ABSTRACT

The purpose of this study was to determine the technical and economic feasibility of operating an anaerobic digester on food waste at a local North Carolina school. This study reviewed literature pertaining to the environmental and operational conditions affecting methane production during mesophilic anaerobic digestion of food waste. Students at Smith Middle School in Chapel Hill were observed to throw away 0.64 kg of food each month, which was estimated to produce 95 L of methane. Three methane-to-energy conversion methods were analyzed. Using methane directly in a boiler was found to be most cost-effective. A food waste-to-energy system (FWTE) was designed to maximize methane production during anaerobic digestion and to inexpensively transfer it into a boiler. Regulatory procedures for the approval of FWTE use in North Carolina schools were also outlined.

A cost / benefit analysis was conducted using the combination of Smith Middle School plus two neighboring schools. Construction and regulatory approval costs were estimated at $14,400. Financial benefits from offsetting natural gas usage were estimated at $1,100 / year and unable to payback the initial investment before the end of the FWTE lifetime. Environmental benefits, based on the effect of CH_4 on global warming in CO_2 equivalents, varied greatly with the price per ton of CO_2. Only a value of $37 or more per ton of CO_2 prevention would allow the FWTE to break-even within 4 years.

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1.0 Introduction

Renewable energy sources have the potential to provide sustainable, low-cost energy in an era when our society questions the longevity of our fossil fuel reserves. Capturing methane (CH_4) from organic waste through anaerobic digestion is one such renewable energy source that can reduce the solids load on a landfill, decrease the impact of greenhouse gases emitted from organic waste, and provide a continuous supply of renewable energy. This is a low-cost, low-maintenance, mature technology that has the potential to provide a reliable source of energy in an economically profitable fashion.

Anaerobic digestion is a process in which microorganisms metabolize biodegradable compounds into carbon dioxide (CO_2), water, CH_4, and trace gases. This process can be carried out over a range of temperatures with a variety of organic inputs and in numerous digester designs, all of which affect the amount of methane produced. An anaerobic digester requires an anaerobic (oxygen-free) environment, organic waste, and appropriate microorganisms that collectively contribute to methane production. By adjusting the environment and operating conditions of a digester, a steady-state production of methane can be maintained. As methane is produced, it rises to the top of the digester and can be used for energy production. The methane can be combusted in a boiler or engine to produce usable energy. Instead of allowing methane from anaerobic biodegradation of organic waste in a landfill without a biogas recovery system to escape directly into the atmosphere, it can be consumed in a controlled environment to capture its energy potential and offset greenhouse gas effects.

The purpose of this study was to determine the technical and economic feasibility of operating a small-scale food waste-to-energy system. In particular, the feasibility of

implementing such a system at a public school was evaluated. If technically and economically feasible, anaerobic digestion of food waste at a school could also provide an excellent learning opportunity for the students at the school, with respect to areas such as sustainability, renewable energy production, and biodegradation.

2.0 Background and Literature Review

2.1 The Microbiology and Fundamentals of Anaerobic Digestion

Anaerobic digestion has been used since the 19th century to stabilize wastewaters in septic tanks and to treat sludge in wastewater treatment plants (van Lier et al. 2001). It is a four-step process, as shown in Figure 2.1, which begins with hydrolyzing complex substrates and using the products, acids and sugars, for acidogenesis. The fatty-acid products of acidogenesis are used in acetogenesis, which creates acetate and hydrogen that ultimately are consumed in the methanogenesis phase. Hydrolysis is known to be the rate-limiting step of anaerobic digestion, followed by methanogenesis.

The fundamentals of anaerobic digestion begin with the microorganisms. Mesophilic bacteria are those that achieve maximum growth at temperatures of 20-40°C. Some anaerobic digesters operate at temperatures of 50-65 °C to promote the activity of thermophilic microorganisms, but this study focused on mesophilic digestion. The predominant classes of mesophilic bacteria during anaerobic digestion are *Bacteroidetes* and *Chloroflexi* (Leven et al. 2007). These bacteria attack cellulose particles by secreting an enzyme into the bulk liquor that hydrolyzes particles without adhering to their surface (Noike et al. 1985).

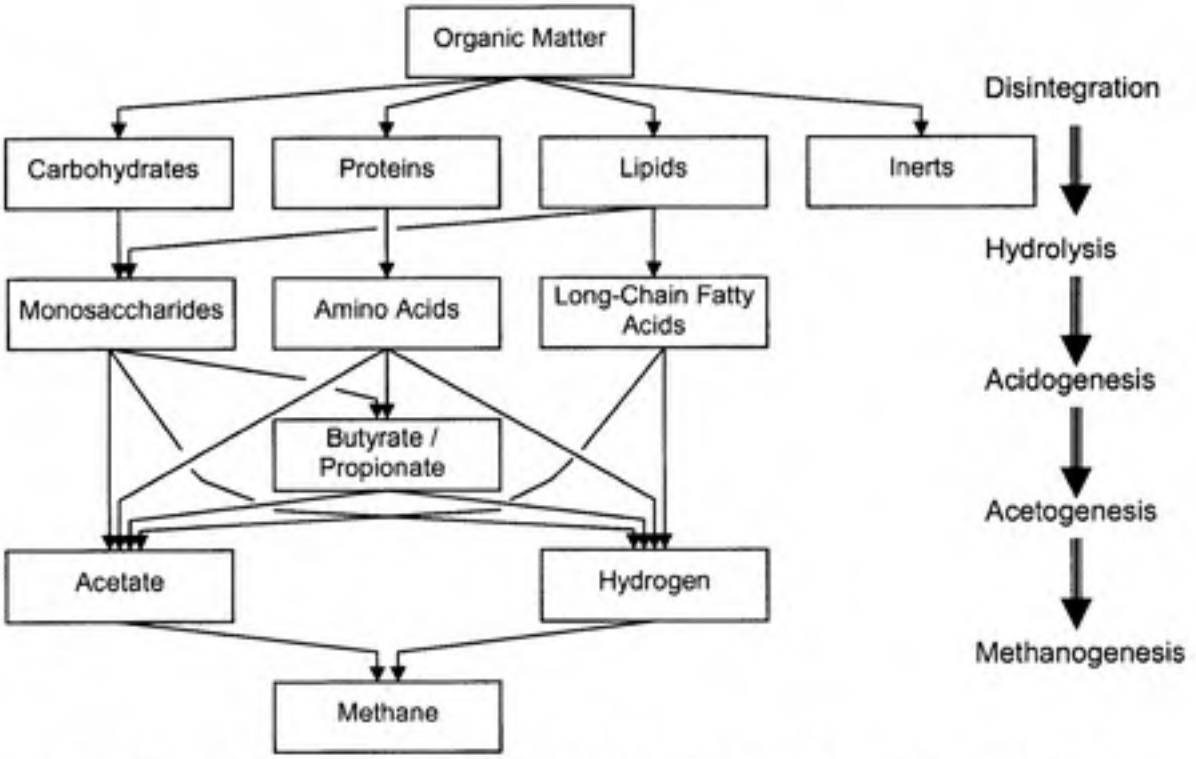

Figure 2.1. Flow-chart of substrate degradation via anaerobic digestion process resulting in the production of methane (Rozzi and Remigi 2004)

Other important microorganisms in anaerobic digestion are the archaea. Recognized as a separate kingdom, archaea (methanogens) are the main contributors to methane production during anaerobic digestion. There are two types of methanogens: the acetoclastic methanogens convert acetate to CH_4 and CO_2, and the hydrogenotrophic methanogens convert H_2 and CO_2 to CH_4. The methanogenic genera include *Methanospirrilum*, *Methanosarcina*, *Methanoculleus*, and *Methanosaeta* (Chynoweth 1996; Leven et al. 2007). Of these methanogens, *Methanosarcina* are the most stable and efficient at utilizing acetate and can be encouraged over *Methanosaeta* with semi-continuous loadings, such as once per day (Conklin et al. 2006).

2.2 Factors Affecting Digestion

2.2.1 Environmental Factors

Every microorganism requires a specific environment in which to flourish without inhibition. Such environments must maintain appropriate temperatures, pH levels, carbon-to-nitrogen ratios, and low concentrations of harmful substances. Each of these factors can be adjusted to maximize the production of methane during anaerobic digestion.

First, the mesophilic temperature ranges for anaerobic digestion requires the least external energy input and was chosen as the optimal temperature range for the application of digesting food waste on a school campus. The normal range for mesophilic digestion operation is 30-40 °C. Higher temperatures increase both hydrolytic and methanogenic digestion, but at higher temperatures mesophilic organisms become inhibited. The maximum mesophilic temperature is therefore 40 °C, but 35 °C is a safer temperature at which to operate to ensure mesophilic organisms are not inhibited.

Many authors agree that a pH of 7 ± 0.2 optimizes the methanogenesis process (Liu et al. 2007; Verrier et al. 1987; Yadvika et al. 2004). A lower pH of 6 - 6.5 catalyzes hydrolysis and allows a higher production of methane than lower pH values in a batch reactor, even though a pH of 4 - 4.5 is optimal for hydrolysis (Hutnan et al. 2000). Methanogenesis failures can occur when pH values drop below 6.1 or surpass 8.3, while permanent damage to the microflora can occur at a pH of 5.1 (Mata-Alvarez et al. 2000; Rao and Singh 2004). The pH naturally decreases when volatile fatty acids (VFA) produced through hydrolysis and acidogenesis accumulate due to an imbalance of VFA formation and consumption by methanogenic activity. Only continuous methanogenic

activity can fully compensate for this imbalance. However, adding $NaHCO_3$ or other alkaline agents can regulate the pH of the digester and should be added as needed (Hutnan et al. 2000).

The carbon-to-nitrogen ratio is important to optimize the performance of a digester's microbial community (Gunnerson and Stuckey 1986). C:N ratios are calculated from the percent mass of the organics that is carbon divided by the percent mass of the organics that is nitrogen. Optimal C:N ratios range from 20:1 to 30:1, depending on the reactor operations and the organics used in anaerobic digestion (Kivaisi and Mtila 1998; Viswanath et al. 1991). The percent mass of the organics that is phosphorus may also be of importance. A C:N:P ratio of 120:7:1 was examined and determined to be suitable ratio (Viturtia and Mata-Alvarez 1989). Finally, C:N ratios should not exceed 50:1, as inhibition will occur (Viswanath et al. 1991).

Common inhibitors found in the anaerobic digestion of wastewater sludge are derived from the common by-products of the organic waste during hydrolysis. Ammonia, for example, is a known inhibitor of anaerobic digestion. Ammonification of organic nitrogen and volatilization of ammonia during leachate recirculation in a solid-waste landfill are the primary sources of ammonia during anaerobic digestion (Iglesias et al. 2000). Digesters with a high protein content often have ammonia toxicity problems (Gunnerson and Stuckey 1986), although concentrations that lead to inhibition have varied between studies. In one study, ammonia concentrations of 750, 3,400, and 4,400 mg-N/L during mesophilic anaerobic digestion of acetate all contributed approximately the same level of inhibition (Fujishima et al. 2000). However, in a thermophilic experiment by Wiegant and Zeeman (1986), it was found that ammonia concentrations

above 3,500 mg-N/L caused hydrogenotrophic methanogen inhibition, while acetoclastic methanogen inhibition occurred at levels above 4,500 mg-N/L.

Other nitrogen compounds, which are produced from organic nitrogen and residual oxygen that might be introduced in an anaerobic system, are far more inhibitory than ammonia. Of these, nitric oxide (NO) is the most inhibitory compound. NO is a nonspecific cell poison (Kluber and Conrad 1998) that Tugtas and Pavlostathis (2007) found to cease methanogenesis irreversibly at a concentration of 8 mg/L. Nitrous oxide is the next most potent nitrogen compound inhibitor, followed by nitrite and then nitrate. Unlike nitric oxide, the other oxidized nitrogen compounds do not cause long-term inhibition with a one-time exposure. However, prolonged exposure can change the consortia to favor denitrifiers and thereby reduce the number of methanogens and acetogens, effectively shutting down methanogenesis (Tugtas and Pavlostathis 2007). Table 2.1 lists the concentrations of nitrate, nitrite, nitric oxide, and nitrous oxide that were inhibitory for varying timeframes in a study of methanogenic cultures by Klüber and Conrad (1998).

Table 2.1. Various concentrations of nitrogen compounds capable of inhibiting methanogenesis (Klüber and Conrad 1998)

Nitrate (mM)	Nitrite (μM)	NO (μM)	N_2O (μM)	Duration (d) of inhibition of CH_4 production
20	590	0.027	114	43-57
10	200	0.019	182	24-27
1	30	0.001	1	4-6

Another common inhibitor of methanogenesis is oxygen. Oxygen can enter a digester during loading periods, by being enveloped within the feed material. Methanogen growth can be completely arrested through both competition with aerobic microorganisms and toxic effects of oxygen. Aerobic microorganisms grow much faster

than methanogens on the same substrates if oxygen is available in a system. Further, oxygen can lead to the production of superoxide and hydrogen peroxide, which are toxic to methanogens (Imlay 2002).

The most frequent inhibitors of methanogenesis are VFAs. VFAs, such as acetate, butyrate, and propionate, are formed during acidogenesis, all of which can have inhibitory properties, though butyrate is the least problematic as it is degraded quickly (Gijzen et al. 1987). Too much acid production due to overloading of the digester lowers the pH level and can inhibit anaerobic digestion. Of these VFAs, propionate is the main cause of methanogenic inhibition (Chynoweth 1996; Gunnerson and Stuckey 1986). Acetate production is beneficial as it is a substrate for methanogens unless enough is produced to lower pH levels. For example, if acetate accumulates in an anaerobic system beyond propionate levels, this indicates the rate of acetate formation has exceeded the rate at which methanogens can degrade the acetate (Gallert et al. 2003). Such an observation may precede a drop in pH. Without a proper alkalinity adjustment, VFA concentrations should be below 2000 mg/L to avoid a significant drop in pH (Yadvika et al. 2004). The amount of sodium carbonate or lime added to a system to neutralize its acidity should be based on acid equivalents of the VFAs present.

Uncommon inhibitors in the anaerobic digestion of food waste are metals, surfactants, and sodium. Heavy metals, such as copper, chromium, cadmium, zinc, nickel, and lead, are reported to be inhibitory to VFA degradation, in order of their severity. Tables 2.2 and 2.3 provide the concentrations of these metals found to inhibit 50% of total VFA degradation and methane production, respectively, in an anaerobic sludge bed system (Lin and Chen 1999).

Table 2.2. Results for 50% inhibition of total VFA degradation (Lin and Chen 1997)

Concentrations (mg/L)		
Metal	HRT 1 day	HRT 2 days
Cadmium	55	180
Chromium	37	140
Copper	31	130
Nickel	81	440
Lead	1400	3200
Zinc	58	200

Table 2.3. Results for 50% inhibition of methane production. HRT: Hydraulic Retention Time (Lin and Chen 1997)

Concentrations (mg/L)		
Metal	HRT 1 day	HRT 2 days
Cadmium	450	330
Chromium	200	250
Copper	90	130
Nickel	2000	1600
Lead	8800	8000
Zinc	690	270

Surfactants are large, amphiphilic organic molecules and can be classified as ionic or non-ionic. Table 2.4 presents the concentrations and inhibitory levels of five surfactants during anaerobic digestion in one study. This table suggests that non-ionic surfactants, such as Triton X-100, are less toxic than are cationic surfactants, such as Alkamon DS and Catamin AB, but on par with anionic surfactants, such as Sulfanol NP-1 and sodium dodecylsulfate. Cationic surfactants are deemed toxic to methanogens and other microorganisms, as they impair the functioning and integrity of biological membranes. Liquefaction of a cell membrane results in the impairment of their barrier properties, thus maiming the cell (Shcherbakova et al. 1999).

Table 2.4. Inhibitory concentrations of various ionic surfactants are shown in columns for 20%, 50%, and 80% inhibition. The percent inhibition is the ability of the surfactants to reduce the rate of methanogenesis occurring in their presence (Shcherbakova et. al., 1999).

Surfactant	Inhibitory Concentration (mg/L)		
	20%	50%	80%
Sulfanol NP-1	292	675	1250
Sodium Dodecylsulfate	228	573	925
Alkamon DS	78	154	235
Catamin AB	195	345	495
Triton X-100	214	538	883

Sodium is a potential inhibitor even though it is necessary for the metabolic functions of microorganisms. A sodium concentration of 350 mg/L is thought to be the optimal concentration to aid microbial growth (Patel and Roth 1977). Higher

concentrations inhibit methanogenesis by upsetting metabolic functions (Metcalf and Eddy 2003; Rinzema et al. 1988). When additional nutrients are added to an anaerobic system along with sodium, such as nitrogen, phosphorus, or sulfur, the inhibitory effects of sodium can be reversed. Further, anaerobes can adapt to higher sodium concentrations without showing symptoms of inhibition (Feijoo et al. 1995). Any inhibition due to sodium, metals, or surfactants can be avoided by not overloading the anaerobic digestion system with any of these substances or by using appropriate source-separation techniques.

2.2.2 Common Operating Parameters

Additional factors that can be controlled to maximize methane production from an anaerobic digester are relevant to the operation of the digester. These factors include the solids retention time (SRT), the solids loading rate, and the moisture content of an anaerobic digester. Each of these factors affects the amount of degradation that occurs within a digester and the timeliness in which methane production occurs.

The average amount of time solids reside in a digester, the SRT, can vary widely depending on its design and operating conditions. The SRT can be calculated by dividing the volume of the reactor by the volumetric loading rate (volume per unit time) of the system. Long residence times, such as 100 - 200 days, allow for a thorough degradation of solids and maximize the yield of methane from organics. However, depending on the solids loading rate, this could result in a very large reactor volume that would be expensive. Shorter residence times of 2 - 20 days allow for small reactor volumes but proportionally higher loading rates. At high loading rates, organic degradation may decline and the full methane production potential would not be achieved (Kalia et al.

1992). Further, short retention times may also flush out degradative microorganisms that are attached to organic substrates, thereby decreasing future degradative abilities of the system. This was shown by Gallert, et al. (2003) when they reduced the residence time of an experimental digester from 20 to 10 days. Acetate and propionate accumulated, suggesting that methanogens were being lost from the system (Gallert et al. 2003). To illustrate the importance of correctly matching the retention time to the reactor volume and loading rate, Viswanath et al. (1991) experimented with hydraulic residence times of 8, 12, 16, 20, and 24 days in conjunction with a fixed reactor volume and loading rate of 38 kg total solids m^{-3} d^{-1} that allowed for the variance in actual volume of solids introduced to the reactor each day. They found that only the retention times higher than 16 days led to stable performance.

A specific solids loading rate for a certain digester size exists that can optimize methane production, which if surpassed will not proportionately increase gas production (Yadvika et al. 2004). As loading rates increase in a reactor, the fermentation products, volatile fatty acids (VFA), increase proportionally up to a certain point when the fermentative microorganisms reach maximum conversion rates and produce less than a proportional amount of VFAs (Gijzen et al. 1987). Raynal et al. (1998) argue that the inhibition of VFA production can be attributed to the higher concentrations of hydrolytic microorganisms that produce VFAs and thrive in a higher loading rate environment, whereas Gijzen et al. (1987) believe it could be prevented by removing the increased amount of VFAs from the system. As VFAs accumulate with increased loading rates, methanogenesis becomes inhibited after a certain point. Methanogenic inhibition could also be attributed to a hydrolysis problem if the density of solids in the digester is too

great. This would limit the exposure of the organics to hydrolytic microorganisms, thereby not producing sugars and acids for consumption by acidogenic and acetogenic bacteria, effectively restricting fermentative activities (Rao and Singh 2004).

It is important to know how best to manipulate the loading rate of an anaerobic digestion system to optimize methane yield and under what conditions a system can remain stable. During startup of a reactor, keeping a low loading rate can eliminate any lag-time between the hydrolytic/acidogenic and acetogenic/methanogenic phases. Once the methanogenic population has grown large enough, intensifying the loading rate will yield more methane in a stable environment (Vavilin et al. 2002). To determine the loading capacity of a reactor, the loading rate can be increased step-wise until the reactor is unable to maintain a steady-state. Once stable operation is achieved, methane production responds quickly to load variations. Under stable conditions, the rate at which the microbes degrade the waste changes proportionally with the amount of waste that is put into the system, thereby making the loading rate the limiting factor, not the microbes (Raynal et al. 1998).

High moisture content in anaerobic digesters can have a positive effect on the production of methane. Moisture content is defined here as the amount of water contained within a substance or slurry. One researcher showed that if a slurry containing meat, carrots, or cabbage begins digestion with a 98% moisture content and the moisture begins decreasing thereafter, methane production per gram of volatile solids will decrease proportionally (Lay et al. 1997). Further, if the moisture content in a high solids slurry drops below 80% during the digestion of food waste, then methanogenesis will cease (Mata-Alvarez et al. 2000). Figure 2.2 illustrates this well as the left column of charts

shows an increasing lag-time between phases with decreasing moisture content, while the right column of charts shows increasing methane yields with increasing moisture content. Other scientists suggest that the optimal moisture content is 91-93%, as a higher solids concentration overloads the fermenting bacteria and a higher moisture content inhibits acidogenic and methanogenic microorganisms, as illustrated in Figure 2.3 (Fujishima et al. 2000; Yadvika et al. 2004). Additionally, moisture content can affect the degradation of individual compounds within a system. In one study, lowering the moisture content helped the degradation of protein, proportionally inhibited degradation of carbohydrates, and had little effect on lipid degradation (Fujishima et al. 2000).

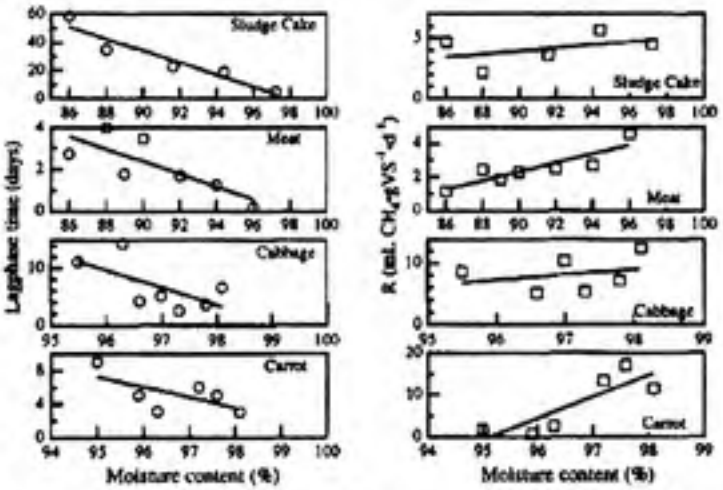

Figure 2.2. Effect of moisture content during food waste digestion on lag-time between phases and methane yield from volatile solids (Lay, et. al. 1997)

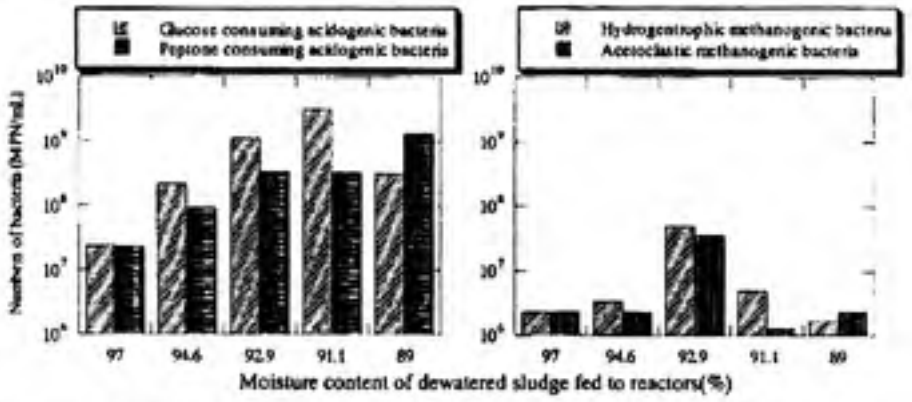

Figure 2.3. Effect of moisture content on bacterial populations (Fujishima, et. al. 2000)

2.3 Digester Designs and Processes

There are many different processes and designs for an anaerobic digester, but there are two main designs that can be used with a variety of processes and modifications for specific purposes: single-phase and two-phase systems. A single-phase reactor is the simpler of the two, in which fermentation, acidogenesis, and methanogenesis occur simultaneously. This style of reactor can then be loaded once and sealed until fermentation and methanogenesis are complete, semi-continuously loaded where new substrate is added periodically, or continuously loaded where new substrate is constantly flowing into the reactor. The entire anaerobic digestion process is done all in the same location. If the process is "wet", meaning a total solids content of less than 20%, mixing is usually involved. If the process needed is "dry", meaning a total solids content between 20-50%, vertical compression, horizontal plug-flow, and biogas recirculation are typical means of moving waste through the reactor, made popular by the Dranco, Kompogas, and Valorga companies, respectively (Lissens et al. 2001). The processes shown in Figure 2.4 illustrate these "dry" reactor designs.

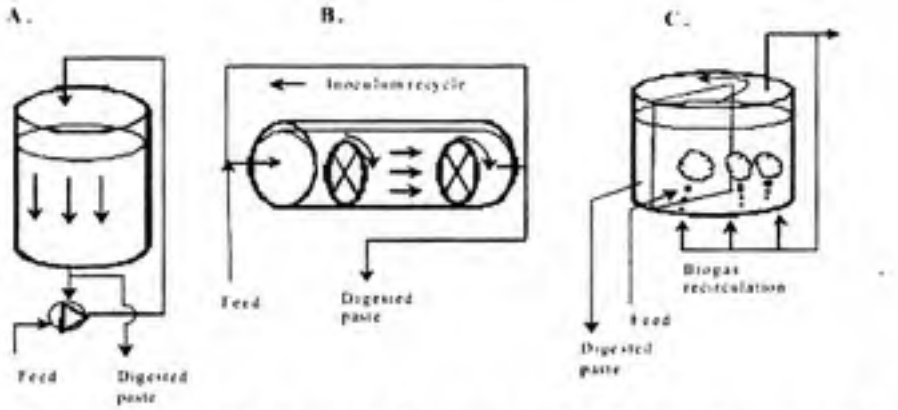

Figure 2.4. "Dry" reactor designs: A) Dranco, B) Kompogas, and C) Valorga (Lissens, et al. 2001)

The second main reactor design is the two-phase system, which separates the anaerobic digestion process spatially in one or multiple reactors with semi-continuous or

continuous loading. Hydrolysis and acidogenesis function optimally at lower pH levels than acetogenesis and methanogenesis (see Figure 2.1). A two-phase system separates these functional groups to optimize methane production by permitting each step to occur at optimum rates (Lissens et al. 2001; Mata-Alvarez et al. 2000). Some systems separate these groups into two reactors, a hydrolytic reactor and a methanogenic reactor. One research group suggests a 2-3 day hydrolytic retention time in the hydrolytic reactor, and 8-9 days in the methanogenic reactor to extract a high methane yield from food waste (Pavan et al. 2000). Another type of two-phase system utilizes one reactor by creating nominal plug-flow conditions, either vertically or horizontally, where recent additions to the reactor begin hydrolyzing and acidifying. As more waste is added near the reactor entrance, the downstream sections of the reactor become more methanogenic and the material becomes fully digested. This ensures a stratification that spatially separates the phases of anaerobic digestion (Bouallagui et al. 2005; Svensson et al. 2007). Bouallagui, et al (2005) utilized a tubular reactor that had waste moving longitudinally in a semi-continuous fashion. Svensson, et al (2007) used a vertically flowing reactor with a straw bed to act as non-clogging support material to aid digestion.

Mixing is a final design aspect. Intermittent mixing of organic waste in a digester enhances digestion rates presumably by promoting contact between microorganisms and undigested waste. However, continuous and vigorous mixing disrupts spatial connections between bacteria and substrates (Wilkie et al. 2004).

2.3.1) Pre-treatment Considerations

Treating either the reactor contents or food waste prior to digestion can influence the effectiveness of the anaerobic digestion process. The proper inoculum in an

anaerobic digester can act as a catalyst for the system by promoting methanogenic activities. Inoculum is typically already-digested waste that contains the appropriate microorganisms. The more inoculum seeded into the anaerobic reactor prior to digestion the more stable the system is and the less likely inhibition will occur (Wang et al. 1997). Chen and Hashimoto (1996) found that quantifying the amount of chemical oxygen demand (COD) in the substrate and comparing it to the amount of COD in the inoculum gave a significant insight to the qualitative ratio of food to microorganisms, being dependent on inoculum volume per substrate volume. They determined that a substrate-to-inoculum ratio of 4.8 (each measured as COD) gave higher methane yields than a ratio of 38.5, meaning the less substrate COD and the more inoculum COD, the faster methane will be produced. Chen and Hashimoto (1996) also suggest using inoculum with a buffering capacity to maintain microbial activity in the presence of high VFA concentrations. Inoculum is typically taken from the effluent of an existing anaerobic digester of the same type, as the microflora needed for proper digestion would already be established in this material and then mixed in with the addition of the substrate.

Reducing the size of the organic waste prior to digestion creates more surface area for the microorganisms to attach and degrade it. Mechanical size reduction of substrate can lead to a more rapid degradation and a reduction of the volatile solids remaining after digestion. Shredding also enhances biogas yields of fibrous materials and reduces retention time (Palmowski and Muller 2000). One author found an average increase in biogas production of 17% by macerating cattle manure prior to digestion (Angelidaki and Ahring 2000). This shows that the smaller the substrate, the more methane can be produced from the substrate. For example, 0.088 and 0.40 mm substrate particle sizes led

to maximum production of biogas compared to 1.0, 6.0, and 30 mm particles (Yadvika et al. 2004). Ghosh et al (2000) found a 9% methane yield increase by reducing particles from 2.2 mm to 1.1 mm, while Mata-Alvarez et. al. (2000) reported insignificant improvements in methane production by reducing particles from 20 mm to 5 mm. If source-separation of organics from metals and other inorganic material was not efficient, a magnet could be incorporated with the shredder to remove the metals (Hansen et al. 2007).

Biological and chemical additives, such as plants, weeds, crop residues, and microbial cultures can stimulate microbial activity. The type of additive to be used depends on the substrate to be degraded. Increases in biogas production from additives appear to be due to adsorption of the substrate onto the additive's surface. Powdered leaves and legumes improve biogas production, as do tomato plant waste and digested crop residues. The improvements range from 10-80% increases in biogas production. Additions of cellulolytic bacteria can also aid in biogas production (Yadvika et al. 2004). Alkali treatments prior to mesophilic digestion of newsprint for short durations improved the bioconversion of newsprint to methane while maintaining neutral pH levels (Mata-Alvarez et al. 2000). Further, phosphate additions to maintain levels of at 15 mg PO_4-P/L can be used to keep necessary microbial nutrients available (Wang et al. 1997).

2.3.2 Leachate Recirculation

Leachate is a liquid produced during the degradation of substrates by percolating through solid waste, containing dissolved or suspended materials from the waste. The quantity of the leachate is directly related to the amount of water entering the anaerobic digestion system (Tchobanoglous et al. 1977). In semi-continuous systems, the

recirculation of leachate can enhance biogas production, and the more frequent the recirculation occurs, the more biodegradation that occurs and biogas that is produced (Viturtia and Mata-Alvarez 1989). Some authors have shown leachate percolation to be an effective method of mixing and that degradation relies on leachate retention time (Cho and Park 1995; Nguyen et al. 2007). Further, leachate recycling at a retention time of 22.5 days compared to no leachate recycling at a retention time of 33.7 days produced more biogas and emitted lower levels of CO_2 (Lastella et al. 2002). If the leachate is spread homogenously over the waste during recirculation and has more layers of solid waste to pass through, fewer VFAs and less COD will appear in the next round of leaching (Iglesias et al. 2000). Finally, leachate recirculation was shown in one study to increase the pH level and alkalinity, which can allow for a higher organic loading rate to be implemented (Nordberg et al. 2007). However, recirculating all leachate can be inhibitory due to high VFA concentrations, but by diluting the leachate with water, the pH of the leachate can be stabilized (Nordberg et al. 2007). Some investigators even recycled digested slurry, achieving an increase in biogas production due to introducing well-developed bacterial populations into the feed material (Lastella et al. 2002; Yadvika et al. 2004).

2.4 Expected Outputs from Anaerobic Digestion

The anaerobic digestion of organic waste produces biogas, a nutrient-rich sludge, and heat. Emitted biogas contains methane, CO_2, and water vapor, plus trace gases depending on the digested material. Substances capable of degrading quickly consist mainly of carbohydrates, proteins, and fats, whereas ligneous substances do not degrade at all and hemicellulose-rich substances degrade slowly, but have a significant potential

for methane production (Mahnert et al. 2005; Wang et al. 1997). Of these, protein degradation can produce the most methane followed by hemi-cellulose (even though it degrades more slowly than cellulose), then cellulose, and finally lignin; estimated methane production at 25˚C is 517, 424, 415, and 0 L-CH_4/kg, respectively at (Wang et al. 1997).

The amount of methane produced from food wastes depends on their composition. Fruits yield more methane (310-510 L/kg-VS) than storage roots (<0.25 L/kg-VS) and woody plants, which have the lowest methane yield of any plant group (Shiralipour and Smith 1984). Grease from a sludge trap, which is 90% fat, can produce the most methane of the food wastes researched, at a value of 900 L/kg-VS (Davidsson et al. 2007). High methane yields from fats can be attributed to their high H/C ratios and high biodegradability (Cho and Park 1995). Some foods were not found to have been tested in mesophilic anaerobic digestion where their methane yields could be determined. Methane yields can theoretically be calculated using protein, cellulose, and hemicellulose concentrations, or their calorific content. Calculating the methane yield from the carbon content of the organics can overestimate methane production, as the digestion of organics besides those listed would inflate the actual methane yield, non-methanogenic degradation could occur and some carbon is converted to cellular mass during microbial growth (Eleazer et al. 1997).

Of the components in biogas, methane is the most important for energy recovery. Methane is a colorless and odorless hydrocarbon that is a gas at ambient temperatures, with an energy value of 50.1 kJ / g-CH_4, or 35.8 kJ / L-CH_4 (see Appendix 7.1.1), and a maximum burning temperature of 2148 °C (Metcalf and Eddy 2003). However, Lastella

et. al. (2002) found the energy content of biogas to be between 21.5 and 24.4 kJ / L. Biogas contains between 55% and 80% methane, depending on the temperature, waste composition, and processing procedure (Kalia et al. 1992; Knol et al. 1978; Leven et al. 2007; Nguyen et al. 2007). The energy value of methane provided in Metcalf and Eddy (2003) is used in the remainder of this report for conversions of liters of methane to kilojoules of energy.

The other components of biogas (CO_2, water vapor, and trace gases) are of little consequence to the function of an anaerobic digester. The main concerns for these products all depend on how much of each is present in the biogas. CO_2 produced is between 20-45% of the biogas and must be taken into account for biogas storage. The percent water in the biogas is important because if too much water exists in the biogas, it can dampen the energy output from burning the biogas and can also contribute to corrosion of materials in the digester and those used to convey or store the gas. Finally, trace gases such as hydrogen sulfide are corrosive and can affect the lifetime of mechanical devices through which biogas passes.

After digestion, a nutrient-rich sludge is produced along with biogas. This sludge effluent can be used as fertilizer, though it might not be as effective as chemical fertilizers or composts. Some people worry that once the sludge is applied to farmland, the digested waste will have a strong odor and that pathogens will contaminate the crops. A study by Furukawa and Hasegawa (2006) compared the amounts of indicator bacteria in the effluent from the anaerobic digestion of kitchen waste and cattle manure. Further, this study compared the digested effluent to a chemical fertilizer rich in nitrogen, phosphorus, and potassium to determine if a higher bacterial count was found in

harvested spinach and komatsuma from land-applied digested-waste or chemical fertilizer. There was no significant difference in the rapid utilization of nutrients between the digested kitchen waste and the chemical fertilizer. No *Escherichia coli*, fecal streptococci, or *Vibrio parahaemolyticus* was found in any harvested leaf, nor were there any significant indicator bacteria differences between applied digested kitchen waste or cattle manure (Furukawa and Hasegawa 2006). This implies that food waste that could have been partially consumed and then thrown away might not lead to significant bacterial contamination of crops after digestion and land application

Finally, anaerobic digestion is an exothermic process. Heat is given off by the anaerobic bacteria and methanogens digesting organic waste. This heat is generally not significant enough to influence the digestion process, and is even seen as a positive byproduct as it contributes to maintaining a mesophilic temperature within the digester.

3.0 Methods

3.1 Food Waste To Energy Analysis

To understand the food waste stream that could be utilized by Smith Middle School for anaerobic digestion, the amount and the characterization of the food waste generated each school day was needed. To estimate these variables, the food waste generated at the Smith Middle School cafeteria during lunch was weighed and observed over the course of one month, approximately three times per week. Through collaboration with 7th grade science teachers and the cafeteria staff, the food waste was source-separated in plastic bags by both students and cafeteria staff. The bags of food waste produced by both cafeteria staff and students were then weighed on a scale by an observer or cafeteria staff member (Table 3.1). The types of food thrown away were

recorded by the students and an observer along with approximate composition. These approximations were further categorized into five main food categories: grains, fruits, meats, vegetables, and miscellaneous. Table 3.2 represents the estimates of the amounts of waste by category.

Table 3.1 Amount of food waste generated over the course of one month by both the cafeteria staff and 7th grade class of Smith Middle School.

Date (in 2007)	Cafeteria Waste (kg)	7th Grade Class Waste (kg)
Sept 25	N/A*	4.5
Sept 27	N/A*	3.2
Sept 28	N/A*	4.5
Oct 2	8.2	4.1
Oct 4	10	2.7
Oct 5	N/A*	2.3
Oct 9	6.4	N/A*
Oct 11	7.3	N/A*
Oct 12	8.6	N/A*
Oct 16	N/A*	4.5
Daily Average	8.1	3.7

*** N/A indicates dates in which waste was not collected**

Table 3.2 Characterization of the food waste from Smith Middle School and the methane yields for the respective food categories per day.

Food Category	Percent by Weight of Smith Middle Food Waste Stream	Average Methane Yield ($L\text{-}CH_4$ / kg-VS)*	Theoretical Methane Production ($L\text{-}CH_4$) for 19.1 kg of Food Waste*
Grains**	40%	275	2,100
Fruits**	25%	81	387
Meats**	15%	340	974
Vegetables**	15%	83	238
Miscellaneous***	5%	0	0
Total			**3,700**

*** See Appendix 7.1.1 for calculations**
**** See Appendix 7.2.0 for collected data**
***** The Miscellaneous category encompasses paper bags, dairy products, and non-degradable materials thrown away**

The 7th grade class that generated 3.7 kg of food waste per day consisted of approximately a third of the entire middle school. The other two grades, 6th and 8th, have been assumed to produce the same amount of food waste per day, making the estimated

total amount of food waste produced 11.1 kg per day by the students during their lunch break. Combined with the food waste generated from the cafeteria a total of approximately 19.1 kg of food waste is produced per day at Smith Middle school.

To derive the energy potential from this mixed food waste, the amount of methane by wet-weight of the food waste was needed. Methane potentials for the wet-weight of 12 specific foods were derived from research articles on anaerobic digestion, while three times as many methane potentials were derived from the calorific values the United States Department of Agriculture published in 2002 (Gebhardt and Thomas 2002). Even though these values did not always match the type of food described, such as pizza remnants or a quesadilla, many of the methane potentials and calorific values for the types of food on the lunch menu of Smith Middle School were found. As the USDA reported calorific values for numerous foods that could be used in determining an average methane potential for mixed food waste, only 38 were selected that most closely matched the food described on the October 2007 Smith Middle School lunch calendar. The calorific values presented by the USDA were derived from heating values measured from combusting the food. It can be assumed that this heating value is directly correlated to the amount of methane that could be produced through digestion. These values were applied to the average weights in the five different food categories and then averaged categorically. Such averaging is appropriate because the food waste stream changes day by day; for example, instead of having green beans again tomorrow for lunch, the cafeteria staff might serve carrots. Table 3.2 displays the mean estimated methane yields derived for the first four food categories. The miscellaneous category is omitted, as an assumption that 5% by weight of the waste thrown away is liquid (for example, the

cafeteria staff throws out remaining sauces) and would have negligible methane production.

With the maximum amount of methane that can be produced from the daily food waste stream of Smith Middle School, the energy content of this waste was determined. Assuming that for every gram of methane, 50.1 kJ of energy can be produced (Metcalf and Eddy 2003), approximately 37 kWh (see Appendix 7.1.1 for conversions) is the maximum amount of energy that can be produced from the anaerobic digestion of 19.1 kg of food waste generated at Smith Middle School. Over the course of one month, with at most 23 days of school during which food waste would be generated, the maximum amount of energy that could be derived from the accumulated food waste would be approximately 846 kWh.

3.2 Energy Production

3.2.1 Electricity Production

To produce electricity from biogas, two possible pathways were researched. The first possibility is using a gas combustion engine as an electrical generator. The efficiency of these engines depends on the manufacturer, but it was assumed that an average Otto-cycle engine is approximately 25% efficient. A combustion engine would require the biogas to be compressed and mixed with a natural gas stream in roughly a 3:1 biogas-to-natural gas ratio in order to maintain a high enough temperature to keep moisture from collecting inside the engine. Even with these limitations, combustion engines are generally inexpensive, have multiple manufacturers, and technicians needed to repair them are easily found.

The second possibility researched was generating electricity via a Stirling engine, where biogas would be burned without compression. In a Stirling engine, the heat energy released from burning the biogas is captured by a compressed helium chamber that pushes two pistons in a relatively energy-efficient manner. The pumping of the pistons generates an electric current at an electrical production efficiency of 30-35% (Alternative-Technologies-Subgroup 2006). Limitations to using a Stirling engine on a small scale are the large capital cost required to purchase the engine, there are few producers, and none of the manufacturers found can produce an engine as small as required for this project.

3.2.2 Natural Gas Substitution

Smith Middle School, like most schools, has a boiler for heating purposes. The fuel source the school uses is natural gas from the local supplier, Public Service Gas Company of North Carolina (PSNC). The gas supplied to the school passes through a burner at a pressure specified by the manufacturer, generally between 34.5-103 kPa (5-15 psi) (personal contact from a PSNC engineer), to produce heat. After the natural gas pressure steps down from the PSNC distribution system, and before the gas passes through the burner, biogas can be mixed into the natural gas stream at the same pressure. This means the gas captured from the anaerobic digester must be brought up to the pressure the burner requires. Further, the biogas contains trace sulfides that would produce sulfuric acid once it is burned in the boiler, making a sulfide scrubber necessary in order to maintain the life-span of the boiler. Once the biogas is burned in the boiler, it directly offsets the natural gas needed by the heat value produced, which depends on the

methane content in the biogas. For this study, the methane content was assumed to be 60%.

3.3 Financial Viability of Energy Production Methods

The monetary value of the biogas energy produced depends on how the gas is used. The two possibilities analyzed here for using this energy source are combusting the gas in a generator for electricity production, or offsetting the current demand for natural gas by combusting the biogas in an existing boiler, offsetting the need for natural gas. Either energy conversion method has its technical limitations and inefficiencies, but the final feasibility determinant is the return-on-investment of each method.

The first economic factor to be reviewed is the revenue that can be obtained from either pathway. Revenue from the biogas-to-energy process comes from utilities paying back the school for electricity produced (called net metering), from the state government supplementing the school for producing a renewable energy supply, or from the savings the school would accrue from either offsetting their own electricity usage on a closed-grid or from offsetting the natural gas supplied to the boiler. The prices used to calculate the revenue from these options were obtained through communications with the North Carolina Green Energy Program (NC Green Power), PSNC, and Duke Energy. NC Green Power is an independent, non-profit organization in North Carolina supported by all the utilities in the state, which has the goal of supplementing the state power supply with "green" energy (non-fossil fuel derived energy). NC Green Power supplements individual power producers as well as informs utilities of their duty to pay these producers for their electric energy contribution (NC-Green-Power). It was determined that NC Green Power would pay between $0.01-$0.02 / kWh for biogas to electricity

conversions (personal communication with Victoria McCann, Assistant Program Manager for NC Green Power). Further, an electric utility would pay between $0.02 and $0.045 / kWh for electricity production by an individual. This yields a range of $0.03 to $0.065 / kWh for electricity production from biogas by an individual producer in North Carolina. The lower and upper limits of payback per kWh are designated as NC Green Power Low Price and NC Green High Price, respectively.

The prices from the utilities PSNC and Duke Energy were determined through phone conversations with company representatives in January 2008. A representative from PSNC estimated the price they charge Smith Middle School for natural gas at $1.25 / Therm, which is equivalent to $0.0427 / kWh (see Appendix 7.1.1). It is assumed that the energy produced by the FWTE would directly offset the energy produced from burning PSNC natural gas required by a Smith Middle School boiler. The last price alternative considered, Closed Loop Duke Energy Avoided Cost, represents the possibility that Smith Middle School could run a section of their electric grid solely on the electricity produced from the FWTE. This would entail disconnecting a section of their grid from Duke Energy, and connecting it in series with an electric generator. As the school would no longer need Duke Energy services, this would be considered an avoided cost. A Duke Energy representative estimated the price they charge for electricity at $0.1024 / kWh, which is the Closed Loop Duke Energy Avoided Cost.

3.3.1 Additional Schools

Smith Middle School is located between Chapel Hill High School and Seawell Elementary School, and is within walking distance of each. It is feasible that food waste from one, two, or all of these schools could be utilized in an anaerobic digester located at

Smith Middle School. Table 3.3 illustrates the student population of each school for the 2007-2008 academic year and the estimated amount of food waste generated per day. This assumption that food waste generation is directly proportional to the student population of a school was derived from the observed food waste generation of Smith Middle School (0.64 kg-food waste/student-month). This table also shows the potential monthly revenues for biogas to offset natural gas needs of Smith Middle school and the amount of energy that would be produced from these food waste combinations using the assumption that the system's efficiency is 75% (0.95 kWh / student-month). Simply, the more food waste generated the more biogas that can be produced, and therefore the more revenue that can be obtained from biogas production.

Table 3.3. Student populations and their food waste generation for combinations of schools neighboring Smith Middle School that could contribute to an anaerobic digester.

School Combination	Student Population	Amount of Food Waste / Day (kg)
Seawell Elementary	555	15.9
Smith Middle	668	19.1
Chapel Hill High	1,754	50
Smith + Seawell	1,223	35
High + Seawell	2,309	65.9
High + Smith	2,422	69.1
All Three Schools*	2,977	85

*** This option includes Smith Middle, Seawell Elementary, and Chapel Hill High schools**

3.4 REGULATIONS

When considering the feasibility of the implementation of an FWTE at a public school, it is important to consider the regulations involved in gaining permission to construct and operate this system. The main areas of concern are that this system produces an explosive gas in the vicinity of school children and that it requires the

handling of food waste, which is a sanitation concern. Fortunately, these concerns can be addressed and incorporated into the design of the digestion system.

3.4.1 Local Regulations

The Chapel Hill Township building inspector would need to approve the plan for the construction of an FWTE. The building inspectors require a fee of $58.00 for an inspection of a heat pump, which is a similar application, and a $52.00 fee for re-inspections (Town-Of-Chapel-Hill 2008). A conversation with Joe Askew, an inspector for heating and cooling systems in Chapel Hill, suggested that approval for the construction of this project would be allowed if the Chapel Hill Fire Department, the North Carolina Labor Department, and the Underwriters Laboratories (UL) in Research Triangle Park (RTP) were to give their individual approvals of this project. He stated that the designs for the project must be drawn up by a licensed professional engineer.

A conversation with Matt Lawrence, Deputy Fire Chief of Chapel Hill, confirmed the regulatory requirements cited by Mr. Askew. His main concern was the storage of the biogas. He indicated that the storage tank should be outside of the building away from other potential hazards. A sketch of the room and the FWTE would need to be drawn for approval along with a brief description of the biogas composition. The fire chief would inspect the plans prior to construction and visit the site after construction to grant approval. Mr. Lawrence said his department would be likely to approve plans if the UL were to approve it prior to his review of the plans.

The Chapel Hill-Carrboro City Schools Planning section would be concerned about the volatility and storage of the methane. From a conversation with Steve Taynton, Chief of School Planning for Chapel Hill-Carrboro City Schools, the following plans

must be submitted in order to gain School Planning approval: the site plans of the digester system and utility requirements, a material inventory, scaled floor plans with wall sections and ceiling heights, mechanical and electrical drawings, a schedule for project completion, and appropriate energy efficiency considerations (Ward 1998). Finally, the School Planning Section requires the plans for construction to be reviewed by a local building inspector who can issue a building permit.

The Chapel Hill-Carrboro City Schools Facilities Maintenance Division would also require a site plan, economic and energy study, and that the plans for construction be reviewed and permitted by a local building inspector. The site plan for the FWTE must include a scaled map and description of the project. The scaled map would consist of dimensions for the system in relation to the other components within the work space, such as wall sections, ceiling height, and proximity to other machinery, and would show the facility location and size in relation to the existing building. The project description can be general, but should include the construction materials and drawings for the mechanical, electrical, and plumbing systems to be utilized. The economic and energy study would need to include the information laid out in the site plan along with the utility requirements of the system and a schedule for finishing the project. The project should be energy efficient based on the Energy Guidelines for School Design and Construction.

Finally, the principals of the schools involved must give their approval, especially the principal of Smith Middle School where the digester would be located. Principal Valerie Reinhardt of Smith Middle was contacted and asked about her concerns for such a system to be in operation on her campus. In addition to the concerns addressed so far, her concerns included odor control, storage of the waste, physical space the FWTE would

require, and the impact on the daily routine of the students and staff. The odor from this system would be produced during the expulsion of old waste and the generation of leachate. Odor can be minimized by properly sealing the anaerobic digester and expedient removal of effluent generated by the digester. As the storage of the food waste would either be in the digester, or removed from the school, this should not be issue. The physical space required is important and an appropriate space within the school compound would have to be found. The routine of the students and teachers would not change much. In the cafeteria, students and teachers would separate their organics from inorganics, as previously demonstrated during sampling, and potentially continue this source separation within their class rooms. However, a FWTE operator would need to grind the collected organic waste and wash the grinder outside in order to reduce odor. Daily cleaning around the influent and effluent compartments of the FWTE would be necessary to reduce odor as well.

3.4.2 North Carolina Regulations

The first statewide regulation issue is the concern about the permission from the relevant state agency for producing and combusting methane. Charles McEachern, a professional engineer in the Division of Air Quality at the North Carolina Department of Environment and Natural Resources, was contacted to determine whether a permit was necessary for this small-scale FWTE. He noted that most permits are for large-scale operations like wastewater facilities or landfills, and are not needed for operations that produce less than five tons of methane per year. All of the school combinations would produce below this limit, as even the methane produced from all three schools would produce approximately 2 tons of methane per year (see Appendix 7.1.1). Therefore, none

of the school combinations would require an air quality permit for yearly methane production.

The North Carolina Department of the Environment and Natural Resources (NC-DENR) would need to approve the method in which food waste would be handled at a North Carolina school. Their Division of Waste Management has regulations concerning the sanitation of transporting food waste within a school by qualified individuals. Michael Scott, an Environmental Program Supervisor in the Waste Management Division, reported that waste movement under 1 yd^3 is not regulated and is considered the same as a compost program. In contrast, waste transported for these purposes that is greater than 1 yd^3 requires a demonstration period of one year prior to approval pending project details. As the maximum amount of food waste to be transported from all three schools combined would be 187 lbs, or approximately 0.6 yd^3 (see Appendix 7.1.2), no approval from the NC Division of Waste Management is required.

A question was brought by the Chapel Hill Town Building Inspector about the energy that the biogas-to-energy system would deliver and if the Department of Labor would need to regulate this. This aspect only applies in the usage of boilers to heat water, for capacities greater than 200,000 Btu/hr (Berry 2006). The FWTE would deliver approximately 17,500 BTU/hr (see Appendix 7.1.2), far below the need for state regulation. An additional state code that needs to be recognized is the North Carolina Gas Fuel Code. Under this code for boilers, the installation of boilers must meet the above standards. The ASME CSD-1 regulation was also consulted and was in concurrence with above standards (Tingen and Long 2006). To summarize, no regulatory

measures need to be addressed for the FWTE by the North Carolina Department of Labor, since the size and pressure of the boiler would not change.

The North Carolina Division of School Support's School Planning Section would also need to certify that the handling of food waste is in accordance with the sanitation requirements of 15 A NCAC 18A .2600 and 15A NCAC 18A .2400. The former regulation is the rule governing the sanitation of restaurants and other food-handling establishments and the latter is the rule governing the sanitation of public, private, and religious schools (Ward 1998). As these regulations must be met under current operations at the school, the staff of a public school would already be trained in the proper handling of food waste to the extent these regulations require.

Further, to keep in accordance with the regulations from the School Planning Section, a complete set of final working drawings for the management of the food waste must be approved by the Environmental Health Services Section of the Division of Environmental Health prior to construction. The site plans should include dumpster and waste container locations, and all related cleaning facilities. Upon approval, the plans can then be forwarded by Environmental Health Services Section to the local health department for comments and permitting (Ward 1998). To satisfy this requirement, drawings previously submitted by a school for food waste management could be updated to include the usage of the food waste in the anaerobic digester prior to removal from the school.

3.4.3 National Regulations and Codes

The National Board of Boiler and Pressure Vessel Inspectors review the safety valve capacity of a steam boiler, among other aspects. If an alteration to a certified steam

boiler with a working pressure of less than 15 psi increases the boiler output heating rate, then a certified National Board of Boiler and Pressure Vessel inspector must certify that the new output is within the range of the current safety valve. Otherwise, a new safety valve with a higher capacity must be installed (personal communication with Terry Parks, Manager of Field Services, The National Board of Boiler and Pressure Vessel Inspectors). As the FWTE system will not be installed in order to increase the heating output of the boiler, certification should not be necessary. However, the output heating value should be monitored and if the output does increase, an adjustment should be made to the system in order to reduce it to the normal operating level.

Engineers at the UL in RTP were uncertain of the regulations that the FWTE would fall under. The most conclusive recommendation was to receive a New and Unusual Evaluation by contacting their Customer Service Group. This would entail a preliminary investigation to check if the UL could offer their services to affirm product safety. If the UL investigator decided that their services could be rendered, an engineer would observe the FWTE in operation to either create new or combine current standards to ensure approval of this device. The cost of a field evaluation and approval would be approximately $1000, which would allow for this system to be installed permanently in an industrial setting.

4.0 Results and Discussion

4.1 Comparison of Energy Production Methods

The economic differences between using a combustion engine, a Stirling engine, and a boiler system are shown in Figure 4.1. This graph illustrates the monthly revenue from either selling electricity back to a local electric utility or offsetting energy needs

against the efficiency of the anaerobic digestion and energy conversion system. It is important to recognize that the energy conversion efficiency relies first on the digestion efficiency. As previously noted, the digestion efficiency was assumed to be 75%, while the energy conversions to electricity are assumed to be 25% and 35% for a combustion engine and a Stirling engine, respectively. Table 4.1 illustrates the differences between the energy conversion methods with their overall system efficiency values and the prices associated with each. From this table, which was derived from Figure 3.1, it is discernible that using the biogas in a boiler provides the most revenue per month as there is no loss of efficiency in converting the biogas to electricity. As the boiler option has the potential to generate the most revenue and will have a far lower capital cost than would be required to purchase an engine, the boiler was selected as the energy conversion system considered during the design aspect of this project.

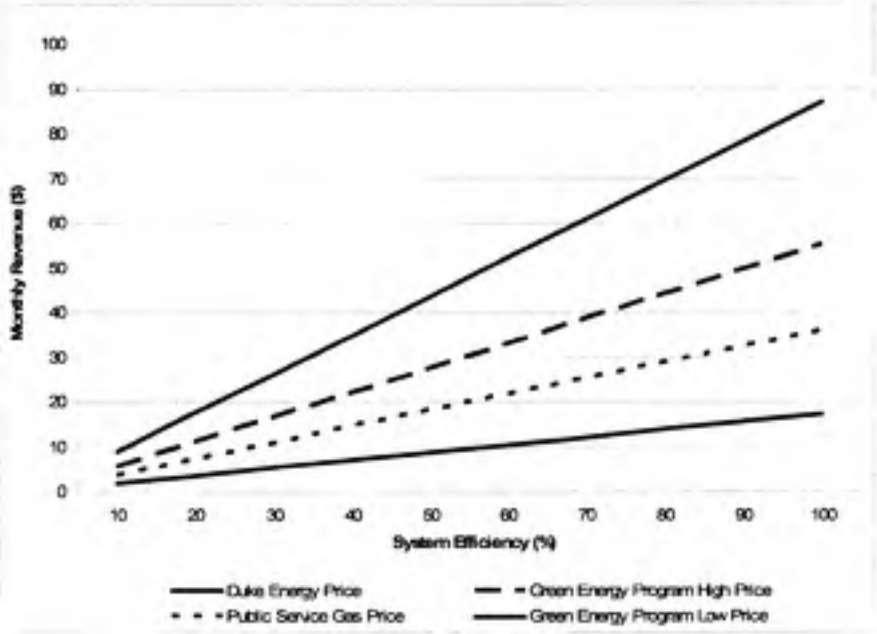

Figure 4.1. Monthly revenue from harvesting biogas for producing or offsetting needed energy versus total system efficiency, including digestion and energy conversion. This information is based on food waste generation rate of 19.1 kg / day.

Potential revenues for each school combination are shown in Table 4.2 using the PSNC price per kilowatt-hour. As expected, the largest school population would produce the most food waste and therefore the most energy. The combination of all three schools producing energy in a boiler system was thereby selected to analyze the technical and economic feasibility of an FWTE.

Table 4.1. Comparison of estimated monthly revenue for different energy conversion options with their respective efficiencies.

Energy Converter	Max Overall Efficiency	Estimated Monthly Revenue*			
		Closed-Loop	Low Green Energy	High Green Energy	Offset Natural Gas
Combustion Engine	18.75%**	$16	$3	$10	n/a
Stirling Engine	26.25%**	$23	$4	$14	n/a
Boiler	75%***	n/a	n/a	n/a	**$27**

*** See Appendix 7.1.3 for calculation**
**** The engines have a combined efficiency of anaerobic digestion and energy conversion**
***** The boiler efficiency takes into account the digestion efficiency only because the biogas would directly offset natural gas consumption**

Table 4.2. Energy production potential and estimated revenue from offsetting boiler gas usage using various combinations of food waste generated by the neighboring schools of Smith Middle that could contribute to an anaerobic digester.

School Combination	Monthly Energy Production (kWh)*	Monthly Revenue ($)	Yearly Revenue ($)**
Seawell Elementary	529	23	210
Smith Middle	634	27	250
Chapel Hill High	1,661	71	640
Smith + Seawell	1,163	50	450
High + Seawell	2,190	94	850
High + Smith	2,296	99	890
All Three Schools	2,824	121	1,100

*** A system efficiency of 75% was assumed.**
**** Note that the yearly revenue is based on the school year of nine months.**

4.2 Anaerobic Digestion System Operation

To maximize methane production, the optimal operating parameters must be utilized. It can be assumed that the moisture content of the fruits and vegetables thrown

away is at least 90%, while the grains, including cooked pasta and bread, may have a lower moisture content of 50%, and the meats may have a moisture content of approximately 60% (USDA 2008). From observing the cafeteria staff at Smith Middle, the remainder of the food waste is liquid from sauces that would be at least 99% water. The total moisture content can therefore be assumed to be a weighted average of 70%. As a moisture content over 90% is preferable for anaerobic digestion of solids (Fujishima et al. 2000; Lay et al. 1997), an addition of 5.7 L of water per 19.1 kg of food waste would bring the moisture content to approximately 90%. The need to add water would be up to the judgment of a digester operator, because the moisture content of waste might vary considerably from day to day as the composition of the waste varies. Adding water to the digester would only be required until leachate produced in the effluent could be recirculated into the digester, which would help optimize the degradation of the solids and offset the need for additions of water (Cho and Park 1995; Nguyen et al. 2007; Viturtia and Mata-Alvarez 1989). Additional water would also be needed during regular operations to wash the grinder and the inlet and outlet compartments of the digester to prevent odor.

For complete anaerobic digestion of volatile solids in a batch reactor, a retention time of 100-200 days would suffice. However, this is an infeasible amount of time to retain solids on a small scale where semi-continuous feeding is occurring. It is also recommended that too short a retention time be avoided. Cho and Park (1995) found that a batch digestion of food waste with 87-90% moisture content completed the majority of methane production from the food waste after 15 days (Figure 4.2). Because the kinetics of batch digestion are not directly comparable to digestion in a semi-continuous reactor, a

solids retention time of 30 days is assumed for the design considered in this project. A residence time of 30 days should permit methane production to approach its maximum potential (Yadvika et. al. 2004).

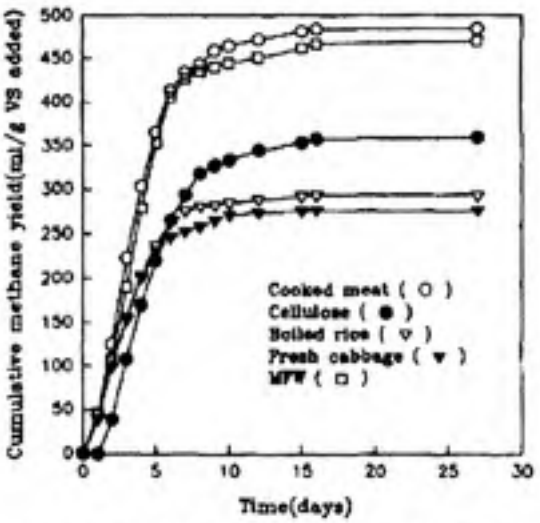

Figure 4.2. Methane production over time from food waste in a batch digester with 87-90% moisture (Cho and Park, 1995)

The solids loading rate may not be constant as students and cafeteria staff will throw away whatever waste they have. Such variability could be accounted for in a more detailed design, by quantifying longer-term variability in daily waste production. A reasonable design criterion might be the maximum five-day running average. Variability in loading can be a potential problem that would have to be monitored by checking the amount of biogas produced to see that it is correlates positively with the loading rate. Fluctuations in biogas production would suggest inhibition within the digester and would more than likely be due to excessive VFA production and therefore low pH levels. Other inhibitory factors are controllable, as source separation would keep out metals, excess sodium, and cleaning products containing surfactants or ammonia, and airtight seals would be used to minimize the amount of oxygen entering the digester.

Intermittently mixing solids within a digester has also been shown to enhance digestion (Wilkie et al. 2004). To do this, a device could be attached to the digester for easy operation that would be able to churn at least the most recently added food waste to enhance hydrolysis. However, such a device could deteriorate the structural integrity of a digester or add significant costs by requiring a custom made digester, and therefore is not recommended. Instead, particle reduction prior to feeding the digester would be easier and more cost effective, and would increase methane production as well. Comminution of feed material improves biogas production, especially from fibrous waste (Mata-Alvarez et al. 2000; Palmowski and Muller 2000).

Inoculum addition is an important start-up procedure for an anaerobic digester (Maroun and El Fadel 2007). As indicated earlier, the more inoculum-to-substrate present in a digester during startup, the more quickly the digester will reach optimal methane production (Chen and Hashimoto 1996; Hashimoto 1989). From these considerations, dewatered effluent from a mesophilic anaerobic digester, which could be found at many wastewater treatment plants, should be obtained to fill as much of the digester as possible. Since the envisioned application for food waste is a semi-continuous operation, filling the digester at the beginning with inoculum will enhance the production of methane from the food waste fed to the digester. Over time, the inoculum will be removed from the digester as more of the influent food waste becomes fully digested.

With these parameters optimized, the anaerobic digestion process could yield a food waste-to-methane efficiency of 70-80% of the maximum theoretical yield. It is improbable to have 100% of the maximum potential methane yield because it is

impossible to guarantee that all the food particles will come into contact with anaerobes during the time allotted.

In should be noted that over the weekends and during the school year holidays, food waste would not be generated and therefore not enter the digester. This does not impact the regular operations of the digester as the food waste in the digester during these time periods would simply be left inside and allowed more time to degrade. Once school resumed and new food waste was added to the system, operations would resume as normal. During the long summer break, no food waste would be generated regularly and therefore the system could be shut down and cleaned out until school resumed. Each year the system operations could be restarted as if it were beginning for the first time using the proper inoculum.

4.3 Digester Design

The equipment and instruments needed for the anaerobic digestion of food waste produced from all three schools and for the safe transfer of methane from the digester to a boiler system are shown in the following schematic (Figure 4.3). Figure 4.3 depicts the relative sizes of the components and how they are connected which is briefly described in Table 4.3. The components and their respective costs are detailed in Table 4.4. The criteria used in selecting components for the FWTE were: commercially available, inexpensive, easy to operate, and capable of facilitating methane production and transfer.

The design of a digester encompasses all of the system parameters mentioned in previous sections. One of the most important aspects of the design is how large the digester should be. Taking into account the amount of food waste produced daily and a 30-day residence time, Table 4.5 shows the digester volume required to store just the

food waste, the food waste plus water to increase the moisture content, and the designed digester volume that includes a headspace of 15%. A commercially available 1000-gal tank used as the digester could store the combined waste produced by all three schools in one month, with a full volume of about 3 m^3 (800 gal). This particular tank was chosen because it is pre-fabricated, which reduces costs, and has a thick enough wall (0.9 cm, or 0.35-inch) to adequately support the alterations required for the purposes of this project. A specifically designed stand is also available for this cone-bottomed tank to support it when it is fully loaded.

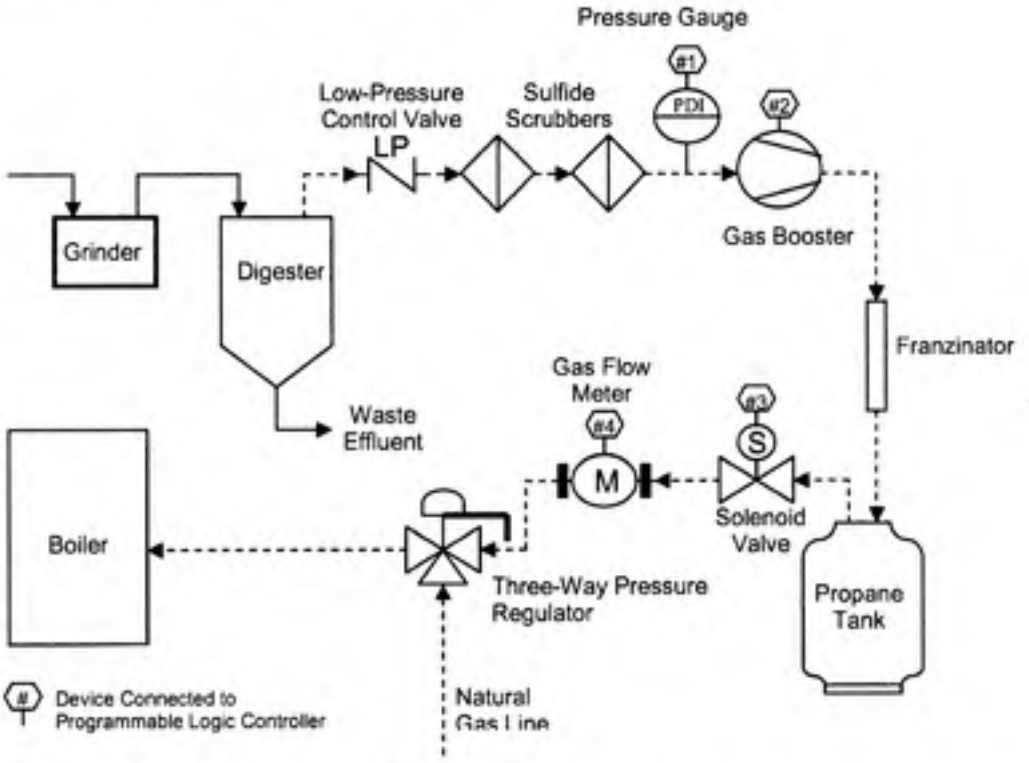

Figure 4.3. Food waste to energy system schematic.
***Note that four devices are connected to a programmable logic controller (PLC) that is not displayed as it is not directly involved in the flow of biogas.**

Food waste will be processed by the chipper / shredder prior to loading into the digester. Particle size reduction increases surface area and subsequently enhances food waste degradation. This grinding can be done best in large volume by an electric

powered chipper / shredder. Hand-powered particle size reducing machinery would be cumbersome for an operator. The chipper / shredder chosen for this project is the McCulloch MCS1400 made by McCulloch/MTD Consumer Products, Inc. with an inlet hopper area of approximately 0.18 m^2 (1 ft^2) and capable of shredding branches with a 3.8 cm (1.5-inch) diameter. For space considerations, this unit can be easily pushed into storage when not in use or carted outside for operation and cleaning (Green-Culture 2007; McCulloch 2008). To clean the grinder, a cleaning solution should be used to scrub off food waste particles in its inlet hopper and on its blades. Once all particles have been removed using the cleaning solution, water should be used to flush over the grinder to remove any cleaning solution.

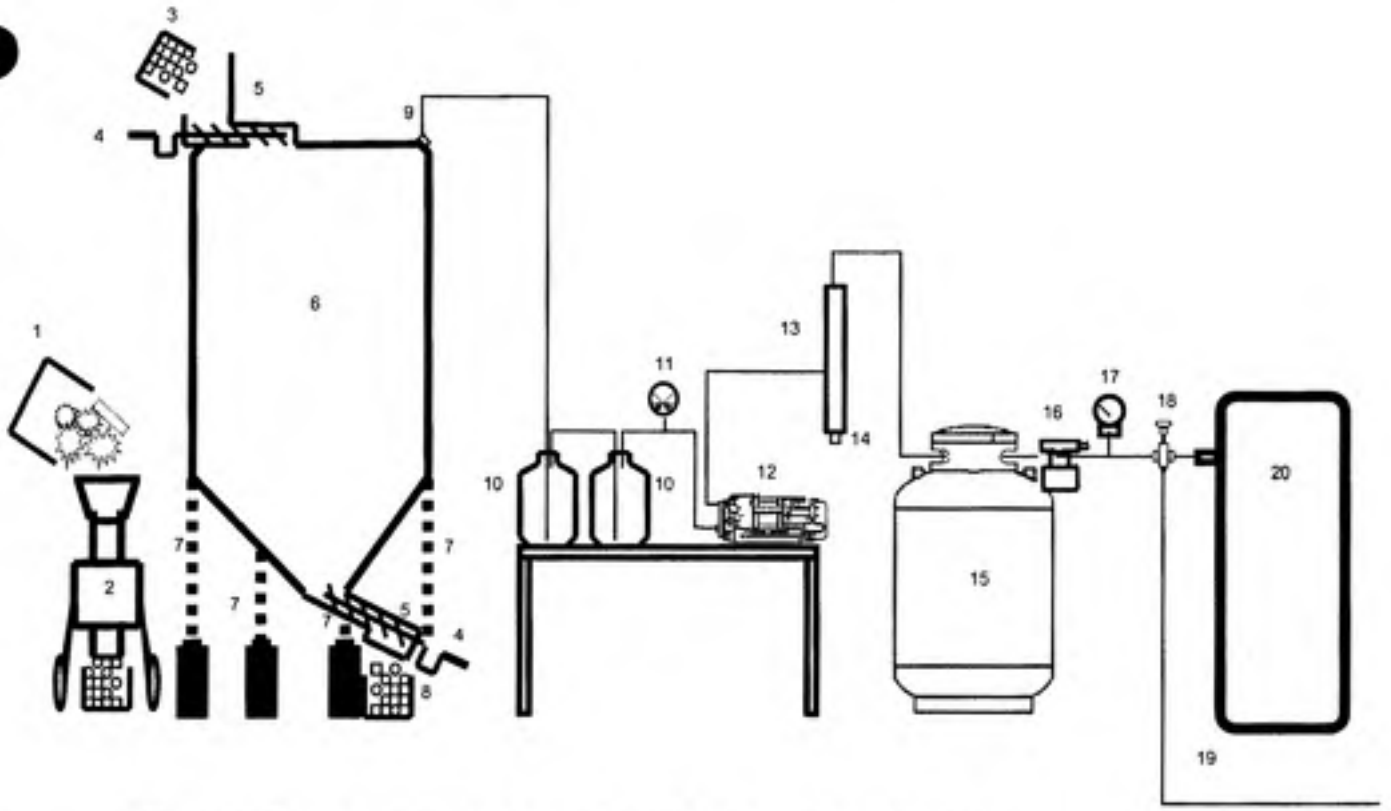

Figure 4.4. Food waste to energy system drawing, see Table 4.1 for description.

Table 4.3. Legend for food waste-to-energy system drawing

Location	Description	Equipment
1	Food waste entering the chipper / shredder	A school food waste bin
2	Food waste maceration and exit into a school waste bin	The Deluxe Electric Chipper Shredder
3	Food waste entering the digester inlet	A school food waste bin
4	Hand crank for moving food waste into and out of the digester	Ice Auger with 6-in diameter
5	Digester food waste influent / effluent compartments with a hermetic seal	6-in PVC pipe and rubber cap
6	Digester	1000 gal cone-bottomed tank
7	Metal supports for the digester	
8	Food waste effluent	A school food waste bin
9	Biogas outlet	Through-wall coupling, spring-loaded check valve, and 3/8-in natural gas tubing
10	Sulfide scrubbers	Schedule 80 PVC pipe with steel wool
11	Biogas pressure check	3210 photohelic pressure gauge
12	Biogas pressurization	AGT-4 Gas Booster
13	Biogas / water separation – Franzinator	6-in diameter steel pipe, 2 ft long
14	Water release valve	
15	Biogas storage	420 lb propane tank
16	Biogas release valve	General service solenoid valve
17	Biogas flow check	Gas flow meter
18	Biogas pressure step-down and mixing with Public Service Gas line	3-way regulator
19	Public Service Gas line	
20	Boiler	

Once the waste is shredded, it can be manually poured into the digester with the appropriate amount of water through the inlet compartment. This compartment will consist of a 0.18 m^2 hopper capped with a rubber gasket joined to a 6-inch diameter Schedule 80 PVC pipe hermetically sealed to the top opening of the digester. An auger within the PVC pipe can be manually cranked by its handle protruding from the PVC pipe, allowing food waste to drop into the digester. The digester is kept airtight by the food waste stuck between the auger blades and the sides of the PVC pipe. This inlet compartment will be welded horizontally to the top of the digester to ease operation. The

inlet hopper will be kept tightly covered at all times except during loading to further minimize air intrusion and in order to control odors.

Table 4.4. Specific equipment list and prices for constructing the FWTE

Item	Manufacturer	Unit Cost	# of Units	Total Cost
Deluxe Electric Chipper Shredder + shipping	McCulloch / Green Culture	$240.00	1	$ 240.00
1000 Gallon Cone Bottom Tank + Support Stand + shipping	ACE Roto Mold	$1467.00	1	$1467.00
6" Ice Auger	Ardisam, Inc.	$45.00	2	$ 90.00
Photohelic 3210 Gauge	Dwyer	$253.00	1	$ 253.00
420 lb Propane Gas Tank	Worthington Cylinders	$437.00	1	$ 437.00
Stainless Steel General Service Solenoid Valve + shipping	ASCO Valve, Inc.	$170.00	1	$ 170.00
2-3ft 6"-dia Schedule 80 PVC Pipe - Solid bottom cap and screw top	Fabricated	$27.50	4	$ 110.00
5 lbs Steel Wool Reel: Grade 00 + shipping	Palmer Engineered Products, Inc.	$32.00	1	$ 32.00
Pressure Regulator	Carotek	$87.00*	1	$ 87.00
10ft 6"-dia Schedule 80 PVC Pipe	Lowe's	$27.00	1	$ 27.00
3/8" Yellow Natural Gas Flexible Pipe / ft	Lowe's	$4.00	30*	$ 120.00
10 ft 2"-dia Galvanized Steel Pipe	Home Depot	$16.00	1	$ 16.00
3/8" Through-Wall Coupling Durable White Nylon Compression Tube Fitting	McMaster-Carr	$5.00	1	$ 5.00
3/8" Polyvinylidene fluoride Spring-Loaded Ball Check Valve	McMaster-Carr	$15.00	1	$ 15.00
Influent and Effluent Hoppers (PVC, Rubber Gasket, Angle Iron)	Fabricated	$25.00*	2	$ 50.00
Programmable Logic Controller + Accessories	Automation Direct	$600.00	1	$ 600.00
Gas Flow Meter	Clark Solutions	$1000.00*	1	$1000.00
Natural Gas Booster	Haskel International	$2600.00	1	$2600.00
Miscellaneous for connecting tubes to devices				$ 100.00*
Grand Total for Equipment Costs				**$ 7,419.00**

* **Estimated**

After the waste has been degraded in the digester, it will be pressed out of the bottom of the tank due to compression by later waste additions. The outlet compartment will be similar in design to the inlet compartment. A similar PVC pipe would be joined

to the bottom of the tank at a 30° to 45° angle from horizontal as the outlet with a similar auger capable of cranking out digested waste. A rubber gasket and cap would cover the end of the PVC pipe to keep leachate from draining onto the ground when not in use. Before the effluent is removed, a bucket should be positioned underneath the pipe outlet to catch the leachate once the outlet cover is removed. To capture leachate for recirculation, a screen could be used to catch the effluent waste prior to removal from the school to allow the leachate to drain out.

Table 4.5. Digester volume requirements under various scenarios (combinations of schools).

School Combination	Amount of Food Waste / Day (kg)	Food Waste Volume per Month (m^3)	Working Digester Volume w/ H_2O (m^3)	Designed Digester Volume (m^3)*
Seawell Elementary	15.9	0.383	0.492	0.566
Smith Middle	19.1	0.460	0.591	0.679
Smith + Seawell	35	0.843	1.083	1.245
Chapel Hill High	50	1.205	1.547	1.779
High + Seawell	65.9	1.588	2.039	2.345
High + Smith	69.1	1.665	2.138	2.458
All Three Schools	85	2.048	2.630	3.024

*** The design volume accounts for an additional 15% above the working volume as head space.**

As biogas is produced, it will vent from the digester through an approved natural gas tubing line at the top of the digester. The tubing would be connected to the tank by a 3/8-inch diameter durable white nylon compression, through-wall coupling in series with a 3/8-inch polyvinylidene fluoride spring-loaded ball check valve with a cracking pressure of 6.9 kPa (1 psi). This will allow the pressure in the digester to build to 6.9 kPa prior to extraction (McMaster-Carr 2008). The gas tubing will be a 3/8-inch, flexible, copper-lined tube approved for use with natural gas, connecting the digester to the rest of the FWTE. It is possible that a malfunction may occur that would impede the check valve from operating correctly in order to release the biogas. An appropriately sized mechanical pressure relief valve should be attached to the digester to ensure the structural

integrity of the digester tank and not allow gas pressure to inhibit the anaerobic digestion process. However, the relief valve should not be set to a pressure low enough to impede gas booster operation. This relief valve should be connected in a way to vent the excess gas outdoors.

The biogas will first be routed to a pair of parallel sulfide scrubbers that consist of two 2-3 ft long 6-inch Schedule 80 PVC pipe in series to avoid corrosion of downstream components. These PVC pipes would be filled with steel wool and capped with a solid bottom and a screw top. Schedule 80 PVC pipe was chosen due to its high pressure tolerance (1.9 MPa, or 280 psi) and its low-cost. As the biogas passes through the steel wool to an outlet pipe at the top of the container, any hydrogen sulfide in the biogas will interact with the steel wool, effectively removing the hydrogen sulfide from the biogas stream. The pipes can be periodically checked, one pair of sulfide scrubbers at a time to keep gas flow continuous, to replace any degraded steel wool. To avoid mixing air with the biogas, the newly cleaned PVC pipe would have a vacuum attached to remove any air from the pipe.

Biogas pressure would be monitored by a photohelic pressure gauge downstream of the scrubbers. The recommended gauge is the Dwyer 3210 Series. This gauge is capable of detecting pressures between 0-69 kPa (10 psi) with an accuracy of ±2% and is equipped with two programmable set-point outputs that can be used to send high and low gas pressure signals to the PLC (Dwyer). These set-point pressures would be determined by the low flow / pressure requirements of the next component, a natural gas compressor. An analog output accessory can be ordered as part of the photohelic gauge to chart

pressure fluctuations in order to determine whether inhibition was occurring in the digester.

The natural gas booster chosen is the AGT-4 Gas Booster made by Haskel International. This booster can accommodate a 14 L/min methane gas flow at a pressure of 21 kPa (3 psi) and boost it to 1.4 MPa (200 psi) (Hirabayashi 2008). Haskel International (2008) found that this gas booster could compress a low-flow gas from 28 kPa (4 psi) to a maximum pressure of 8.6 MPa (1250 psi). If the lower and upper pressure limits of the photohelic gauge were set at 21 kPa and 34 kPa (5 psi), respectively, the gas booster could begin operating at 34 kPa pressure would compress the biogas to a pressure greater than 1.4 MPa. The compressor would then turn off when the inlet gas pressure dropped to 21 kPa. The pressure limits should be modified to optimize booster operation without allowing the gas pressure to build within the digester and sulfide scrubbers to a critical level. The aforementioned flow rate of 14 L/min may vary daily depending on the quantity of CO_2 produced in conjunction with the methane. For the combined waste produced by all three schools, the average daily gas production rate would be approximately 20,600 L at STP (see Appendix 7.1.2).

As for the thermodynamics concerned with this process, if the booster has an inlet pressure of 25 kPa (P_1) and an exit pressure of 1.5 MPa (220 psi, P_2), respectively, and an inlet temperature of 35°C (T_1), the exit temperature will be 93°C (T_2) according to Equation 1, with γ, the specific heat ratio, being 1.31 for methane.

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(1-1/\gamma)} \quad \text{.....[1]}$$

Once the biogas has been compressed, it will pass through a franzinator, which is a 0.61 m (2 ft) long vertical steel pipe with a 5.1 cm (2 in) diameter and a rubber gasket

on either end. A franzinator removes water from the compressed gas through condensation. This occurs as the heated gas is injected into the middle of the pipe, aimed towards the bottom. As the gas circulates to the bottom and travels back up the top of the pipe to the outlet, the gas rapidly cools and water condenses onto the sides of the pipe. The water is collected in the bottom of the franzinator and can be removed with a valve. Optimal positioning of the franzinator requires it to be placed in a cool location (for example, against a concrete wall) to promote condensation.

The pressurized gas would be stored in a propane tank capable of safely storing methane and delivering the largest amount of methane to the boiler at a time. The largest storage tank commercially available that would be safe for volatile gas storage is a 420 lb propane tank with a 454 L capacity. The 420 lb propane tank is made by Worthington Cylinders, with a rating for 1.8 MPa (260 psi), and a relief pressure of 2.7 MPa (390 psi) (Worthington-Cylinders-Corporation 2007). The combined waste from all three schools would produce approximately 920 moles of gas at STP (see Appendix 7.1.2), which at an operating temperature and pressure of 35°C and 25 kPa (3.6 psi), respectively, is approximately 94,700 L-biogas. If the biogas were pressurized to 1.5 MPa (220 psi), then the gas would have a volume of 1,800 L. This tank could store approximately 4 hours of biogas production at this daily rate. Finally, to transport the gas to the boiler, the propane tank release valve would be connected in series to the next component, the solenoid valve. If a malfunction with the solenoid valve occurs and pressure increases in the propane tank, a built in relief valve would vent excess gas at a pressure of 2.7 MPa. For safety purposes, the propane tank should be stored outdoors.

The solenoid valve is an electromechanically controlled valve that will open based on a signal from the PLC. The valve would be signaled to open when the propane tank pressure reaches an upper limit. A solenoid valve offers fast and safe on/off switching, is compact, requires little power, and is very reliable. Solenoid valves are also made to have a long lifetime. For this project, the stainless steel general service solenoid valve, series 8210R1 made by ASCO Valve, Inc, was selected for its ability to withstand a range of pressures between 34.5 kPa (5 psi) and 2.1 MPa (300 psi). It also has a low-flow impedance rating of 4Cv / 3.46Kv, and has an inlet pipe size of 0.5-in (ASCO-Valve-Inc. 2008).

Once the gas has been released from the storage tank and passes through the solenoid valve, a gas flow meter can measure the amount of gas passing from the digester into the boiler and pass the information on to a PLC to be recorded. This information is useful to determine the amount of biogas passing into the boiler daily. It is placed after the storage tank as the pressurized gas ejected from the gas booster would be heated, around 125°C, and would have time to cool off after passing through the storage tank. In case the gas remained heated, a Series 7000 Optional Low Flow Meter was chosen to incorporate protection against this higher temperature along with a capability to handle pressures between 1.4-2.8 MPa (200-400 psi) and a low-flow of 55-225 L/min (Clark-Solutions 2008).

The final component in series with the digester and boiler is a regulator that controls the outlet pressure of the digestion system before it flows into the boiler system. A regulator steps down the pressure of the biogas flow from the storage tank to the pressure needed to match that of the natural gas inlet pressure to the boiler. The main

factors that dictate the selection of a regulator are the outlet pressure, inlet flow, and whether or not the regulator will mix the biogas and natural gas streams. As every boiler has different inlet pressures and flows, it is difficult to size an appropriate regulator for this system that could be used in any application. Therefore, it is advised to use a three-way regulator that will have the biogas as one input, the normal stream of natural gas as the other input, and a mixed stream into the boiler as the output. As the FWTE will be producing biogas semi-continuously, the regulator must be able to easily maintain normal natural gas flow and pressure. A possible less expensive route would be to purchase a two-way regulator that takes in biogas and outputs a lower pressure biogas in series with a plug-flow valve and a T-joint to control flow and mix the biogas and natural gas stream, respectively. A variable proportioning ratio valve would be appropriate, but should be checked by an engineer during operation to ensure a proper mixture.

To achieve gas flow optimization, a PLC should be installed to monitor and control the various components already mentioned, such as the photohelic gauge, the natural gas booster, the solenoid valve, and the gas flow meter. The PLC would require linear programming to control these devices on a real-time basis for sequential relay control, though once programming is complete, changing parameter values is easy. Along with the installation of a PLC, high current external relays are required for each of the FWTE electrical components. Add-ons to a PLC could include extra power and additional interface software to ease operation. Such a PLC is the DL05 CPU Direct Logic Micro PLC, made by Automation Direct (Automation-Direct 2008).

4.4 Environmental Benefits

Global warming is believed to be caused by the increased levels of greenhouse gases in the atmosphere, such as CO_2, water vapor, and methane. These gases arise from

many different anthropogenic sources that include fossil-fuel burning, industrial factories, large-animal farms, and landfills. At some of these anthropogenic sources, it is possible to sequester the gases, particularly methane, and either store them or use them for energy production. The use of methane in the form of biogas is useful as an energy source to offset the need for natural gas consumption. In addition, combusting methane prevents it from contributing to global warming, as it has a 21- to 25-fold greater effect than CO_2, by weight. A research paper by Chynoweth (1996) found the effect of methane on global warming to be 21 times that of CO_2 due to its ability to absorb infrared light directly and photochemically produce ozone, carbon dioxide, and water vapor. In 2001, the Intergovernmental Panel on Climate Change (IPCC) reported that the greenhouse gas effect caused by methane was 23 times stronger than that of CO_2 (Ramaswamy et al. 2001). The IPCC released a new report this year stating that methane actually has a CO_2 equivalence of 25 (Forster et al. 2007). Therefore, by either sequestering or combusting methane into its constituents, the greenhouse gas effect is reduced.

Food waste can be a contributor to the production of greenhouse gases depending on the method in which it is disposed. Food waste can either be mixed within the municipal solid waste (MSW) stream or separated from it (Figure 4.5). If it is mixed within MSW, it is most often taken to a landfill where the methane produced from anaerobic biodegradation is either captured for energy production or is released into the atmosphere. If the food waste is separated at the source of disposal, it can be aerobically composted or anaerobically digested. Methane is captured during the anaerobic digestion process and can then be used for energy production or flared if there is no conduit for producing energy from the methane. The production of energy from methane in a landfill

or through anaerobic digestion ends with the same result, meaning these pathways are comparable. However, of these alternatives, the most likely disposal route of food waste is to enter a landfill where methane is not captured, but released into the atmosphere. This pathway results in the worst greenhouse gas effect and is what this project seeks to avoid.

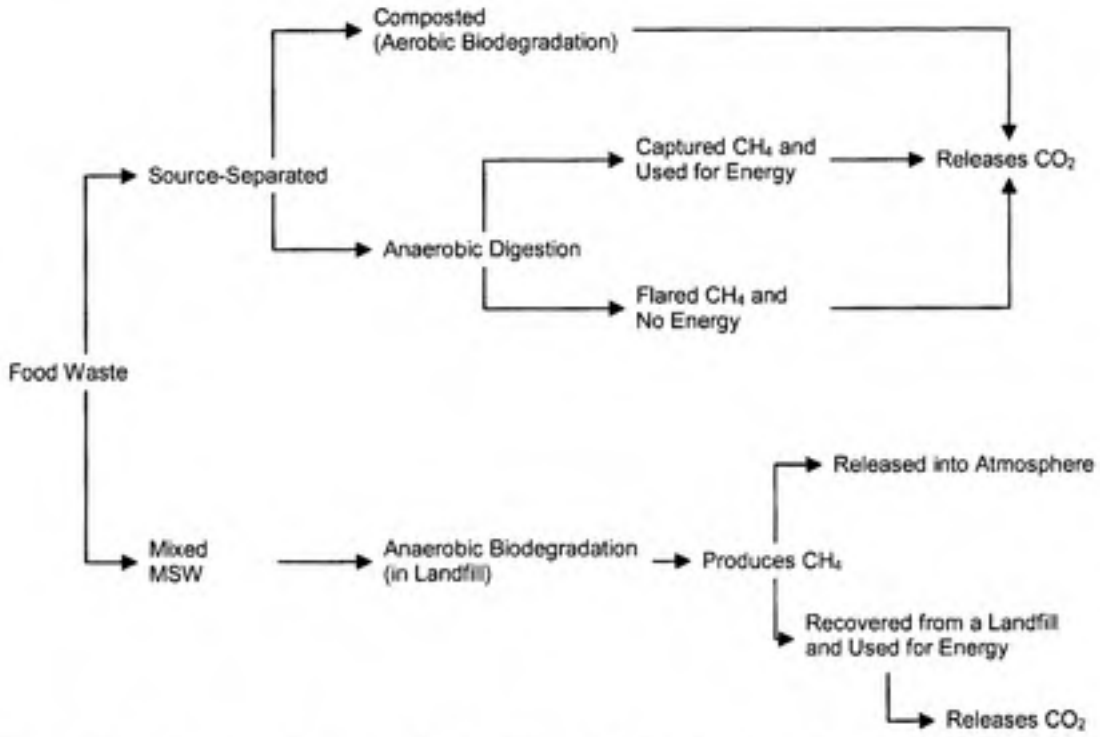

Figure 4.5. Food waste pathways to releasing CO_2 or CH_4 into the atmosphere

To quantify the impact of capturing methane for energy use instead of releasing it into the atmosphere at a landfill, the most widely used correlation between methane and CO_2 equivalents, a factor of 21:1, will be used. Table 4.6 represents the methane not emitted into the atmosphere in tons of CO_2 equivalents and gallons of gasoline if Smith Middle School, all three schools, all the schools in North Carolina, or all the public schools in the United States were using an equivalent FWTE as described herein for energy production. Notice the combined food waste from all three schools could be

harnessed to avoid the emission of the equivalent of 110 tons of CO_2 per school year. This amount of CO_2 has an equivalence of 11,000 gallons of combusted gasoline. However, if all of the schools in North Carolina were to incorporate an anaerobic digestion system, the equivalence of 51,000 tons of CO_2 per school year would not be emitted into the atmosphere. The economic savings of an FWTE is addressed in the Cost/Benefit Analysis section.

Table 4.6. CO_2 and gasoline equivalents of methane production from food waste using a 75% efficient anaerobic digestion system for energy production for a variety of school combinations.

	Smith Middle School	All Three Schools	**All North Carolina Schools**	All USA Schools
Students	668	2,977	**1,396,522**[1]	49,113,474[2]
Food (lbs / Day)	42	187	**87,800**	3,090,000
Production of CH_4 (m^3 / Month)*	63.8	284	**133,000**	4,700,000
CO_2 Equiv. Saved (Tons / School Year)**	25	110	**51,000**	1,800,000
Gasoline Emission Equivalents (Gallons)**	3,000	11,000	**5.4×10^6**	1.9×10^8

*** The ratios used to create this table are a daily food waste production-to-student population of 0.0629 lbs/student and a monthly methane production from food waste-to-student population of 95 L/student, which are based on the findings from Smith Middle school.**
**** See Appendix 7.1.4 for calculations**
References: 1. (North-Carolina-Department-of-Instruction 2006), 2. (National-Center-for-Education-Statistics 2007)

Further environmental factors that should be recognized are the prevention of CO_2 release from offsetting natural gas consumption, the educational impacts on students, the use of the effluent food waste for fertilizer, and the benefits of not throwing out food waste, though the economic benefits of these are either negligible or immeasurable. The use of biogas instead of natural gas was expected to result in a significant prevention of CO_2 emissions. It was determined from the Energy Information Agency website that preventing 28.3 m^3 of Natural Gas would prevent 55.5 kg of CO_2 from being released into the atmosphere. The environmental impact of preventing natural gas from being

combusted using the described FWTE is approximately 1,800 m^3 annually for combined waste from all three schools. The resulting environmental savings is 4.5% that of the savings found from not releasing methane into the atmosphere at a landfill, as not using natural gas only prevents the release of 1 mole of CO_2 instead of the 21 CO_2 equivalents of 1 mole of CH_4. Therefore, preventing natural gas from being combusted can be deemed insignificant and therefore was not used in the overall economic analysis.

Schools with FWTEs could incorporate anaerobic digestion systems in their science classes and allow students to visit their digester to see it in operation. The digester can be used as a means to teach concepts in microbiology, waste management, energy consumption and production, and/or climate change. These benefits are immeasurable as the value of educating a child is priceless.

The food waste effluent from an anaerobic digestion system is full of simple monomers and nutrients easily consumed by plants and bacteria in agricultural fields. This could either provide the participating school another financial incentive by selling the effluent, or it could simply pass on the benefits to local farmers free of charge. The sooner this waste is removed, the less smell that would emanate at the school. If odors become too great a concern, the effluent waste could be aerobically composted prior to using it as fertilizer. Sanitary concerns may arise from using the digested food from a local school on crops. The pathogen content is expected to be low but should be evaluated prior to use to insure safety (Furukawa and Hasegawa 2006).

The benefits of not throwing out food into a dumpster are difficult to quantify and deemed negligible. If the food waste effluent is used for fertilizer, food waste would be eliminated from the municipal sold waste (MSW) stream at the school. This would

decrease the daily load on a waste management truck (WMT) by 85 kg. The volume of this excised waste once compressed within a typical waste management truck (WMT) with a compaction capacity of 950 kg / m^3 would be 0.089 m^3. If a typical WMT has a volume of 35 m^3 then a weekly reduction of this food waste would free 1.3% of the total volume of one WMT. At most, this extra space may allow one WMT to extend its normal collection route by one or two facilities / homes per week. Further, as this omission of food waste from the regular MSW stream would be insignificant, it would not affect the amount or type of waste management necessary. Costs savings associated with not hauling the food waste would be insignificant as would the cost of transporting the food waste on a daily basis between the schools, which are less than a half mile apart. For these reasons, the economic value of removing this volume of waste from the normal MSW stream was not calculated. It would especially be of no consequence if the food waste effluent was put back in the MSW stream instead of being put to use as a fertilizer.

4.5 Cost / Benefit Analysis

The most viable school combination (all three schools) was assumed for use in this cost / benefit analysis. The cost / benefit analysis began by assessing the initial investment and operating and maintenance (O&M) costs of the FWTE over the assumed lifetime of the system, 20 years. The financial and environmental benefits were then analyzed, followed with a comparison of these costs and benefits.

4.5.1 Costs

The initial investment costs for the FWTE depend on the equipment costs and the regulatory costs to obtain state and local institutional approval. Table 4.4 is a list of the prices needed for the construction of the described FWTE. The total cost of the digester

is approximately $7,400. The main regulatory costs, estimated at $2,000, consist of hiring a professional engineer and the UL to review, certify, and approve the use of the FWTE. The cost of constructing the digester depends on the amount of skilled labor required and if a professional contractor would be required by local or state regulatory agencies. It was assumed that the cheapest cost of construction would be $5,000, which would include at least 200 hours of work by a graduate student, at least 10 hours of consultation with a contractor, additional hours of volunteer labor, and donations.

The annual O&M costs of the FWTE are unknown, but have been assumed to be a percentage of the total equipment cost. These costs were assumed to be 10% for the first two years and 5% for all the years of operation thereafter. This assumption is based on the likelihood that during the startup years of operation, some equipment would need to be either replaced or reinstalled for better performance. Costs for labor are considered negligible as a custodian or staff from the cafeteria could be trained in operating the digester. Additionally, there would be electricity costs for continual operation of the FWTE instrumentation; however, for the most part these costs would be minimal. The natural gas booster would require the most electricity, though it is difficult to estimate its electricity demand. As gas production would vary day-to-day, the number of times the booster triggered would vary, which would constantly change its electricity demand. These operating costs for the instrumentation were therefore assumed to be negligible.

4.5.2 Benefits

To assess the financial benefits of this FWTE, the probability of increased natural gas prices should be taken into account. Considering global energy consumption, it is feasible that the cost of natural gas will increase at a rate of at least 1% faster per year

than the cost of the materials needed for constructing this system, based on a 2002-2007 residential gas price trend (EIA 2008). For the increase in natural gas prices compared to the cost of other materials, low, average, and high rates were assumed to be 0.5%, 1%, and 3%, respectively. These varied rates were applied only to the yearly revenue generated from the combination of all three schools in Table 4.2, which was $1,100.

In order to monetarily quantify the environmental impact of methane reduction, the avoidance cost of emitting methane into the atmosphere must be taken into account. As CO_2 is more commonly exchanged in emissions markets, it can be assumed that the average price of one ton of methane is equal to the price of 21 tons of CO_2. However, the true price of a ton of CO_2 is unknown and widely debated. The Stockholm Environment Institute (SEI) studied voluntary carbon offset purchases and found that companies, such as TerraPass, NativeEnergy, and The CarbonNeutral Company, are offering carbon offsets at an average price of $12.35 per ton-$CO_2$ (Kolmuss 2006). The Chicago Climate Exchange (CCE), as of April 9, 2008, reported that the price of one ton of CO_2 is $6.00 (Chicago-Climate-Exchange 2008). The European Climate Exchange (ECE), as of April 9, 2008, foresees the price of one ton of CO_2 to be €23.55 ($37.03) by December 8, 2008 (European-Climate-Exchange-Carbon-Financial-Instruments 2008). As the FWTE would most likely fall in the carbon offsets category, the SEI price was used as the average price to illustrate the environmental savings of preventing landfill gas from being released for different school combinations, shown in Table 4.7. A low and a high range of $6.00 from the CCE and $37.03 from the ECE, respectively, were used for comparison in the cost / benefit analysis. When these ranges are applied to the combination of all three schools,

they yield a low, average, and a high annual economic benefit of approximately $670, $1,400, and $4,100, respectively.

Table 4.7. Environmental savings from preventing the release of methane from landfills for different school combinations.

	Smith Middle School	All Three Schools	**All North Carolina Schools**	All USA Schools
Environmental Savings: Preventing Landfill CH_4 Release ($ / Year)*	$310	$1,400	**$642,000**	$23 million

*** See Appendix 7.1.3 for calculations**

Finally, the value of future costs and benefits needs to have a present value. Discount rates depend on the source of finances, length of time being accounted for, and the risks involved. As there is no real way of assessing the value of future money for the FWTE, it can be assumed that the annual discount rate would be approximately 5%. As there is no certainty involved in this assumption, a low, an average, and a high range discount rate were used for sensitivity purposes. The rates assumed were 3%, 5%, and 7% for the high, average, and low discount, respectively.

4.5.3 Break-Even Analysis

The payback period, which is the amount of time required to break-even on an initial investment, of an energy producing venture often determines its economic viability. This analysis compared the initial investment and O&M costs to the financial and environmental benefits of this project, shown in Figure 4.6, assuming an average discount rate of 5% and an average natural gas price increase rate of 1%. Three different prices for a ton of CO_2 ($6.00 - Chicago Climate Exchange, $12.35 - Stockholm Environment Institute, and $37.03 - European Climate Exchange) were used in combination with the financial benefits of the combination of all three schools to

determine the payback period of the FWTE. The payback periods of the CEE, SEI, and ECE price options were within 14, 9, and 4 years, respectively.

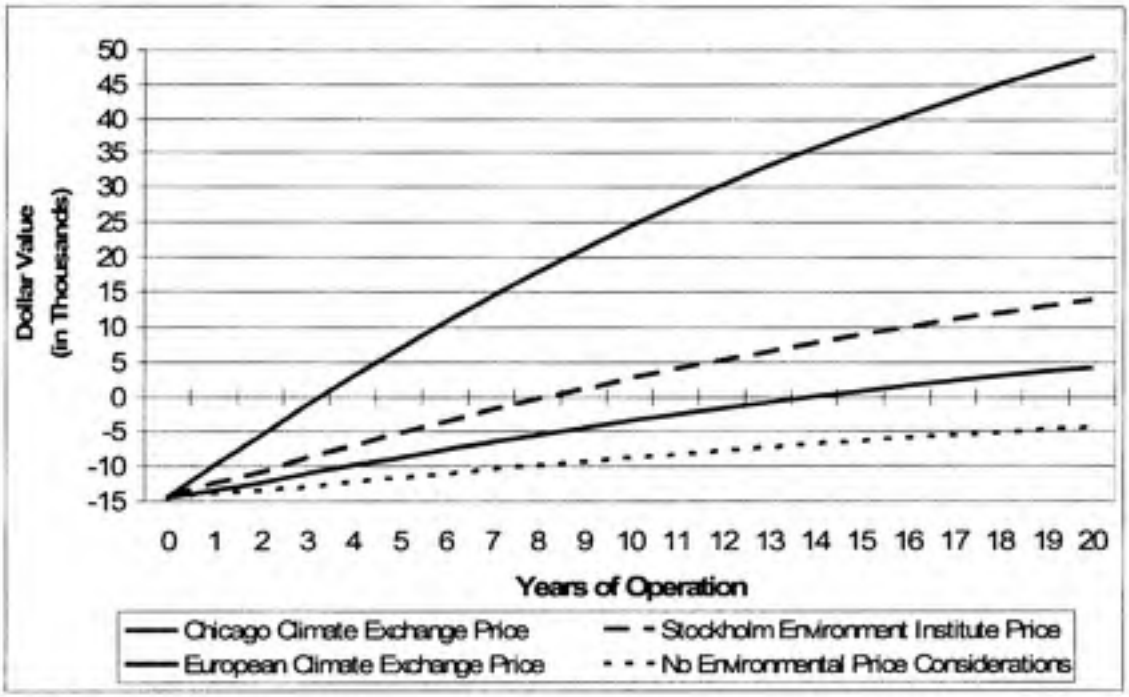

Figure 4.6. The aggregate cost / benefit analysis of the initial investment costs, O&M costs, financial benefits, and environmental benefits for the combination of all three schools in order to compare the effect different prices for a ton of CO_2 on the payback period of this FWTE. Each option incorporates the financial benefits.

The results of the aggregate economic cost / benefit analysis, illustrated in Figure 4.6, yielded the net worth of the FWTE at the end of its lifetime, displayed in Table 4.8. The highest price, ECE price, yielded the highest net benefits of $49,200. Not accounting for the reduction of greenhouse gas emissions yielded a debt of $4,400. This table illustrates how important it is to determine whether the system will be judged solely on financial terms or a combination of financial and environmental considerations so as to appropriately express the value of this FWTE.

Table 4.8. Net benefits from the combination of all three schools using three different prices for environmental benefits and one option that used financial benefits only

Environmental Benefits Option	Dollars / Ton of CO_2	Net Benefits after 20 Years of Operation*
Chicago Climate Change Price	$6.00	$4,300
Stockholm Environment Institute Price	$12.35	$13,900
European Climate Exchange Price	$37.03	$49,200
No Environmental Price Considerations	$0.00	– $4,400

*** See Appendix 7.1.3 for calculations**

4.5.4 Sensitivity Analysis

It is important to recognize that the results of this study were derived from a conglomeration of research articles, current prices, and educated estimates and variability between these results and an actual study would be inherent. Specific areas of variability were analyzed that have the potential to influence the outcome of the break-even analysis for this system. These variables include the percent of theoretical methane production capable of being generated, the initial investment needed for construction costs, and the discount and natural gas price increase rates.

The assumed 75% anaerobic digestion efficiency was determined to be a high estimate for converting food waste into methane. A potentially more realistic efficiency would be 60%, though this efficiency was derived from researchers who used only one or two of the biogas production enhancement techniques described in this study (Yadvika et al. 2004). For comparison, if this system was incapable of enhancing biogas production, an anaerobic digestion efficiency of 45% may result. Table 4.9 compares these various anaerobic digestion efficiencies in terms of yearly natural gas offset savings and the net financial benefits at the end of the FWTE lifetime. Notice that the yearly savings of $660 for the 45% anaerobic digestion efficiency option is less than the first two years of O&M costs. If the O&M costs for the FWTE were to remain higher than the yearly natural gas

savings, than this FWTE would be more in debt after 20 years than just the initial investment costs.

Table 4.9. Financial benefits sensitivity due to variability in the anaerobic digestion efficiency of converting food waste into methane.

Anaerobic Digestion Efficiency	Yearly Natural Gas Offset Savings ($)	Net Financial Benefits after 20 Years of Operation ($)	Percent Reduction of the FWTE Initial Investment after 20 Years
75%	1,100	-4,400	69%
60%	875	-7,600	47%
45%	660	-10,600	26%

With respect to the construction costs of this FWTE, the lowest possible cost was taken into account, being $5,000. If the labor from graduate students and minimal consultation was not adequate, hiring a consultant to construct the FWTE would be necessary and could reasonably cost $20,000. A four-fold increase in construction costs would increase the overall initial investment cost to $29,400. This new expenditure would eliminate the possibility for this system to break-even by the end of the FWTE lifetime using the environmental benefits from either the SEI or CCE prices for CO_2. Only using the ECE price would this system break-even (after 9 years) before the end of the FWTE lifetime.

If these CO_2 price options used the low and high discount rates and natural gas price increase rates instead, the CCE, SEI, and ECE price options would have payback periods that varied by ± 4, ± 1, and 0 years, respectively. A strictly financial benefits option, which excludes environmental price considerations, was also assessed. In that case, the value of energy recovered from biogas produced in the FWTE would payback initial investment costs of the FWTE at a 3% discount rate and 3% natural gas increase rate in its 20th year with a net present value of $370. This analysis shows that the future value of money and of natural gas can significantly impact the outcome of an economic analysis.

5.0 Conclusion

Anaerobic digestion can be used to derive energy from food waste. In this report, methane potentials of various food wastes have been quantified and an FWTE system for extracting this energy has been illustrated and explained. The components of the FWTE described herein were chosen as the most basic framework to deliver a low flow and low pressure biogas from a digester to a boiler system for energy production. These components were also chosen for their inexpensive costs and commercial availability.

To satisfy the regulatory requirements that pertain to the implementation of an FWTE at a school in North Carolina, five steps must be taken. First, the principals of the schools involved in the FWTE that would allow the collection and separation of food waste and the installation and operation of an FWTE on their campus must approve of the idea. Second, a professional engineer must be hired to create specific schematics of the FWTE, site and construction plans, analyze the FWTE system efficiency, verify FWTE heating rate for the North Carolina Department of Labor, and sign off on these plans along with a waste management plan. Third, the UL must be contacted to arrange for an investigation followed by a New and Unusual evaluation once the FWTE is constructed. Fourth, all plans, analyses, and UL and professional engineer certifications must be sent to the local fire department and building inspector, the North Carolina Division of School Support Planning Section, and the City School Facilities Maintenance Division. The final step is to send a revised waste management plan to the North Carolina Divisions of Environmental Health in the Health Services Section and of School Support Planning Section. With the approvals of all these regulatory institutions, the construction and operation of an FWTE in a North Carolina school would be allowed.

The economic feasibility of generating energy from food waste through anaerobic digestion at a North Carolina school was found to depend on the amount and composition of their food waste, the digestion efficiency, the conversion to energy efficiency, the initial investment costs, the annual operating costs, the regulatory approvals, the financial benefits from energy production, and the environmental benefits from reducing the release of methane. Using values for these variables derived from government, academic, and commercial sources, costs and benefits have been estimated to assess the practical and economic feasibility of a small-scale food waste-to-energy system. The result of this assessment is that the FWTE described in this report for the combination of Smith Middle, Seawell Elementary, and Chapel Hill High schools is economically feasible with a payback period within 4 years, if the price of preventing the emission per ton of CO_2 is assessed to be $37, and a lifetime profit of $49,200 could be obtained. The quantified environmental value derived from $37 / ton of CO_2 has the potential for being redeemed in monetary form if an investor, or commercial entity, were to purchase the CO_2 equivalents offset by the FWTE using this school combination. If an investor were available to purchase these offsets, the financial cost / benefit analysis would greatly improve in favor for the construction of this FWTE. More plausible prices for an American investor to use for a ton of CO_2, $12.35 or $6.00, reduce the total lifetime economic benefits to $13,900 or $4,300, respectively, while their respective payback periods are 9 and 14 years, respectively. However, if the environmental benefits of the FWTE are ignored completely, the system would never break-even within its lifetime and would have a net deficit of approximately $4,400 after 20 years.

This break-even analysis illustrates the importance of monetizing environmental benefits. In strictly financial terms, this FWTE system is infeasible. However, by appropriately valuing its impact in terms of decelerating global warming by not releasing methane into the atmosphere from food waste, by offsetting fossil fuel energy use, and by teaching future decision-makers the importance of renewable energy, this project could be deemed feasible. It is important to note that environmental benefits can be monetized and should be to represent most appropriately how society values them. With perfect information about potential environmental benefits and risks for any goven project, variations in the valuation of environmental benefits would be eliminated, such as between the CCE and the ECE. Monetizing these intangible benefits can assist decision-makers by directly linking environmental benefits to financial benefits to produce overall societal benefits.

5.1) Future Work

It is important to recognize areas for improvement of this research and of the viability of the FWTE. As this was a paper study analyzing the theoretical methane yields of a sample amount of food waste with a presumed characterization, a more thorough investigation of the amount of food waste and of the methane potential collected from all three schools would provide more substantive data to analyze the feasibility of the FWTE. Further, each of these schools has a breakfast program where food waste from both the students and cafeteria could be routinely collected to increase the viability of this FWTE. Since not as many students eat breakfast at public schools as for lunch, the quantity would be less and may fit into the currently designed digester without the need of a larger system.

Additional research could be spent on reducing the costs of building the FWTE. Finding cheaper equipment, designing the system to need fewer skilled construction techniques, and utilizing UL certified systems would all reduce the initial costs. If the FWTE were constructed at one school in North Carolina, the next school to construct this system would not need UL approval and thereby not need to expend $1,000.

Future research to improve the viability of the FWTE is not solely constrained to better understanding the potential methane production derived from food waste at a given school, searching for cheaper means to design and construct the system, and investigating the potential entrance of small-scale anaerobic digestion into the carbon offsets market. Other research avenues could be enhance biological activity in the digester (permitting the use of a smaller reactor), to design an efficient method for removing CO_2 from biogas to increase its heating value, or to figure out how to increase the efficiency of a combustion or Stirling engine to make electricity production from biogas a more viable option. Succeeding in any of these research opportunities could make the mass production of small-scale food waste-to-energy systems financially viable.

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7.0 APPENDICES

7.1 DESIGN CALCULATIONS

7.1.1 Energy from Food Waste Calculations

Calculation of Energy in 1 Liter of Methane at Standard Temperature and Pressure
(50.1 kJ / g-CH_4) * (16 g-CH_4 / 1 mol-CH_4) * (1 mol-CH_4 / 22.4 L-CH_4)
= 35.8 kJ / L-CH_4

Conversions between Joules, Kilowatts, and British Thermal Units
1 Btu = 1,055.0558 J
1 kWh = 3.6 MJ

Calculation of Methane Potential from Food Waste Data Reported by Knol et al. (1978)
VS = Volatile Solids
MP = Methane Potential

$$MP = \frac{m^3.Biogas}{kgVS} * \%CH_4 of.Biogas * \frac{1000.L}{1m^3} * \frac{kg.VS}{kg.WetWeight} * \%VS.Decomposition$$

MP units are L/kg-wet weight

Calculation of Methane Potential from Food Waste Data Reported by Lay et al. (1997)
Carrot moisture content is 6.78% (Wang and Xi 2005)
MP-Carrot L/kg-wet weight = 269 L/kg-dry weight * 93.22% dry content
MP-Carrot = 250.5 L/kg-wet weight

Calculation of Methane Potential from Food Waste Data Reported by Lay et al. (1997)
Potato moisture content is 16% (Thiewes and Steeneken 1997)
MP-Potato L/kg-wet weight = 203 L/kg-dry weight * 84% dry content
MP-Potato = 170.5 L/kg-wet weight

Calculation of Methane Potential from Food Waste Data Reported by Shiralipour and Smith (1984)
Potato moisture content is 16% (Thiewes and Steeneken 1997)
Assume a VS% of 75 for a Sweet Potato
MP-Sweet Potato L/kg-wet weight = 350 L/kg-dry weight * 84% dry content * 75%-VS
MP-Sweet Potato = 220.5 L/kg-wet weight

Conversion of USDA Calorific Food Values to Methane Potential (MP)
MP = Max CH_4 (L/kg)
Calorific Food Value = CFV (kC/kg)
1 kC = 4.1868 kJ
Max CH_4 = CFV * (4.1868 kJ / kC) / (35.8 kJ / L-CH_4)

Calculation of Average Maximum Methane Potential by Food Category

Average Maximum Methane Potential = Avg CH_4 (L/kg-VS)

Example 1:

$$\text{Avg CH4}_{\text{Grains}} = \frac{\text{Max CH4}_{\text{Bagel}} + \text{Max CH4}_{\text{Biscuit}} + \text{Max CH4}_{\text{FrenchBread}} + \ldots + \text{Max CH4}_{\text{FlourTortilla}}}{n_{\text{TotalGrains}}}$$

Example 2:

$$\text{Avg CH4}_{\text{Fruits}} = \frac{\text{Max CH4}_{\text{Apple}} + \text{Max CH4}_{\text{Apricot}} + \text{Max CH4}_{\text{Banana}} + \ldots + \text{Max CH4}_{\text{CannedPineapple}}}{n_{\text{TotalFruits}}}$$

Calculation of Maximum Theoretical Methane Yield for Food Waste Generated at Smith Middle School

Weight of Food Waste Generated per Day at Smith Middle School = SMFW-W (lbs)

$SMFW\text{-}W_{Grains} = 16.8$

$SMFW\text{-}W_{Fruits} = 10.5$

$SMFW\text{-}W_{Meats} = 6.3$

$SMFW\text{-}W_{Vegetables} = 6.3$

$SMFW\text{-}W_{Miscellaneous} = 2.1$

Percent by Weight of Smith Middle Food Waste Stream = SMFW-P (%)

$SMFW\text{-}P_{Grains} = 40\%$

$SMFW\text{-}P_{Fruits} = 25\%$

$SMFW\text{-}P_{Meats} = 15\%$

$SMFW\text{-}P_{Vegetables} = 15\%$

$SMFW\text{-}P_{Miscellaneous} = 5\%$

Max Theoretical Methane Production per Food at Smith Middle = Max'FoodType'CH_4

Max'FoodType'CH_4 = SMFW-P * SMFW-W

Max Theoretical Methane Production for All Food Waste at Smith Middle = TotalCH_4

TotalCH_4 = Max$FruitCH_4$+ Max$GrainsCH_4$ + Max$VegetablesCH_4$ + Max$MeatsCH_4$

Conversion of Therms to kWh

1 Therm = 100,000 Btus * (1055 J / Btu) * (1 kWh / 3.6 MJ) = 29.3 kWh

Yearly Methane Production

Max Theoretical Daily Methane Production for All three schools = 16,465 L

Max Yearly Methane Production = (16,465 L-CH_4/ day) * (23 days / month) *
(9 months / year) * (1 mole-CH_4/ 22.4 L) *
(16 g-CH_4/ 1 mole-CH4) * (1 kg- CH_4 / 1000 g-CH_4) *
(2.2 lbs-CH_4/ 1 kg-CH4) * (1 ton- CH_4/ 2000 lbs-CH_4)
= 2 tons-CH_4

7.1.2 FWTE Calculations

Density of Food Waste Calculation
Assumed to be 0.95 g/cm^3
Example: Food Waste Volume = 187 lbs Food Waste * (2200 g / 1 lb) / (0.95 g / cm^3) * (1 ft^3 / 28317 cm^3) * (1 yd^3 / 27 ft^3)= 0.56 yd^3

Heat-Flow Rate from the All three schools Combination Calculation
Assumed Monthly Energy Potential from All three schools = 2824 kWh
Heat-Flow Rate = (2824 kWh / month) * (1 month / 23 days) * (1 day / 24 hours) * (3600 kJ / kWh) * (0.9478 Btus / kJ) = 17,500 Btus / hr

Average Daily Biogas Production Rate for All Three Schools
Biogas Volume = (16,465 L-CH_4) * (75% System Efficiency) / (60% CH_4)
= 20,600 L-Biogas

Biogas Storage Calculations
PV=nRT

$$\text{Moles of Biogas} = \frac{1atm * 20{,}600L}{(0.0821atm * L)/(K * moles) * (273K)} = 920 \text{ moles}$$

$$\text{Operating Volume of Biogas} = \frac{(0.0821atm * L)/(K * moles) * (35 + 273K) * 920moles}{0.2448atm}$$

= 94,700 L-Biogas

$$\text{Volume for Daily Pressurized Biogas Storage} = \frac{(0.0821atm * L)/(K * moles) * (93 + 273K) * 920moles}{14.96atm}$$

= 1800 L-Biogas

7.1.3 Economic Calculations

Calculating Monthly Revenue from Different Energy Conversion Methods Using Different Energy Prices
System Efficiency (SEff) = 75%
Monthly Revenue = (Max L-CH_4 / day) * (23 days / month) * (35.8 kJ/L-CH_4) * (0.000277778 kWh / kJ) * Price ($ / kWh) * SEff

Calculation of the Environmental Savings of Preventing the Release of Landfill Methane
Example for All Three Schools
SEI Price = $12.35
Environmental Savings / Year = ($12.35 / ton CO_2) * (110 tons CO_2 / year)
= ~$1,400 / year

Calculation of the Environmental Savings for Offsetting CO_2 from Natural Gas Use
Example for All Three Schools
SEI Price = $12.35
Environmental Savings / Year = ($12.35 / ton CO_2) * (1 ton CO2 / 2000 lbs-CO2) * (122 lbs-CO2 / 1000 ft^3-CH4) * (16,465 L-CH_4 / day) * 75% * (23 days / month) * (9 months / year) * (35.8 kJ / L-CH_4) * (1 Btu / 1.0550558 kJ) * (1 ft^3-CH_4 / 1026 Btus)
= $64 / year

Calculation of Net Benefits
Example for All Three Schools
Assume Discount Rate (DR) of 5%
Assume Natural Gas Price Increase Rate (NGPIR) of 1%
Assume Price for Ton of CO_2 = SEI Price = $12.35
Total Equipment Costs = TE Costs = $7,414
Total Regulatory Costs = TR Costs = $2,000
Total Construction Costs = TC Costs = $5,000

Assume O&M Costs are 10% of TE Costs for 1st two years = $740
Assume O&M Costs are 5% of TE Costs for all years thereafter = $370

Yearly Financial Revenue = YF Benefits = $1,100
Yearly Environmental Revenue = YE Benefits = $1,400

Net Investment Costs (NIC) = TE Costs + TR Costs + TC Costs

$$\text{Net Benefits} = -\text{NIC} + \sum_{n=1\,year}^{20\,years} \frac{YFBenefits + \{YEBenefits * [1 + (n-1) * NGPIR]\} - O\,\&\,MCosts}{(1+DR)^{n-1}}$$

7.1.4 Environmental Benefits Calculations

Calculation of Yearly CO2 Equivalents Saved Using the FWTE
Example Calculation for All Three Schools
Yearly CO_2 Equivalents Saved = (16,465 L-CH_4 / day) *75% * (23 days / month) * (9 months / year) * (1 mole-CH4 / 22.4 L) * $\left(\frac{21\,\text{moles.}CO_2\text{ - }1\,\text{mole.}CO_2}{1\,\text{mole.}CH_4}\right)$ * (44 g-CO_2 / 1 mole-CO_2) * (0.000001102311311 ton-CO_2 / 1 g-CO_2)
= 110 tons-CO_2 / year

Calculation of Yearly CO2 Equivalents Saved as Gasoline Emission Equivalents

Example Calculation for All Three Schools

Gasoline Emission Equivalents = (110 tons-CO_2 / year) * (2000 lbs / 1 ton) *

$$(1\ \text{kg} / 2.2\ \text{lbs}) * (1000\ \text{g} / 1\ \text{kg}) * \left(\frac{1 gallon Gasoline}{2421 gC * 99\% * \frac{44 gCO_2}{12 gC}} \right)$$

= 11,400 Gallons of Gasoline Equivalents

Table 7.1. Smith Middle school cafeteria lunch menu for the month of October, 2007

Oct 2007 Menu

	Monday	Tuesday	Wednesday	Thursday	Friday
Week Ending 10/ 05/2007	*Pancakes with Syrup Cheese Quesadilla with Salsa Baked Potato w/ Chili Meat & Cheese with Wheat Roll Pinto Beans Fresh Orange	*Sausage Biscuit Fried Chicken with Wheat Roll Grilled Cheese Sandwich Mixed Vegetables Chilled Pears Cherry Crisp	*Chilled Fruit Cocktail Beef & Bean Burrito with Salsa Chicken Patty Sandwich w/Cheese Sweet Yellow Corn *Tossed Salad with Dressing Chilled Apricots	*Scrambled Eggs Rotini w/ Spaghetti Sauce and Garlic Bread Hot Dog on a Bun Collard Greens Frosted Gelatin	*French Toast Sticks with Syrup BBQ Beef on a Bun Turkey & Noodles with Wheat Roll Green Beans Chilled Peaches
Week Ending 10/ 12/2007	*Pancakes with Syrup Ham & Cheese Melt Chicken Nuggets with Sauce and Wheat Roll Steamed Carrots Chilled Pears	*Ham & Cheese Egg O'Bagel Beef & Macaroni with Wheat Roll Hot Dog on a Bun Garden Peas Baked Beans Fresh Apple	*Cheese Biscuit Oven Baked Chicken w/Wheat Roll Sloppy Joe on a Bun Coleslaw Broccoli Cuts Fresh Banana	*Scrambled Eggs Beef Lasagna with Garlic Bread Grilled Cheese Sandwich Steamed Carrots Chilled Fruit Cocktail Cherry Cobbler	*Hot Oatmeal Beef & Cheese Nachos with Salsa Fishwich Sweet Yellow Corn Chilled Peaches
Week Ending 10/19/2007	*Sausage Biscuit Cheese Ravioli with Garlic Bread Corn Dog Green Beans Chilled Apricots	*Chilled Pineapple Beef & Bean Burrito with Salsa Chicken Nuggets with Sauce and Wheat Roll Steamed Carrots Fresh Apple	*Fresh Toast Sticks with Syrup Baked BBQ Chicken w/Wheat Roll Double Cheeseburger on Bun with Lettuce and Tomato Collard Greens *Tossed Salad with Dressing Frosted Gelatin	*Frosted Yogurt Cheese Quesadilla with Salsa Pork Egg Roll Spanish Rice Garden Peas Fresh Orange	*Ham & Cheese Egg O'Muffin Chicken Patty Sandwich w/Cheese BBQ Pork on a Bun Baked Beans Fresh Banana
Week Ending 10/ 26/2007	*Grilled Cheese Sandwich Spaghetti and Meat Sauce with Garlic Bread Hot Dog on a Bun Mixed Vegetables Chilled Pineapple Fresh Orange	*Pancakes with Syrup Salisbury Steak with Gravy and Wheat Roll Fishwich Steamed Carrots *Tossed Salad with Dressing Chilled Pears	*Ham & Cheese Breakfast Burrito Vegetarian Lasagna w/Wheat Roll Chicken Nuggets with Sauce and Wheat Roll Green Beans Chilled Fruit Cocktail	*Frosted Yogurt Fried Chicken with Wheat Roll Grilled Cheese Sandwich Sweet Yellow Corn Garden Peas Chilled Peaches	**Teacher Work Day NO SCHOOL**
Week Ending 10/ 31/2007	*Ham Biscuit Meatloaf with Gravy and Wheat Roll Corn Dog Mashed Potatoes Garden Peas Chilled Pineapple	*Chilled Peaches Beef & Macaroni with Wheat Roll Turkey & Cheese Wrap Sandwich *Tossed Salad with Dressing Fresh Orange	*Scrambled Eggs BBQ Chicken with Wheat Roll *Tossed Ham & Cheese Sandwich Green Beans Fresh Banana		
	Breakfast includes Choice of Daily Special indicated by * or Cereal, Cheese and Juice Choice, Bread Choice, and Milk Choice	To Be Considered a School Lunch, Student Must Choose an Entree and at Least 1 Side	Student may also choose a Hot Bun Sandwich, Deli Deli Sandwich, Pizza, or Variety Bar as a daily entree choice and Garden Salad w/Dressing and Fresh Fruit as a daily side item	A variety of milk is available at each meal.	
Milk	**A Variety of Milk is Available with Each Meal**				

Table 7.2. Methane potential for the grains food category

Food Type	Methane Potential (L/kg-wet weight)	References
Bagel	321	USDA (2002)
Biscuit	413	USDA (2002)
Bread Roll, Dinner	351	USDA (2002)
Bread, French	323	USDA (2002)
Bread, Hamburger Bun	332	USDA (2002)
Long Grained Rice	152	USDA (2002)
Macaroni	165	USDA (2002)
Oatmeal	341	USDA (2002)
Pancakes, Butter & Syrup	262	USDA (2002)
Pizza	260	USDA (2002)
Rice, Cooked	107	Lay, et al. (1997)
Spaghetti	165	USDA (2002)
Tortilla, Flour	380	USDA (2002)
Average Potential	**275**	
Standard Deviation	**98**	

Table 7.3. Methane potential for the meats food category

Food Type	Methane Potential (L/kg-wet weight)	References
Bacon	671	USDA (2002)
Beef, Oven-Cooked Lean & Fat	418	USDA (2002)
Chicken Drumstick	313	USDA (2002)
Chicken Nuggets	352	USDA (2002)
Chicken, Fried	352	USDA (2002)
Egg, Scrambled	194	USDA (2002)
Ham, Lean & Fat	285	USDA (2002)
Hot Dog	289	USDA (2002)
Turkey, White	183	USDA (2002)
Average Potential	**340**	
Standard Deviation	**145**	

Table 7.4. Methane potential for the fruits food category

Food Type	Methane Potential (L/kg-wet weight)	References
Apple-Pulp	122	Knol, et al. (1978)
Apricots, Canned	97	USDA (2002)
Banana	108	USDA (2002)
Cherries, Canned	42	USDA (2002)
Mixed Frozen Fruit	115	USDA (2002)
Orange	55	USDA (2002)
Peaches, Canned	87	USDA (2002)
Pears, Canned	87	USDA (2002)
Pineapple, Canned	91	USDA (2002)
Strawberry	51	Knol, et al. (1978)
Tomato	25	USDA (2002)
Tomato Paste	96	USDA (2002)
Average Potential	**81**	
Standard Deviation	**31**	

Table 7.5. Methane potential for the vegetables food category

Food Type	Methane Potential (L/kg-wet weight)	References
Asparagus peels	51	Knol, et al. (1978)
Beans, Baked	109	USDA (2002)
Broccoli, Cooked	33	USDA (2002)
Cabbage	32	USDA (2002)
Carrot	251	Lay, et al. (1997)
Coleslaw	81	USDA (2002)
Collard Greens	30	USDA (2002)
Corn, Sweet	126	USDA (2002)
French Beans	42	Knol, et al. (1978)
Green Beans	41	USDA (2002)
Green Pea	41	Knol, et al. (1978)
Iceberg Lettuce	15	USDA (2002)
Potato	171	Lay, et al. (1997)
Salsa	29	USDA (2002)
Spinach	39	Knol, et al. (1978)
Sweet Potato, Morado	221	Shiralipour and Smith (1984)
Average Potential	**83**	
Standard Deviation	**72**	

Table 7.6. Maximum theoretical methane production from the various school combinations

Food Waste Source(s)	Liters-CH_4 / day	Liters-CH_4 / month
Seawell Elementary (SE)	3,082	70,877
Smith Middle (SM)	3,698	85,052
SE + SM	6,780	155,929
Chapel Hill High (ECHH)	9,685	222,755
ECHH + SE	12,767	293,632
ECHH + SM	13,383	307,807
ECHH + SE + SM	16,465	378,684

7.3.0 Contacts

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