m^3 of biogas with a composition of 65% methane and 35% CO_2.

Using the transformer and ADM1 to calculate annual biogas output for the food waste produced on the downtown campus of Concordia provides similar results to experimentally verified yields. If the standard ADM1 model is modified with values found in literature in order to predict biogas output from food waste, the results are not usable. The transformer is a step forward in allowing the complex model to be used as a design tool without doing months of testing in the laboratory for dozens of specific biochemical concentrations. This is demonstrated below.

If 165 tons of food waste are to be digested annually, this suggests 50 tons of VS. Using the relationship presented in Section 2.2, this represents 100 annual tons of COD or 274 kg daily COD. Factoring in the density of food waste (0.78), 348,000 g of total COD is available per m^3. Assuming 95% VS/TS, COD_p becomes 330,600 g /m^3. Scaling the parameters presented in Zaher's GISCOD paper [25] for food waste with this calculated COD value the following inputs are used in the transformer as well as a 30 m^3 digester volume and flow rate of 1.2 m^3 /day:

1. CODp = 368,400
2. CODs – VFA = 3,150
3. VFA = 7,872
4. TOC = 125,352
5. Norg = 12,600
6. TAN = 1,300
7. OrthoP = 720
8. OrthoP = 886
9. TIC = 40
10. Scat = 25
11. FS = 31,000

As in Section 4.2, the following hydrolysis constants were used: 5.22, 1.86, and 1.24 d^{-1} for carbohydrates, proteins, and lipids respectively. The disintegration constant k_{dis} was set at 0.5 for solid waste according to [25]. The predicted biogas output for the year is 16,400 m^3 or 328 m^3/ton VS at 65% CH_4 [*see Appendix A for code and GISCOD Matlab diagram*]. This is a 10% under-prediction as compared with experimental food waste digestion yields of 367 m^3/ton.

If the standard ADM1 model is used with the above parameters and the same digester size and flow rate, the output is only 342 m^3 of biogas per year which means less than 7 m^3 / ton VS [*See Appendix A for code*]. This failure of digestion is most likely due to the fact that the pH of the system drops because of too many VFAs. The transformer helps combat this by the maximization procedure developed to accurately convert the 11 commonly measured input parameters into more accurate ADM1 input compositions. Without the transformer, extensive bench scale digestion is required of specific food waste samples in order to calculate necessary ADM1 inputs.

Once the biogas output has been determined, there are many available references to determine the energy content of biogas, but an agreed heat of combustion value is 6.25 kWh/m^3 [34]. Knowing there are 18,350 m^3 of biogas available, the total energy content of the biogas can be calculated as 114,688 kWh annually. If the biogas is sent to a 10kW water boiler, 90-95% of the energy or 103–109 MWh/year is available due to boiler efficiency. If the biogas is sent to an internal combustion engine attached to a 3kW generator, then the efficiency drops to 35% and there is only about 40MWh (Fig. 8.) of energy is available. In Concordia's case, it has been calculated that if all 18,350 m^3 biogas were sent to the water boilers located in the same building, the total energy costs for heating could be offset by 3%. The Hall building consumed 648,000 m^3 of natural gas in 2008 to heat the building. Heating accounts for 30% of the total building's energy consumption. Anaerobic digestion of the buildings food waste could offset 1% of the total building energy load.

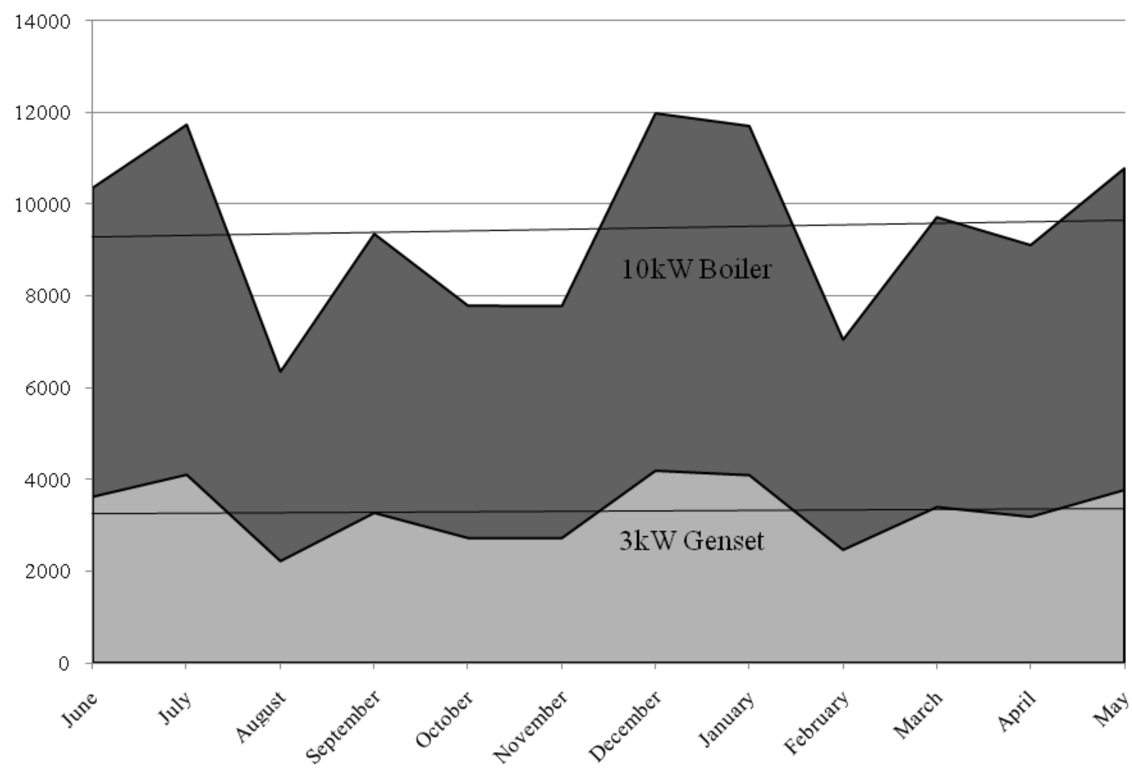


Figure 17. Annual Thermal and Electrical Energy Content of Biogas in kWh

Section 5.4 System Design

Implementing an anaerobic digestion system in the urban environment presents several unique challenges due to the explosive nature of the gases involved and the paradigm shift involved with more waste handling and management occurring inside of city buildings. Additionally, designing a system that is feasible for the amount of waste produced and the amount of space available and retrofitting it to the building also presents unique challenges.

In the specific case of Concordia University the following system design has been proposed and includes a shredder, hydrolysis/pasteurization stage, digestion tank, genset, boiler, screw press to separate the liquid digestate from the solid, composter to continue to neutralize any pathogens remaining in the solids, and aeration tank to neutralize the liquids. The liquid and solid digestate can then be used as nutrient-rich fertilizers.

The proposed plan involves collecting 100 – 165 annual tons organic wastes from various locations on the downtown campus including one large cafeteria, a smaller kitchen, and several coffee shops. Organic waste will be collected daily using 250l bins and will be transported to the greenhouse on the 13th floor of the Hall building. The food waste will be dumped into a 300 l hopper which will feed into a shredder to produce a particle size of 5 mm or less. Shredding the organic material allows for greater surface area for the microbes to break down the organic material and allows the resulting slurry to be pumpable. The shredder will be mounted to a 4 m^3 mixing tank and the shredded product will be mixed with liquid from the storage tank of separated water at the end of the process. This first tank will be where the hydrolysis stage of the AD process begins. A side mounted mixer will ensure a complete mix of the waste as it starts to breakdown. Because hydrolysis can produced very unpleasant odors, the tank is kept under negative pressure and the air is forced through a bio-filter for deodorization before it is vented outside.

The resulting slurry will then pumped into a 30 m^3 polyethylene tank where the anaerobic digestion will occur. This tank will be modified to accommodate a top-mounted mixer and will be insulated with polyurethane and equipped with custom steel cladding. The tank will be protected with over and under pressure vents and an automated, enclosed biogas flare.

The hydrolysis and reactor tanks are sized by the techniques espoused in Section 2.3. If 165 tons of food waste are available for annual substrate digestion, then a flexible HRT can be designed around a desired OLR and solids pumpability. Using a dryness value of 30%, the food waste density is 0.78 kg / m^3. This provides an annual volume of food waste of 211.5 m^3 and a daily average volume of 0.58 m^3. In order to ensure pumpability of the daily shredded input, dilution is needed with at least a 2:1 water to solids ratio to bring the solids down to 15% or less. Due to the fast rate of disintegration and hydrolysis where active bacteria are present (0.5-1days), the hydrolysis tank only needs to be able to contain about 3 days of waste (in case of a shut down or long weekend) so a size of 4 m^3 should be adequate.

In the case of the reactor, using a daily flow rate of 1.2 m^3, a reactor size of 30 m^3 can be suggested and verified. In this case, the HRT would be 25 days which provides an upper limit for biogas production as not much additional biogas production occurs after 25 days. Using a volume of 30 m^3 and a HRT of 25 days, the OLR would be 5.4 kgVS / m^3 / day which is well within the upper range of 10 kgVS / m^3 / day suggested by literature. This sizing will allow for an increased amount of annual waste to be added if, for example, the food waste from a nearby restaurant is added. If the HRT is decreased to 15 days, the daily input flow could be as high as 2 m^3 at 15% or 1 m^3 of VS meaning 285 wet tons of food waste annually.

The top-mounted 1hp mixer on the reactor will have a stainless steel shaft and paddles and will run at a slow rpm approximately 8 hours per day. The tank temperature (35°C) will be maintained by circulating the substrate (15% TS) through a hot-water heat exchanger. This provides additional mixing for the system.

Feeding the digester will be attained through the interruption of substrate re-circulation by using a 3-way valve that diverts the intake of the pump from the digester to the mixing/hydrolysis tank. Slurry will then pumped from the mixing tank to the digester at the predetermined organic loading rate (4-10 $kg/m^3/day$) and the 3-way valve is returned to its re-circulation position for heating and mixing.

In order to combat the amount of the corrosive hydrogen sulfide (H_2S) in the biogas produced by the process, a small quantity of air will be injected into the digester head. This allows the H_2S in the biogas to be converted by bacteria to elemental sulfur that will cling to the tank roof and cleaned when necessary.

Generated biogas will be stored a 10 m^3 double-membrane gasholder. This gasholder is sized by taking the predicted average hourly biogas flowrate and multiplying by a projected amount of hours that the system would be down for repairs as well as the space available for storage. In this case, the 10m^3 gasholder size comes from a 2m^3/hour biogas flowrate, 5 hours of downtime gas preservation, and the size of the proposed greenhouse. If the gasholder is full and the gas utilization system is still down, the gas will be flared until operation resumes. The biogas line will be equipped with standard gas safety devices such as flame arrestor, check valve, and drip trap. Biogas will be directed to a 3kW genset for demonstration purposes or a10 kW biogas boiler for hot water generation.

Part of the hot water can be used for heating the digester circulation system and extra can be used for heating applications in the greenhouse or sent directly to the natural gas heaters located a floor above the proposed AD system. Any biogas overflow will be directed to the flare for destruction. The flare sizing is sized according to predicted biogas production flowrate. In the case of this design, the flare is oversized by two times the flow rate to assure all methane will be oxidized to CO_2 and H_20.

The digestate at the end of the process will be directed to a screw press for manual dehydration. The solids will fall into a container where they can be added to the composter for further digestion/neutralization. The separated liquid will be sent into a storage tank for use in dilution of incoming food waste in the mixing tank or nutrient-rich irrigation for the greenhouse. Any remaining water, once aerated can be sent directly to the sewer. An engineering diagram of the system just described is seen below.

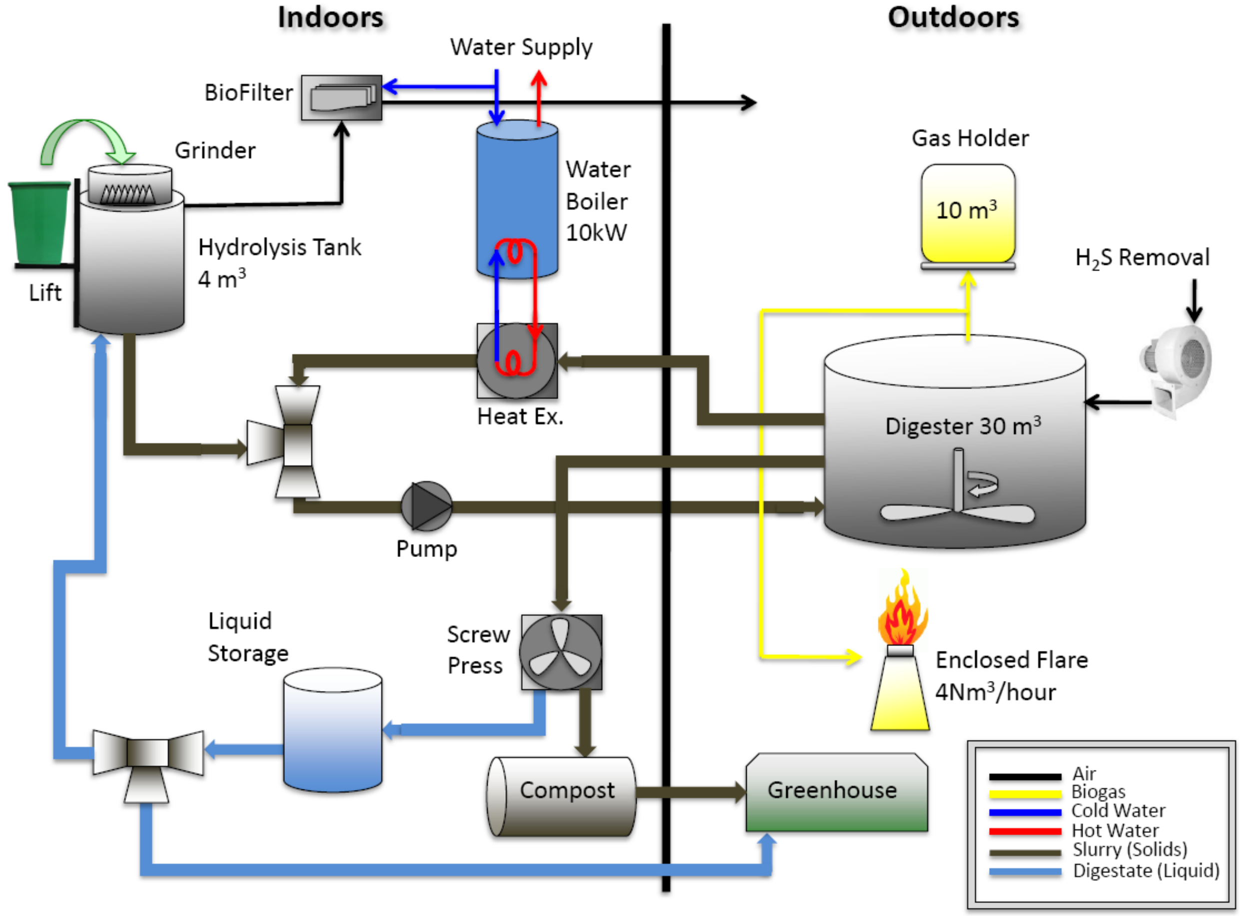


Figure18. Engineering Diagram of Proposed Anaerobic Digestion System

This general design is flexible and could be sized based on expected input tonnage and space requirements to different urban environments. The process will remain the same.

Adjacent to the greenhouse at Concordia happens to be a non-functioning ventilation system room that was used to ventilate chemistry labs below. This room could be cleared of the old equipment and the shredding, loading, hydrolysis, pressing, composting, and aerating stages could occur inside while the digestion tank and flare, and biogas storage could be located in the greenhouse. This concept is shown below in a theoretical plan of the greenhouse.

As seen below in *Figure 20*, the indoor section is divided into a "wet" and "dry" room. The wet room is where the waste comes in, is loaded into the shredder and where the digestate is pumped to be composted. The dry room will house control and monitoring equipment for the process. In the greenhouse, the proposed room for the digester would be technically "outside" as the leftmost exterior wall would be removed so that any unintended biogas leak could escape directly and a dangerously explosive gas mixture could not form in the greenhouse. The $30m^3$ digester would be able to fit easily in the $30m^2$ room as the diameter of the circular tank would be 4 meters and the height only 2.4 meters. The slurry would be pumped from the wet room into the digester and back out while feeding and while not being fed the pumping would just be the heat exchanger loop to maintain the temperature of the substrate.

In order to configure an AD system in an urban environment, special consideration must be paid to standing gas, fire, and building codes as well as health and safety regulations for handling food waste. These issues are addressed in the next section.

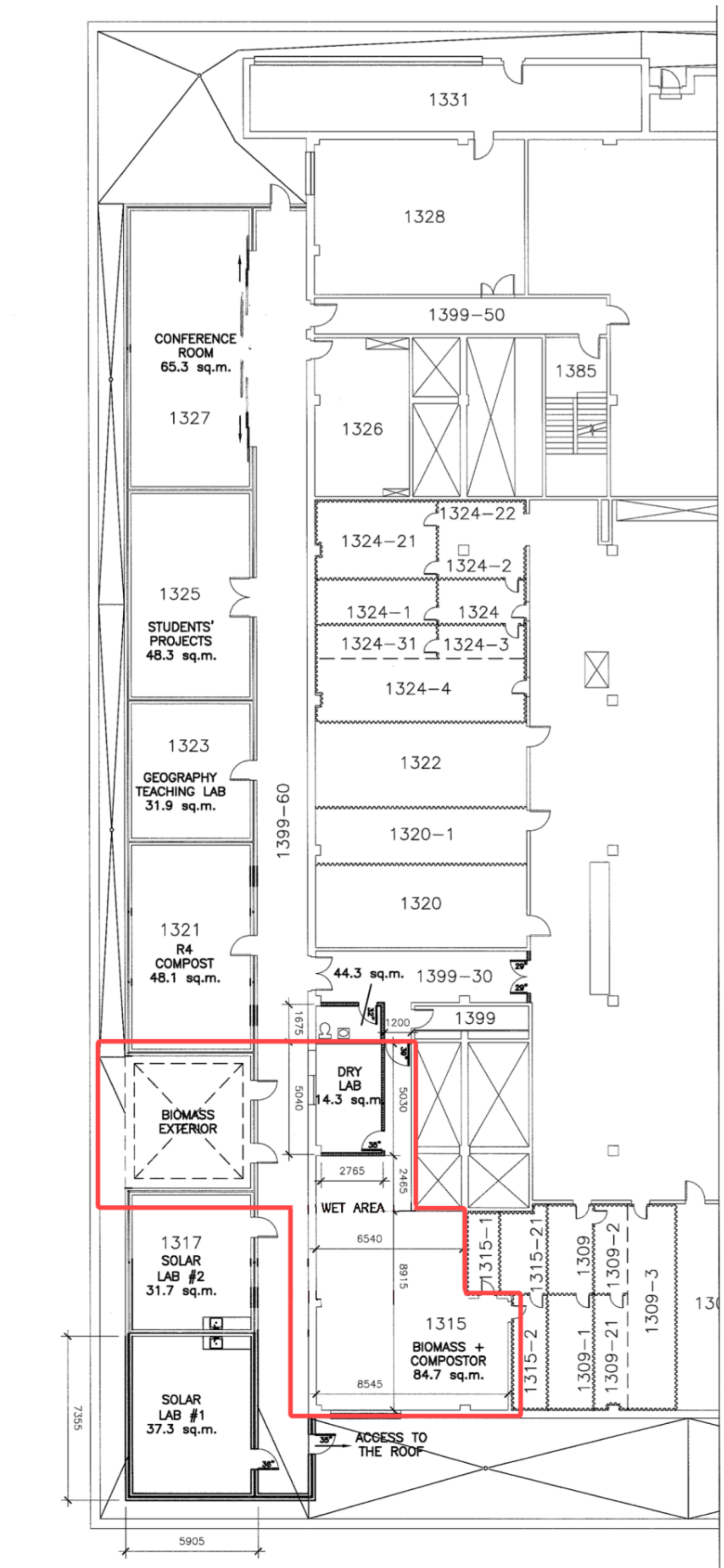


Figure 19. Proposed greenhouse design with AD system highlighted

Section 5.5 Safety Considerations

Due to the possibility of explosive gas/air mixtures existing in biogas facilities, measures that prevent the ignition of a "Dangerous Explosive Atmosphere" must be taken. Explosive areas are 3-dimensional spaces that are divided into zones according to the probability of the development of a dangerous explosive atmosphere due to the percentage of gas present. A list of common flammable gases and their dangerous percentages are listed below.

	Biogas	Natural Gas	Propane	Methane	Hydrogen
Explosion Volume %	6 to 12	4.4 to 15	1.7 to 10.9	4.4 to 16.5	4 to 7

Figure 20. Percentages of Gas Present in Air for Explosion to Occur

For biogas systems, potential flammable zones are classified according to possibility or likelihood of explosion. These zones can be broken down as follows:

Zone 0: Explosive atmosphere that is continuous, long-term, or often

Zone 1: Explosive atmosphere that is occasional

Zone 2: Explosive atmosphere that is unlikely and short-term.

Under normal operating conditions, Zone 0 is virtually non-existent in a biogas system as the system is designed to contain no continuous or long-term explosion zones. The only possible Zone 0 is the intake manifold of a combustion engine if that is connected to the biogas output.

For Zone 1, where a gas or vapor mist can form occasionally, a circumference of 1 meter is required for outdoor situations that have "free ventilation" around all equipment parts, connections, viewing glasses, service openings, and any part of the system that comes into contact with biogas. A distance of 4.5 meters must be respected in closed rooms. Any electrical equipment used in Zone 1 must be rated for Zone 0 or 1 and marked accordingly.

For Zone 2, a distance of 3 meters must be respected around all equipment and system parts classified as "technically tight" meaning they at some point could be opened or dismantled to be cleaned or serviced (connections, discs, viewing glass). Equipment in this zone should be visibly certified and marked for Zone 2. Any enclosed room is considered Zone 2. There is no zone around "permanently technically tight" facility parts [11].

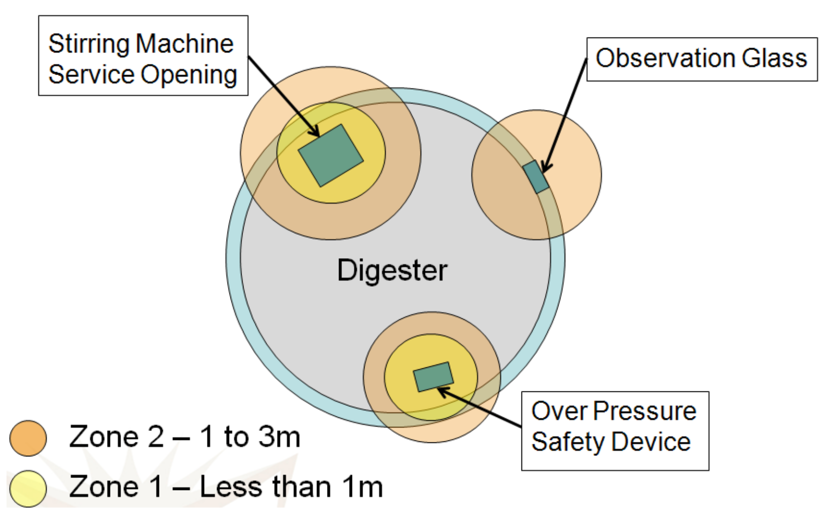


Figure 22. View of Explosive Zones for AD Tank as seen from Above

For biogas storage, the storage vessel must be installed outside or in a room that is well-ventilated. When installed outside, the area 3m around the storage is classified as Zone 2. When stored indoors, the room must be made "smoke proof" and be essentially air tight. This is accomplished by having concrete, brick, metal, or plastered walls. The entire inside of the room in considered Zone 2 including the inlets and outlets of the ventilation system.

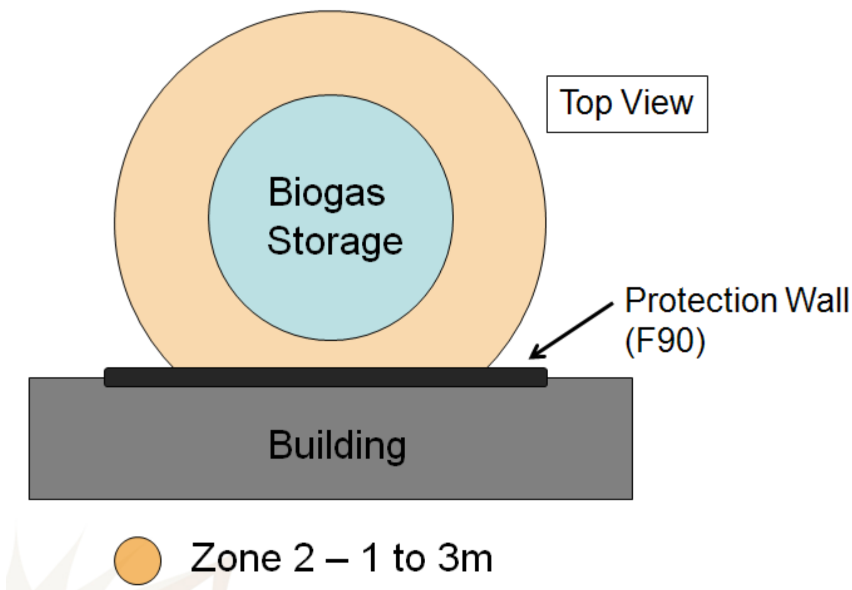


Figure 23. View of Biogas Storage Tank Explosive Zone as Seen from Above

Section 5.6 Energy Usage

This section deals with the energy consumption of the proposed anaerobic digestion system in the Hall building at Concordia University. These figures have been compiled by researching existing systems, reading the specification sheets on appropriate parts, and talking with biogas system operators about how often typical system parts are energized.

Pretreatment Stage:

1. Sidemounted 0.5 HP mixer on the hydrolysis tank – 5min./day	0.473kWh/year
2. Biofilter – Consumes 100W continuously	876kWh/year
3. Food Grinder – 5 minutes per day at 3hp	67.1kWH/year

Digestion:

1. Mixer on top of Digester – 1hp , 1/3 of the time	2,178 kWh/year

Heating of Slurry:

1. Heating load = .3kw during summer/ 1.5kw during winter	7.78 kWh/year
2. Hot water pump = 200 W continuously	1,752 kWh/year

Digestate:

1. Screw Press – 3hp, 30 min/ day	408 kWh/year
2. Recirculation pump – 1hp , 8hrs/ day	2,178 kWh/year
3. Sulphur removal system – 100W continuously	876 kWh/year

Process control:

1. Consumes 200W continuously	1752 kWh/year

From Section 5.2, the annual amount of energy available from biogas produced:

Total Energy Produced = 144,688 kWh

Calculated above the total annual energy consumption:

Total Energy Consumed = 10,095 kWh/year = 7% of total

This leaves 134.6 MWh per year of surplus energy

Section 5.7 Economic Analysis

No novel renewable energy approach or any new technology can be presented as a solution or put into action without a thorough investigation into the cost-benefit analysis. The "bottom line" is often payback period as no one wants to invest large amounts of money into something that won't eventually make them money, or at least save them from spending more money elsewhere. With regard to renewable energy solutions, the long-term cost of not pursuing and funding them is already looming as the planet continues to warm and the population continues to rise and consume increasing amounts of energy.

Working with a biogas engineering firm located in Quebec called Electrigaz, the following prices were quoted in September of 2008.

Electrigaz Quote:

Design and process engineering	$ 18,546
Pre-treatment and mixing tank equipment	$ 30,310
Anaerobic digester equipment	$ 52,256
Feedstock heating and piping equipment	$ 22,650
Digestate management equipment	$ 33,450
Biogas handling & safety equipment	$ 32,320
Biogas boiler equipment	$ 12,900
Process control equipment	$ 4,975
Commissioning & support	$ 10,980
Estimated Total	$ 218,387
Contingency (5%)	$ 10,919
Total Cost	***$ 229,306***

*These costs do not include building modifications to remove the old ventilation system or any construction and assembly costs.

An investigation into potential savings from the proposed biogas system should give an accurate idea of what kind of a payback period a small-scale digestion system like this could have. Included in the savings are potential carbon credits earned by not sending waste to the landfill as carbon credits are now being traded on international markets for 20 CAD (August 2010) [35].

Savings from Anaerobic Digestion of Food Waste:

Annual landfilling cost at Concordia at $131.28/ton	
Savings from AD of 165 tons of waste:	$21,661
Biogas sent to natural gas heating system replacing natural gas	
18,350 m^3 at $0.50 per m^3	$9,175
Total	*$30,790*

Carbon Credits

A carbon credit is equivalent to one ton of CO_2 that has not been released to the atmosphere. The current trading price for one carbon credit is 20 Canadian dollars.

In order to calculate how many carbon credits could be sold by introducing the proposed food waste to energy system, the tonnage of CO_2 should be converted to m^3 so that an accurate comparison can be made.

Volume calculation of one ton CO_2 (1.84 kg/m^3 at 25°C)

One ton = 1000kg

One cubic meter = 1000 liters

One mole CO_2 = 44.0g   (CO_2 = 12.0g + 32.0g = 44.0g)
One ton contains 22,730 moles of CO_2 (1,000,000g / 44.0g/mole)
One mole is 24.47L   (Boyle's law at 25°C and 1 atmosphere pressure)
Volume of one ton CO_2 = 22730moles × 24.47L/mole = 556200L = 556.2m^3

Carbon Dioxide Equivalent for Methane (0.67kg/m^3 at 25C)

A carbon dioxide equivalent is a way to compare the emissions from various greenhouse gases based upon their global warming potential (GWP). Carbon dioxide equivalents are commonly expressed as "million metric tons of carbon dioxide equivalents (MMTCO2Eq)." The carbon dioxide equivalent for a specific gas is derived by multiplying the tons of the gas by the associated GWP.

*MMTCO2Eq = (million metric tons of a gas) * (GWP of the gas)*

Methane has a GWP of 21.

Estimated Carbon Credits for 165 tons of waste diverted from Landfill :

Garbage trucks can take up to 10 tons of waste to fill per trip.

165 tons of waste digested would save 17 round trips to the closest landfill (Lachenaie Landfill) 22 miles away (44 mi. Rt.)

Garbage trucks average 2.8mpg.

17 trips x 44 miles / 2.8 mpg = 267 gallons of gasoline

1 gallon of gas = 4.867 m^3 $C0_2$ = 1,300 m^3 $C0_2$ at 1.84kg/m3 = 2,391 kg $C0_2$

This yields 2.4 carbon credits

Diverted landfill gas credits :

This calculation represents the methane not released into the atmosphere from the food waste by by digesting it instead of sending it directly to the landfill.

18,350 m^3 biogas at composed of 35% $C0_2$ and 65% methane

6,423 m^3 $C0_2$ = 12 tons $C0_2$ = 12 carbon credits

11,928 m^3 CH_4 = 8 tons CH_4 x 21 GWP = 168 carbon credits

Total Carbon Credits =168 +12 + 2.4 = 182

Value of Carbon Credits: 182 x $20 CAD (current trading price) = $3,640 CAD

Payback Period

Total Savings + Carbon credits = $34,430 / year

Total cost of system divided by annual savings:

$229,306/$34,430 = *6.7 year payback period*

Chapter 6

Conclusions and Future Work

The waste generated by the increased urbanization and population of humans will soon become unmanageable. Cities around the world are running out of places to send their waste as landfills are reaching limits and closing down. The organic fraction of municipal solid waste constitutes the main part of the methane produced from landfilling and is a powerful greenhouse gas. Small-scale anaerobic digestion could be used to generate heat and electricity from the organic waste in the urban environment and reduce the amount of waste that is sent to the landfill. Although widely used for wastewater treatment, anaerobic digestion technology has not been applied much to mixed food waste even though it one of the most energy dense substrates. The goal of this thesis was to present anaerobic digestion as a means of extracting methane from food waste and use it as energy, model the problem in a unique way using Anaerobic Digestion Model #1 and provide a case study of the application of this technology on the downtown campus of Concordia University in Montreal.

The unique implications and complications of using anaerobic digestion with food waste as the main input were discussed as the most important operational parameters for waste to energy calculations were presented. Food waste was shown to be a desirable digestion substrate, one that produces large amounts of biogas with a short retention time.

Modeling of complex heterogeneous substrates with ADM1 is notoriously complicated and usually remains with wastewater or biochemistry experts. Recent modifications have been shown to place complex substrate modeling on an understandable level. The transformer for ADM1 inputs developed by Zaher has been shown to work with values taken from literature and thereby allowing direct modeling without having to take complicated measurements in a lab. This allows ADM1 to be used a tool for waste-to-energy calculations.

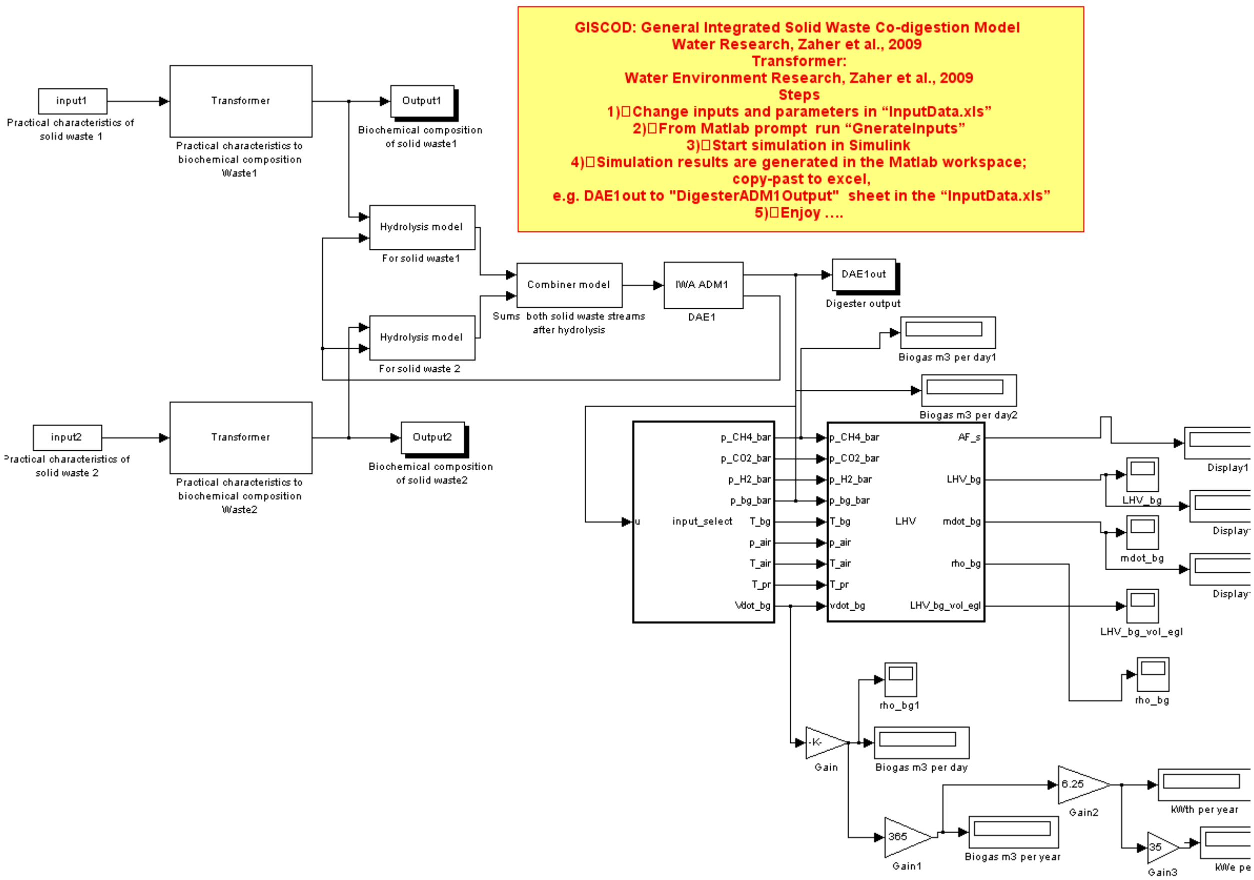
A case study was presented of anaerobic digestion of food waste produced on Concordia's downtown campus. A system design was investigated and a plan for implementation was presented. It was shown that the food waste produced in the Hall building could yield enough biogas to offset the annual heating costs by 3%. A cost estimate of the proposed anaerobic digestion system was presented and it was shown that the annual savings would pay for the system within 7 years.

Future work:

Collaboration with a biochemistry student would be beneficial for future ADM1 research so that the parameter estimation could become more robust. There is a lot of middle ground still left to cover between the wastewater treatment professionals who have an intimate understanding of the anaerobic digestion process and the engineers who are interested in optimum biogas production so that appropriate energy calculations can be made. It would be beneficial for this system to be implemented at full scale or a smaller scale so that testing can be done of actual food waste from location.

Appendix A

GISCOD Implementation Section 5.2



Output Selection from ADM1

```
function [p_CH4_bar, p_CO2_bar, p_H2_bar, p_bg_bar, T_bg, p_air, T_air,
T_pr, Vdot_bg] = input_select(u)
% This block supports an embeddable subset of the MATLAB language.
% See the help menu for details.


T_air = u(37);
%(standard atmospheric pressure in kPa/100 to be in bars)
p_air = 101.325/100;
T_bg = u(37);
T_pr = u(37);
p_H2_bar = u(47);
p_CH4_bar = u(48);
p_CO2_bar = u(49);
p_bg_bar = u(47)+u(48)+u(49);
```

```
Vdot_bg = u(51)/24/3600;
```

Matlab Code for Standard ADM1 Implementation

```
% This file initiates parameter values and sets initial conditions for
the three
% model implementations adm1_ODE, adm1_DAE1 and adm1_DAE2. Note that
some of the
% parameter values deviates from the values given in the AMD1 STR
(Batstone et al)
%
% Christian Rosen, Darko Vrecko and Ulf Jeppsson
% Dept. Industrial Electrical Engineering and Automation
% Lund University
% http://www.iea.lth.se
% 2005

% Modified by N. Curry Summer 2010
clc;
clear;

S_su =  0.024309;
S_aa =  0.010808;
S_fa =  0.29533;
S_va =  0.02329;
S_bu = 0.031123;
S_pro = 0.043974;
S_ac =  0.50765;
S_h2 =  4.9652e-007;
S_ch4 = 0.055598;
S_IC = 0.10258;
S_IN = 0.10373;
S_I = 3.2327;
X_xc = 7.5567;
X_ch = 0.074679;
X_pr = 0.074679;
X_li = 0.11202;
X_su = 0.57565;
X_aa = 0.43307;
X_fa = 0.44433;
X_c4 = 0.18404;
X_pro = 0.087261;
X_ac = 0.57682;
X_h2 =  0.28774;
X_I =  18.6685;
S_cat =  3.3531e-042;
S_an =  1.5293e-041;
S_hva = 0.023204;
S_hbu = 0.031017;
S_hpro =  0.043803;
S_hac =  0.50616;
S_hco3 = 0.092928;
S_nh3 = 0.0021958;
```

```
S_gas_h2 = 1.9096e-005;
S_gas_ch4 = 1.5103;
S_gas_co2 = 0.013766;
Q_D = .174; %166.5395;
T_D = 35;
S_D1_D = 0;
S_D2_D = 0;
S_D3_D = 0;
X_D4_D = 0;
X_D5_D = 0;

S_H_ion = 5.3469e-008;

DIGESTERINIT = [ S_su S_aa S_fa S_va S_bu S_pro S_ac S_h2 S_ch4 S_IC
S_IN S_I X_xc X_ch X_pr X_li X_su X_aa X_fa X_c4 X_pro X_ac X_h2 ...
                 X_I S_cat S_an S_hva S_hbu S_hpro S_hac S_hco3 S_nh3
S_gas_h2 S_gas_ch4 S_gas_co2 Q_D T_D S_D1_D S_D2_D S_D3_D X_D4_D X_D5_D
];

PHSOLVINIT = [ S_H_ion, S_hva, S_hbu, S_hpro, S_hac, S_hco3, S_nh3 ];

SH2SOLVINIT = [ S_h2 ];

f_sI_xc = 0.1;
f_xI_xc = 0.15;
f_ch_xc = 0.45;
f_pr_xc = 0.15;
f_li_xc = 0.15;
N_xc = 0.0376/14;
N_I = 0.06/14;
N_aa = 0.007;
C_xc = 0.03;
C_sI = 0.03;
C_ch = 0.0313;
C_pr = 0.03;
C_li = 0.022;
C_xI = 0.03;
C_su = 0.0313;
C_aa = 0.03;
f_fa_li = 0.95;
C_fa = 0.0217;
f_h2_su = 0.19;
f_bu_su = 0.13;
f_pro_su = 0.27;
f_ac_su = 0.41;
N_bac = 0.08/14;
C_bu = 0.025;
C_pro = 0.0268;
C_ac = 0.0313;
C_bac = 0.0313;
Y_su = 0.1;
f_h2_aa = 0.06;
f_va_aa = 0.23;
f_bu_aa = 0.26;
f_pro_aa = 0.05;
f_ac_aa = 0.40;
```

```
C_va = 0.024;
Y_aa = 0.08;
Y_fa = 0.06;
Y_c4 = 0.06;
Y_pro = 0.04;
C_ch4 = 0.0156;
Y_ac = 0.05;
Y_h2 = 0.06;
k_dis = 0.5; %Changed from 0.5 via Appendix A of ADM1 Bastone Text
k_hyd_ch = 5.22; %Changed from 10 via GISCOD Paper by Zaher
k_hyd_pr = 1.86; %Changed from 10 via GISCOD Paper by Zaher
k_hyd_li = 1.24; %Changed from 10 via GISCOD Paper by Zaher
K_S_IN = 1e-4;
k_m_su = 30;
K_S_su = 0.5;
pH_UL_aa = 5.5;
pH_LL_aa = 4;
k_m_aa = 50;
K_S_aa = 0.3;
k_m_fa = 6;
K_S_fa = 0.4;
K_Ih2_fa = 5e-6;
k_m_c4 = 20;
K_S_c4 = 0.2;
K_Ih2_c4 = 1e-5;
k_m_pro = 13;
K_S_pro = 0.1;
K_Ih2_pro = 3.5e-6;
k_m_ac = 8;
K_S_ac = 0.15;
K_I_nh3 = 0.0018;
pH_UL_ac = 7;
pH_LL_ac = 6;
k_m_h2 = 35;
K_S_h2 = 7e-6;
pH_UL_h2 = 6;
pH_LL_h2 = 5;
k_dec_Xsu = 0.02;
k_dec_Xaa = 0.02;
k_dec_Xfa = 0.02;
k_dec_Xc4 = 0.02;
k_dec_Xpro = 0.02;
k_dec_Xac = 0.02;
k_dec_Xh2 = 0.02;
R = 0.08314;
T_base = 298.15;
T_op = 308.15;
K_w = 2.08e-14;
K_a_va = 1.38e-5;
K_a_bu = 1.51e-5;
K_a_pro = 1.32e-5;
K_a_ac = 1.74e-5;
K_a_co2 = 4.94e-7;
K_a_IN = 1.11e-9;
k_A_Bva = 1e10;     %1e8; according to STR
k_A_Bbu = 1e10;     %1e8; according to STR
k_A_Bpro = 1e10;    %1e8; according to STR
```

```
k_A_Bac = 1e10;      %1e8; according to STR
k_A_Bco2 = 1e10;     %1e8; according to STR
k_A_BIN = 1e10;      %1e8; according to STR
P_atm = 1.013;
p_gas_h2o = 0.0557;
kLa = 200;
K_H_co2 = 0.0271;
K_H_ch4 = 0.00116;
K_H_h2 = 7.38e-4;
k_P = 5e4;

DIGESTERPAR = [ f_sI_xc f_xI_xc f_ch_xc f_pr_xc f_li_xc N_xc N_I N_aa
C_xc C_sI C_ch C_pr C_li C_xI C_su C_aa f_fa_li C_fa ...
f_h2_su f_bu_su f_pro_su f_ac_su N_bac C_bu C_pro C_ac C_bac Y_su
f_h2_aa f_va_aa f_bu_aa f_pro_aa f_ac_aa C_va Y_aa Y_fa ...
Y_c4 Y_pro C_ch4 Y_ac Y_h2 k_dis k_hyd_ch k_hyd_pr k_hyd_li K_S_IN
k_m_su K_S_su pH_UL_aa pH_LL_aa k_m_aa K_S_aa k_m_fa ...
K_S_fa K_Ih2_fa k_m_c4 K_S_c4 K_Ih2_c4 k_m_pro K_S_pro K_Ih2_pro k_m_ac
K_S_ac K_I_nh3 pH_UL_ac pH_LL_ac k_m_h2 K_S_h2 ...
pH_UL_h2 pH_LL_h2 k_dec_Xsu k_dec_Xaa k_dec_Xfa k_dec_Xc4 k_dec_Xpro
k_dec_Xac k_dec_Xh2 R T_base T_op K_w  K_a_va K_a_bu ...
K_a_pro K_a_ac K_a_co2 K_a_IN k_A_Bva k_A_Bbu k_A_Bpro k_A_Bac k_A_Bco2
k_A_BIN P_atm p_gas_h2o kLa K_H_co2 ...
K_H_ch4 K_H_h2 k_P];

V_liq = 27; %1400
V_gas = 2.7;  % 100

DIM_D = [ V_liq V_gas ];

input1=[0 S_su S_aa S_fa S_va S_bu S_pro S_ac S_h2 S_ch4 S_IC S_IN S_I
X_xc X_ch X_pr X_li X_su X_aa X_fa X_c4 X_pro X_ac X_h2 ...
                 X_I S_cat S_an Q_D T_D S_D1_D S_D2_D S_D3_D X_D4_D
X_D5_D;
 10000, S_su S_aa S_fa S_va S_bu S_pro S_ac S_h2 S_ch4 S_IC S_IN S_I
X_xc X_ch X_pr X_li X_su X_aa X_fa X_c4 X_pro X_ac X_h2 ...
                 X_I S_cat S_an Q_D T_D S_D1_D S_D2_D S_D3_D X_D4_D
X_D5_D]';

save input1.mat input1;
```

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