BREE 495
Engineering Design 3

Design Project

A municipal collection, anaerobic digestion, and end-product recuperation system for residential food waste

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Friday April 11, 2008

Executive Summary

This design project seeks to address to increasingly prevalent environmental problems of careless and uneconomical waste disposal and the associated landfill shortage, groundwater contamination by leachate, and greenhouse gas emission.

The objective of this design group was to close the loop on current lax waste disposal practices, thereby using food energy to its fullest potential while simultaneously lightening the environmental footprint associated with landfill waste. With the increasing public awareness and advent of new technologies aimed at halting and most ideally reversing global climate change, it was believed by the group members that such a project would be quite pertinent to current environmental issues and concerns and would initiate the involvement of several communities. This program will hopefully heighten the environmental consciousness of individuals by internalizing and bringing the problem into each and every household, as well as providing a method of solution at the same time.

The project herewith begins with an initial background investigation of the related current issues, practices, research, and industry, and follows with the actual design of a municipal program encompassing the collection, anaerobic digestion, and end-product (biogas and soil-amending digestate) recuperation of household organic waste. The hypothetical location chosen for the project is the RCM (regional county municipality) of Vaudreuil-Soulanges, in the province of Québec, chosen primarily for its population size as well its proximity to the Macdonald campus, in the instance that a pilot project may one day be executed.

Government initiative and support coupled with community involvement and effort are the means by which such a project may launch and thrive. Furthermore, while the implementation of a project of such size comes at no small financial cost, it is the associated significantly reduced environmental cost that compensates for the large capital investment and operating expenditures.

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Introduction

Problem Statement

Generation of waste is a global problem of escalating urgency. Logically, as the population rises, so too does the volume of waste sent to landfill and the consequent landmass required to sustain this consistently incoming volume. If landfill is properly sorted into non-reusable and reusable (recyclables, food scraps, garden/lawn waste) materials, quite a large fraction of the landmass devoted to garbage reception could be negated. In particular, food and green wastes that are not recovered but rather sent to landfill produce leachate (which can potentially contaminate ground water resources) and emit greenhouse gases into the atmosphere when the vegetation decomposes.

Not only will arbitrarily sending all waste to landfill eventually result in a shortage of space, but it also squanders resources that may be diverted and recovered for further use through processes such as recycling, composting, and biogas production (and subsequent electricity generation). This latter method of renewable energy production is thus a further incentive for the recovery of food wastes and green wastes from residential (household, restaurant, office) refuse, for it facilitates the potential diminution of societal dependence on non-renewable fossil fuels.

Background Information

In 2002, the total waste generated by Canada amounted to 30 455 524 tonnes (971 kg per capita), with 39.4 % originating from residential sources. This figure corresponds to approximately 383 kg of household waste produced per capita, 40 % of which contains organics, which consist of food wastes and green wastes (leaves, garden trimmings, grass cuttings) (Statistics Canada, 2005). In 2004, the national average had risen to approximately 418 kg of household waste produced yearly per capita (Environment Canada, 2006).

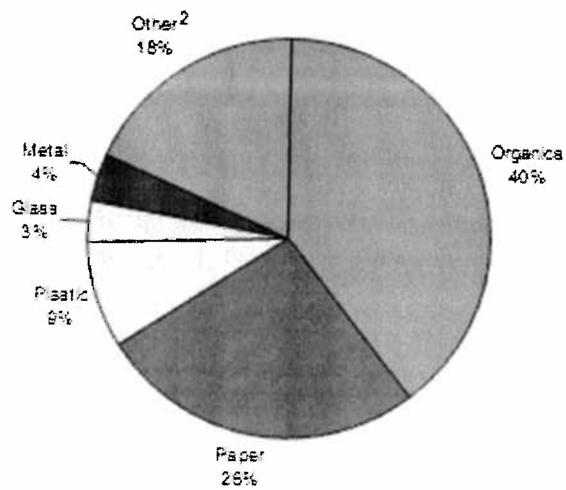


Fig.1: Composition of solid waste by weight, generated by Canadian households

Source: Statistics Canada

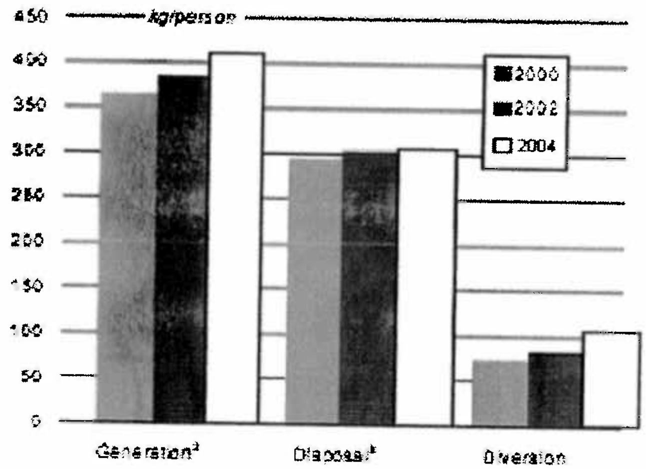


Fig.2: Per capita generation, disposal and diversion of residential solid waste in Canada, 2000 to 2004

Source: Statistics Canada

Approximately 73 % (2004) of this waste is disposed of in landfill, with the remaining 27 % diverted. In 2000, Canada's landfills accepted over 23 000 000 tonnes of waste, with over 50 % directed toward landfills that were diagnosed as having a remaining lifespan of zero to ten years (these constitute 30 % of Canadian landfills) (Statistics Canada, 2005). Therefore, the means by which to reduce waste volumes and thereby increase the longevity of landfill lifespans is to divert all reusable material, such as recyclables (paper, plastic, glass, metal, electronics, polystyrene (Styrofoam), batteries, ink cartridges, etc.) and organics (food scraps, leaves, lawn and garden cuttings).

In addition to conserving landfill space, the major objectives of diverting the organic fraction of garbage from landfill are to reduce the amount of leachate production in landfill, and reduce the emission of greenhouse gases (GHG's) into the atmosphere. Leachate is a combination of water and dissolved solids, which collects at the bottom of landfills. Should the landfill have no lining or be inadequately lined, the leachate may then percolate deep into the soil profile and contaminate ground and/or surface water with heavy metals, acids, and other toxins that it gathered from the surrounding garbage.

The decomposition process of waste in landfills emits landfill gas, which is a mixture of greenhouse gases methane (CH_4) and carbon dioxide (CO_2), small amounts of nitrogen (N_2) and oxygen (O_2), as well as trace amounts of various other gases such as benzene, toluene, vinyl chloride, etc. (Statistics Canada, 2005). In fact, landfill sites are responsible for approximately 25 % of Canada's total methane emissions, which amounted to 5200 kt in 2004. Methane is released from landfill at an approximate ratio of 3:2 to carbon dioxide, and one kilogram of methane has 21 times the warming effect of the same amount of carbon dioxide (Environment Canada, 2006). When methane escapes into the atmosphere, it becomes a greenhouse gas. However, should it be collected and purified, methane can also be used to create electricity — to be used in-situ or sold to the grid.

Present Situation

Composting

For the proposed design to be relevant and operate successfully, it is vital to ensure the population's involvement, both in terms of accessibility to food and green waste disposal services and individual contribution as well. Large-scale composting technologies in Canada include windrows, static aerated piles, in-vessel systems, as well as anaerobic digestion. Since the 1990's, centralized composting facilities have become more widespread, for both residential and commercial use. By 2002, 351 facilities were composting organic waste, an increase from 255 in 2000 and roughly 160 in 1995 (Statistics Canada, 2005). In fact, 1.2 million tonnes of organic material were received by such centralized composting facilities in 2002.

Province/territory	2000	2002
	number	
Newfoundland and Labrador	3	11
Prince Edward Island	x	x
Nova Scotia	16	20
New Brunswick	9	12
Quebec[1]	43	37
Ontario	79	99
Manitoba	21	33
Saskatchewan	21	28
Alberta	32	64
British Columbia	29	41
Yukon Territory, Northwest Territories and Nunavut	x	x
Canada	**255**	**351**

Fig.3 : Number of centralized composting facilities, 2000 and 2002

Source: Statistics Canada

However, funding for waste management differs greatly across Canada. In some provinces, municipalities allot as high as 6 % of total spending to waste management services, while others allot even less than 2 % (Statistics Canada, 2005).

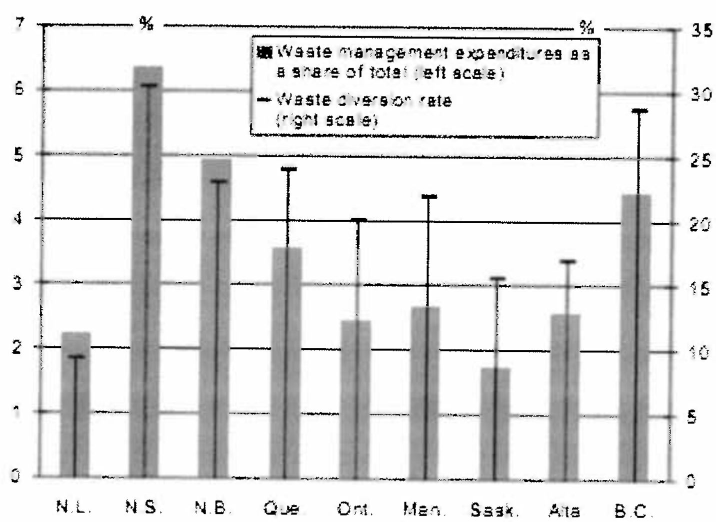


Fig.4 : Waste diversion rate versus waste management expenditures as a share of total municipal expenditures, 2002

Source: Statistics Canada

The above graph demonstrates that a clear positive relationship exists between the amount of funding allocation for waste management services and the percentage of waste diverted from landfill. However, other factors contribute to the success of these services, notably the population's motivation to participate. Nevertheless, it is most often with greater access to recycling and compost programs that greater participation is observed.

Anaerobic digestion

Anaerobic digestion is very rapidly emerging as a green alternative for industries and cities struggling to manage mounting volume of organic waste in landfills and wastewater treatment plants. Anaerobic digestion systems may be used to treat almost any organic material, such as food scraps, lawn and garden cuttings, soiled paper, silage, sewage, and animal manure, with the exception of wood. Anaerobic digestion is also a treatment for odor control as well. The most common existing systems treat animal manure rather than food waste, for manure has a higher degree of putrefaction (decay and odor production) than food waste, and will therefore yield a greater amount of gas. Manure is highly odorous as well. Since the mid 1970's, both India and China have been capturing biogas from small-scale anaerobic digestion for household cooking and electricity, backed by large government subsidies. In fact, anaerobic digestion has been deemed one of the most useful decentralised sources of energy supply by the United Nations Development Programme. With the Clean Development Mechanism (CDM) arrangement under the Kyoto Protocol, industrialized countries with a commitment to reduce greenhouse gas emissions may, as a cheaper alternative to reducing their own, invest financially in the implementation of anaerobic digestion systems in developing countries (United Nations Framework Convention on Climate Change, 2007).

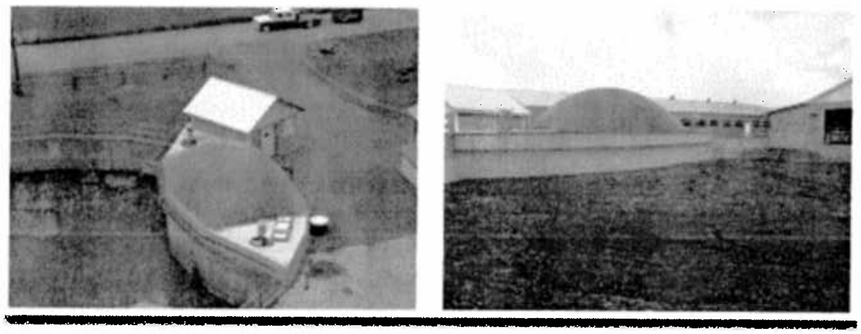


Fig.5 : Anaerobic digester on an Ontario dairy farm produces power from manure
Source: National Resource Council Canada

Literature Review

Collection

If the desire is to recover food waste and design a collection, processing and disposal system for it, the quantity of food waste that is to be dealt with must be determined. This will be a function of the population contained in the area where collection is to be done. The quantity per capita will also vary from one population to another depending on the characteristics of that population. Logically, it is expected to have more waste generation from affluent populations than from poorer populations (Beede and Bloom 1995). According to Morin et al. (2003), the food waste generated in Montreal, a typical well-off urban locality, is in the order of 0.5 to 0.7 kg per capita per day. An additional consideration is the participation level of the population in the collection program. According to the Wisconsin Department of Natural Resources (2007), with the right incentives and the right motivations they have found to have a 94% participation response from their population for their recycling program. If a similar collection system is to be developed for food waste, similar levels of participation could be achieved assuming the right incentives are put in place. From this we can derive an equation for the amount of food waste to be collected as:

Total food waste collected weekly =

[(food waste/cap/yr) * (0.4 organic fraction) * (population of collected area) * (anticipated participation) * (1 yr / 52 weeks)]

Methane production from anaerobic digestion

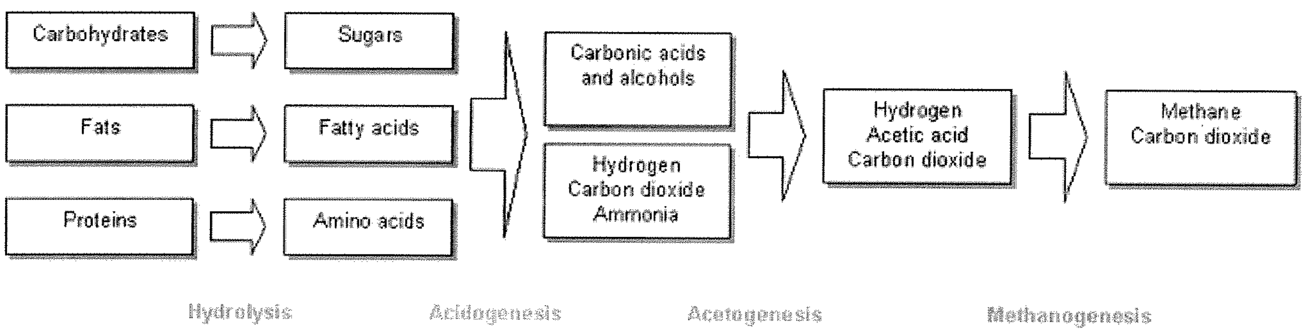


Fig.6: Biogas production through anaerobic digestion

Source: www.wikipedia.org

Before food waste can be process waste into methane it is necessary to understand the reactions and the variables that will drive this reaction. The main principle of anaerobic digestion is that the input, food waste will see the organic polymers (lipids, protein, sugars and carbohydrate) contained in it broken down by bacteria and ultimately converted to methane all in the absence of oxygen. This happens in four major stages. The first step is hydrolysis where the large chains of the organic compounds are broken down to simpler organic molecules (Biology Online, 2007). Once this is done, acidogenesis occurs by acidogenic bacteria, where the simple organic compounds are transformed into simple organic acids (also know as volatile fatty acids) (McLean, 1995). The third stage, where the volatile fatty acids are transformed to acetic acid is called acetogenesis and is done by acetogenic bacteria. This also releases hydrogen which is used by the methanogen to complete the cycle, by converting the compound made by the previous stages into methane. The two major pathways for this last stage are (McLean, 1995):

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2H_2O$$

$$CH_3COOH \rightarrow CH_4 + CO_2$$

Methanogens are somewhat specific and work in temperature range of 30-38°C and 55-60°C and need to be kept at an optimum pH of 6.8 to 7.5 (McLean, 1995).

The pH is an important indicator of the performance of the system. If the system is in equilibrium and stable, then the anaerobic digestion should perform well. The problem with the anaerobic digestion is that the various bacteria performing the digestion don't all have optimum performance at the same pH. The acidogenic bacteria are the first to attack newly introduced waste in the digester. If too much waste is introduced to the digester at once, the acidogenic bacteria will cause the pH to drop, thus inflicting extreme conditions on the methanogens. On the other hand if the digester goes too long without receiving new waste, the pH will rise and be harmful to the acidogenic bacteria. It is therefore necessary to control the mass of input of fresh waste into the digester in order to keep the pH in the optimal range of 6.8 to 7.5. The organic loading rate is a measurement of the quantity of volatile solids added to the digester. According to Fry (1973) an optimum loading rate is that of 2.4 kg VS/ m^3/day.

Practical application to methane production

Energy cost have been rising because of an increase demand for it. This has created a pressure in certain industry sector to come up with ways to lower their dependeny on imports of energy and lead to the appearance of many digester. It is highly desireble to produce methane in sectors where a sources of organic waste are readily available. Below is a squematic of a typical anaerobic digester system found on an animal production farm.

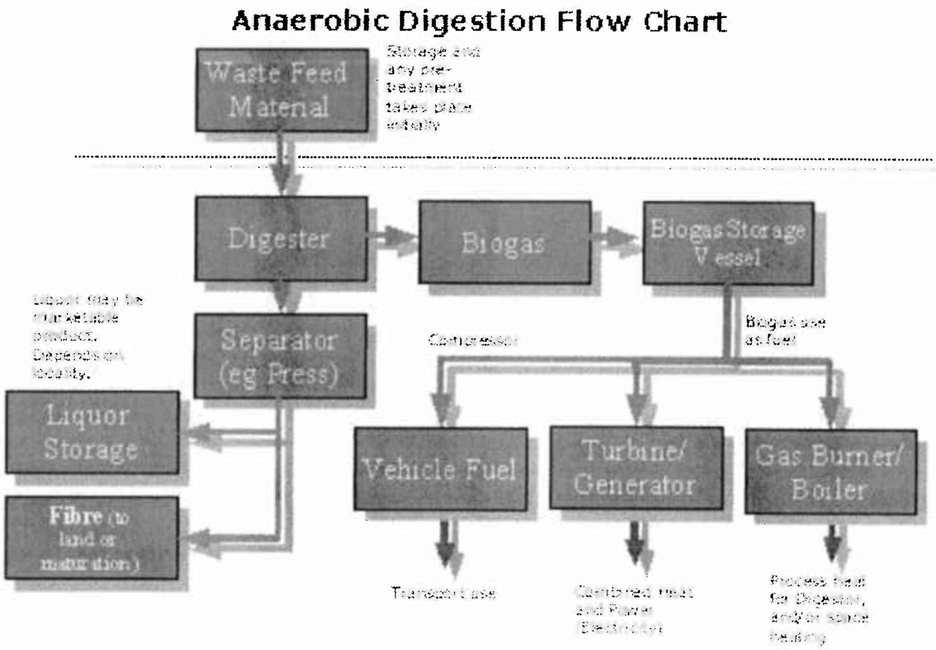


Fig.7: Anaerobic digestion flow chart

Source: Anaerobic Digestion Systems Web Site

In this setup the organic waste (manure) is digested and the methane is deviated to a temporary storage area where it will await its burning to produce electricity. The reaction process of anaerobic digestion as been explained before. But the the reaction variable will influence the type of system best suited. It is important to determine how this process will performe with the inputs which are to be put trough it, i.e. the food waste. Ruihong et al. (2006) have identified that the design and operation of a digester will be greatly affected by the characteristics (both physical and chemical) of the waste inputs. These include moisture content volatile solids content, nutrient content, particle size and biodegradability. Ruihong et al. (2006) also state that methane yield is defined as the amount of methane produced per unit of volatile solids in the waste after anaerobic treatment for a given amount of time for a said temperature. Cho and Park (1995) have found a yield of 472 mL of methane per gram of volatile solids of mixed food waste at

37°C for 28 days (volume at standard temperature (0 °C) and pressure (1 atm)). This is very similar to what Heo et al. (2004) have found. Ruihong Zhang et al. (2006) have also conducted a literature review of some characteristics of food waste and have found moisture content of 74–90% and volatile solids to total solids ratio (VS/TS) of 80–97% and a biodegradability of approximately 81% at the end of the 28-day digestion test. Form this information we can derive a theoretical value of methane produce from a given quantity of food waste input. This is found from,

$$\underline{\text{Methane produced}} = \Big[\ (\text{food waste input}) * (1\text{- moisture content}) * (\text{VS/TS}) * (\text{biodegradability fraction}) * (CH_4 \text{ yield / g VS})\ \Big]$$

This equation will also reflect the time and temperature for which the values where selected. All figures given so far are for a temperature of 35°C for a time of 28 days.

If variables having an impact on the digester system are know and quantified, the best model and size of the operation can be determined. There are different types of digesters possible such as batch or continuous and high or low solid content, or thermophilic versus mesophilic temperature.

Other factors will also affect the type of digester that should be used. One factor is the collection system. If the waste is collected often in small quantity a continuous reactor may be chosen, while large quantities collected after larger time lapse might mean that a batch digester is better suited. Further more bacteria species are diverse which means different bacteria need different conditions to survive. Mesophilic bacteria need optimal living temperature of 35°C while thermophilic bacteria need temperature of 55°C (Loehr, 1984). This means that if foroptimal performance the system must take into consideration the environment in witch it is to be situated. Wether the system is in a temperate climate zone or a tropical climate zone will influence its ability to sustain optimal living temperature.

Batch digester

A batch digester is very simple to operate and require less equipement. It works by simply adding organic waste in a contained chamber and then sealing it until the process is finished (California Energy Commision, 2007). The main disadvantage of these type of digester is that they follow a normal distribution pattern, which means they do not produce an even quantity of methane over time (California Energy Commision, 2007). The production of methane is slow at first, then increases rapidly, peaks and then decreases rapidly.

Continuous digester

Continuous digesters have regular inflow of organic waste and regular removal of by-products. This avoids the normal distribution pattern of the batch digesters and gives a more constant supply of methane. Calculations for such digesters are based on the Continuous Stirred Tank Reactor model. In these digesters, the food waste must reside in the digester long enough to be transformed by the anerobes, therefore this retention time will control the size of the digester (Loehr, 1984). The equation for a continous system sizing is given as,

Useful volume of digester = (volume added per day) * (residence time) (Loehr, 1984)

Other equations are useful to calculate bacterial growth or substrate utilization rate, always following the Continuous Stirred Tank Reactor model.

Yield

Anaerobic digestion yields methane, but it is not pure. What is recovered from the digestion is generally a mixture of approximately 60% methane and 40% carbon dioxide as well as other trace compounds (Governement of Alberta, 2007). The presence of these other trace compounds is problematic, as they dilute the methane, and they must therefore be removed from biogas. The carbon dioxide may easily be removed by bubbling it through water. Another important compound to remove is hydrogen sulphide (H_2S). This compoud is highly corrosive and can be removed with a gas scrubber (Governement of Alberta, 2007). Another way to reduce its content is to add $FeCl_2$ to the digester tank, which prohibits the production of hydrogen sulphide (Chemical Engineering Research Information Center, 2007). The necessity to remove such compounds, however, depends on the type of engine chosen to burn the biogas, for some will burn the biogas as is, while others may run only on pure methane.

Electric conversion

When methane is produced through anaerobic digestion, it may be burned in an internal combustion engine to power a generator and produce electricity. According to Statistics Canada (2007), methane has an energy content of 37.5 MJ/m^3. The efficiency of the transformation from heat to electricity will depend on the method used, for there are several ways to burn methane in order to make electricity. Steam generators, reciprocating engines, or gas turbines may be used. All methods will have different associated efficiencies and in most cases they will be stated by the manufacturer. This means that calculation of electricity production can be made from the following equation:

Electric output = (CH_4 produced) * (heat content of methane) * (conversion efficiency)

This gives work and not power. Power or rate can be obtained by dividing by time. Most of the losses incurred during this process are in the form of heat. This means that the energy lost as heat can be used to heat the digester and/or other buildings of the system or surrounding buildings, depending on the amount of heat produced.

End–products

The final product of anaerobic digestion remaining inside the digester is called a digestate, consisting of both water and solids, which is quite similar both physically and chemically to compost. The actual composition of the solids will depend on the initial composition of the inputs. The conservation of mass law can be applied,

$$\text{Mass of input} = \text{Mass of output}$$

where input is the food waste and output is both the gas produced and the digestate. From this is understood that the digestate will still contain all the nitrogen, phosphorous and potassium it initially contained because the only elements transformed to gas are carbon, oxygen, and hydrogen (CO2, CH4). This will make it a very valuable source of nutrient for the agro-sector. This digestate can be used as a soil-amendment for land application on agricultural fields (Global Warming 101, 2007). In order to maximize efficiency of land application, the acceptable quantity to be applied to the field must be determined. This will be a function of the crop demand, the soil supply and the nutrient concentration of the digestate. The crop requirements vary according to the crop uptake, which varies with the crop type. Values can be obtained from crop advisers or agronomists - professionals who specialise in this area of work.

The nutrient concentration and the soil supply can both be determined through lab analysis of respective samples. If guidelines are followed, there will be minimum impact on the environment which is what is trying to be achieved. Other things to consider for the feasibility of this operation are the availability and proximity of lands suitable for land applications of the digestate, as well as the time period for them to receive these effluents. For example, no application can be performed during winter. This means there may be a need for a temporary storage area or need for an alternate disposable method for a period of approximately one year.

Design

Pre-digestion

Location

The choice of municipality for the hypothetical implementation of this project is the census division and regional county municipality (RCM) of Vaudreuil-Soulanges, in the province of Québec. This specific location was chosen namely for its medium population size, as well as the proximity to the Macdonald campus of McGill University, so that knowledgeable students and professors may have relatively quick and easy access to the site should the design be implemented in the future.

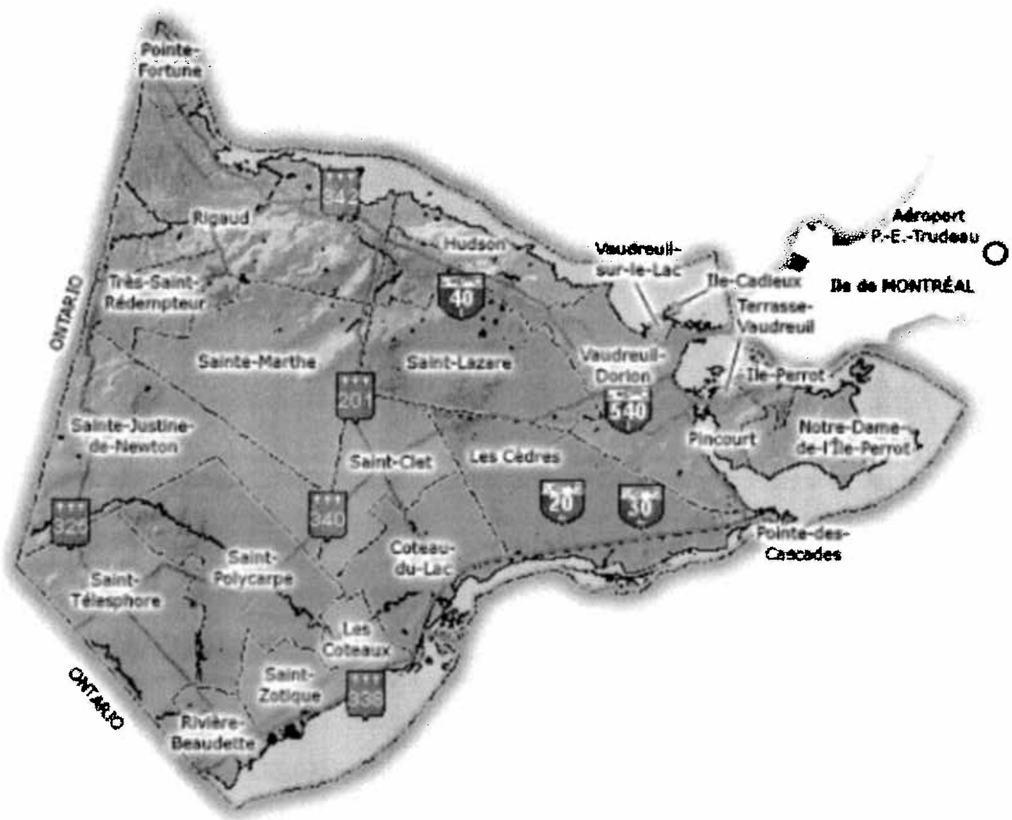


Fig. 8: Map of RCM of Vaudreuil-Soulanges

Source: CLD Vaudreuil-Soulanges

From research of demographic statistics, the population of the Vaudreuil-Soulanges RCM in 2006 was approximately 120 400 inhabitants (CLD Vaudreuil-Soulanges, 2006). Previous analyses demonstrate cyclical trends in growth percentages over periods of 5 and 10 years, as presented in the table below.

Year	**Population**	**Growth (%)**
1991	84 500	---
1996	95 318	12.8
2001	102 100	7.1
2006	120 395	17.9
1991-2001	---	20.8
1996-2006	---	26.3
1991-2006	---	42.5

Table 1: Population and growth statistics, Vaudreuil-Soulanges, 1991 to 2006

The target population density to utilize for the design was chosen as that for the year 2021, or 15 years from the most recent census of 2006. Because population projections as extended as such are unavailable for the RCM of Vaudreuil-Soulanges, it was thus somewhat difficult to predict the potential population of the area in 2021. Considering the population growth of approximately 21 % over a period of 10 years from 1991 to 2001, followed by the boom of 18 % over the next 5 years from 2001 to 2006, this represents a total growth of just over 42 % over 15 years (1991 to 2006) (CLD Vaudreuil-Soulanges, 2006). Therefore, accounting for the significant population boom of these past 15 years, as well as cyclical trends in growth rates, it was estimated that the projected population of Vaudreuil-Soulanges for 2021 would have experienced a total growth of 30 % from 2006, reaching an approximate 156 500 inhabitants (see Appendix A.1).

From past census figures, the approximate number of persons per household varies between 2 and 3 (BC Stats, 2007). Therefore, the 2006 census figure of 2.6 persons per household was chosen to be used, which closely represents the average. This would therefore imply an expected number of nearly 60 200 households.

Collection

Knowing the projected population, the number of inhabitants per household, and the approximate amount of food waste produced per capita weekly, it is now possible to determine the amount of household organic waste to be collected weekly and to develop a pick-up schedule.

For the purpose of this project, it is assumed that Vaudreuil-Soulanges would employ a private contractor to execute the weekly collection of the residential organic waste, in order to avoid the costly investment of actually purchasing, operating, and maintaining the collection trucks. A typical collector truck that may be used for collecting the organic waste costs over $140 000 CDN. Such a truck holds has an average capacity of 25 m^3 (Labrie Environmental Group, 2007). Initially, using 2006 figures, just under 16 truckloads would be required to collect the near 388 000 kg of organic waste produced weekly presently. However, with the calculated 2021 weekly design load of 503 200 kg produced by the inhabitants, roughly 20 truckloads are filled (see Appendix A.2). This implies 4 truckloads per business day, or the coverage of nearly 12 000 homes per day, which can easily be achieved, should multiple trucks be used. The Vaudreuil-Soulanges region will thus be separated into 5 areas, each experiencing organic waste pick-up on a different day of the week.

Pre-treatment

Following collection, the organic waste must to go through several processes before being sent into the digester. Processing is required in order to bring the organic waste to a state that facilitates optimum digestion, as well as to keep the digester healthy and running properly, avoiding any blockage of piping or damage to the machinery.

Before the processing takes place, the collector trucks must to unload their cargo. The trucks will dump the organic waste into a large pit with an unloading conveyor at the bottom. The pit acts as a temporary storage tank, allowing for even flow on the conveyor and thus to the processing step. To avoid bottlenecking of the collection trucks, the pit should be long and large enough for two trucks of 25 m^3 each to dump simultaneously. A volume of 70 m^3 is thus chosen to be sufficient, yet not excessive. To allow for side by side dumping of the trucks, a pit length of 7 m is also assumed.

The conveyor under the pit brings the materials to the necessary processing units which remove foreign objects such as metals, glass, plastics, gravel, and grit, as well as resize the organic matter to the optimum size for digestion.

Removal of the foreign objects is necessary to keep the machinery and the many pumps from being severely damaged. This can be achieved by manual inspection and extraction, or by mechanical removal methods such as magnets and centrifuges. Should a centrifuge be used, it would most likely be employed following the resizing of the waste.

Resizing of the material creates larger surface areas, thereby increasing digestion capacity by allowing the bacteria to reach as much of the material as possible in a short time period. Resizing also allows for the material to be more easily transported by pumping as a liquid. The organic waste should be resized or macerated to a particle size of less then 50 mm in length (Papadimitriou and Stentiford, 2003) and roughly 5 mm in diameter (The University of Southampton and Greenfinch Ltd., 2004). This step takes place immediately before being pumped into a centrifuge or the digester unit itself.

In order to keep the digestion process running at a constant rate, storage of the organic waste is required for overnight and weekend operations. This volume must be sufficient to last for 3 days, and therefore the size of this system it is calculated to be 260 m^3 (see Appendix A.3). The storage of the organic waste is performed before it is resized so as not to promote premature degradation of the waste, and to reduce the required size of the resizing and centrifuge machines.

Anaerobic Digestion

Digester volume

Anaerobic digestion takes place in the digester. The digester should therefore be sized according to the volume to be treated. Several parameters must be considered in order to optimize the digestion process. The retention time of the food waste in the digester is a factor that greatly influences the amount of biogas produced. The size of the digester will also depend on the dilution factor, which is ultimately defined by the permissible loading rate of the food waste. The dilution factor is what determines how much water must be added to the incoming raw food waste.

The following parameter values were chosen from the literature review:

Parameter	***Density***	***Loading rate***	***Retention time***
Value	1000kg/m³	2.4 Kg Vs/m³/day	28 days

Table 2: Density, loading rate, and retention time of food waste in anaerobic digester

The equation used to determine the useful volume of the digester is:

$$V_d = W * Wd * DF * RT$$

where

V_d = Useful digester volume
W = Quantity of waste
W_d = Waste density
DF = Dilution factor
RT = Retention time

DF = VS content / (RT * Loading rate)

and

VS content = (TS fraction) * (VS/TS fraction) * waste density

The dilution factor is calculated from the loading rate, and the quantity of food waste was calculated previously as 72 000 kg/day.

Calculations (see Appendix A.4) revealed that a dilution factor (DF) of 2 is needed (meaning equal parts of water are added to the food waste), and the useful volume of the digester to equal 4032 m^3. Finally, the useful volume was multiplied by a safety factor of 1.5 to determine the actual volume for which to design, 6000 m^3.

Digester tank inner dimensions

The digester is selected to be of cylindrical shape, selected on an economical basis because a circular cross-section offers the maximum volume for a given perimeter.

The internal height of the digester is chosen arbitrarily to be 5 m. According to equation for the volume of a cylinder,

$$V_{cyl} = (\pi) * (\text{diameter}/4)^2 * (\text{height})$$

this means that the internal diameter of the digester must be 40 m (see Appendix A.5).

Digester tank construction

This project has called for a circular cement structure with a radius of 20 m and a depth of 5 m. For this depth the Building Requirements for Structural Concrete, from the

American Concrete Institute (2008), states that a wall and floor thickness of 12 inches must be met with double reinforced steel rebar mesh. The double reinforcement creates a very strong and durable structure and makes the structure more resistant to heat gradients, which is very common and can be quite large in the Québec environment.

In order to prevent the corrosion of the concrete and increase the lifespan of the digester, a PVC geomembrane liner must be installed. In order to install the liner properly, the inner concrete surface must be as smooth as possible to decrease pockets where materials can build up and cause damage. The air pockets may be covered over by plastering the cement prior to the liner installation; this ensures a uniform and smooth surface.

To reduce heat losses and input energy requirements of the digester, all surfaces are going to be insulated. The insulation will be located on the exterior of the concrete with a plastic barrier to keep it out of contact with the soil, and sandwiched between two water tight layers on the cover structure. To insulate the tank, 20 cm of expanded polystyrene will be applied on all sides of the tank. This will reduce the amount of heat loss greatly.

The lid type for this digester is going to be a rigid floating cover design. This type of cover was selected due size and climatic challenges that are present in Québec. The combination of the large digester size and the large snow loads that occur in the province of Québec make solid covers and inflated covers unfeasible for this structure, as designed. A solid floating cover provides support, gas storage and insulation to the system, which essentially covers all the necessities of this system.

Biogas production

The production of biogas by the anaerobic digester will vary according to many factors. In order to determine how much biogas will be produced we need to understand which parameters will influence the overall production. These parameters include the quantity of food waste, as well as its biodegradability, volatile solid content, moisture content, and biogas conversion potential. From the literature review, the required values were found and used as follows, chosen for mesophilic bacterial digestion (35 °C) over a retention time of 28 days.

Parameter	***Moisture %***	***VS %***	***Biodegradability***	***Biogas potential***
Value	85	90	0.8	790 L /kg VS

Table 3: Moisture content, VS content, and biodegradability of digester contents

From the below equation for biogas production,

$$V_{biogas} = FW * (1 - M_{\%}) * VS * F_B * BP$$

where
V_{biogas} = Volume of biogas
FW = Food waste
$M_{\%}$ = Moisture content of waste
VS = Volatile Solid content
F_B = Biodegradability Factor
BP = Biogas potential

the total volume of biogas produced inside the anaerobic digester was calculated to be 6140 m^3/day (see Appendix A.6). An overview of biogas production over time can be seen below.

	daily	***weekly***	***monthly***	***annually***
FW (tonnes)	72	504	2184	26204
Biogas (m^3)	6 140	43 000	184 300	2 242 200

Table 4: Biogas production for food waste input

Digestate (sludge) production

The digester is a definite volume, meaning therefore that the mass exiting will equal the mass entering. The mass of input into the digester was previously determined to be 144 000 kg/day (food waste *and* water). We can therefore use the formula:

$$Mass_{in} = Mass_{out}$$

hence, $$FW + Water = Biogas + Sludge$$

From this, the volume of sludge produced inside the digester, and which must be removed, was calculated to be 137 200 kg/day (see Appendix A.7).

Disposal and use of end-products

The digestion process yields two different products; one is the biogas and the other is sludge. Thus far, the design has simply changed the form of the waste. The simplest way to dispose of the biogas is to burn it. If burned in an internal combustion engine, it is possible to produce energy. The main goal is to make use of this energy.

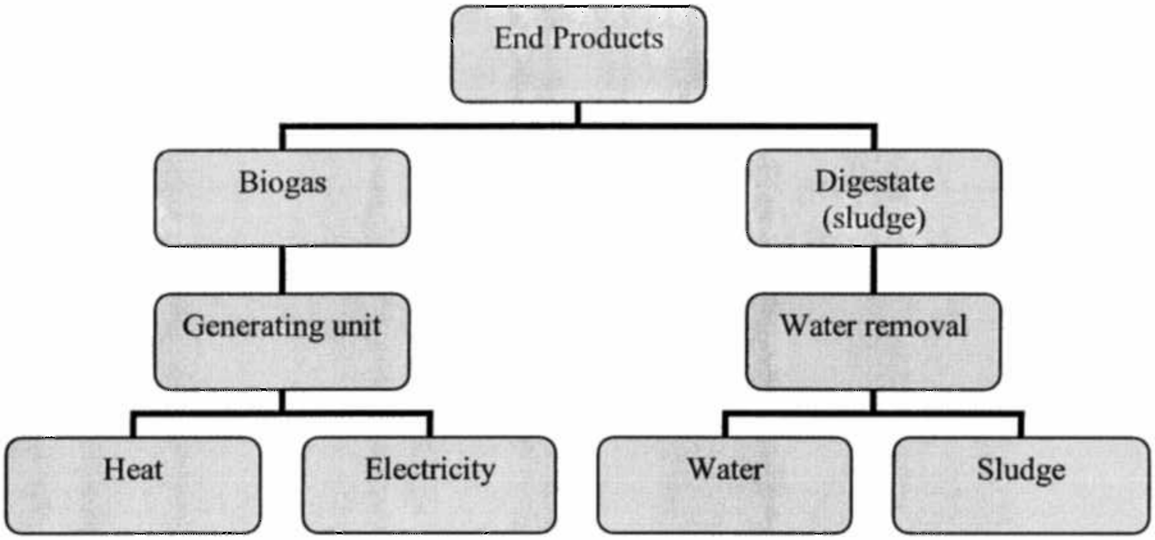


Fig. 9: Schematic of fate of end-products from anaerobic digestion

Liquid sludge disposal

For the simplicity of the design, it is assumed that the liquid waste to dispose of is the same as the initial input (the output volume is slightly less, but the difference is not significant). When the liquid waste portion is removed, it must be pumped into a temporary storage area (in this case, a lagoon) where it will sit until it is taken to be spread on agricultural soil as a fertilizer. We assume that the storage capacity must be 300 days worth of sludge, which is the usual storage period of farm manure lagoons. The quantity of sludge to remove from the digester therefore represents the input masses less the biogas mass. An approximate solid content of the end product sludge can be computed from the equation:

$$S_{\%} = (1 - M_{\%})*(1 - VS)*(1 - F_B)$$

where, $S_{\%}$ = Final solids content of sludge
$M_{\%}$ = Overall moisture content of waste and water mixture
VS = Volatile solids content
F_B = Biodegradability factor

With this formula, the calculated sludge solids content is approximately 2% when it exits the digester (see Appendix A.7). The intended purpose of the disposed sludge is for spreading on surrounding agricultural grounds.

Sludge dewatering

In order to reduce the quantity of sludge to export, water is removed, thus increasing the concentration of solids. According to Roos (2007), 8 % total solids is the maximum desired solid content for sludge which can be pumped without too many complications. The amount of water to remove was determined, using the following equation,

$$m_r = m(1 - \frac{M_{\%i}}{M_{\%f}})$$

where,
m_r = Water to remove
m = Quantity of sludge
$M_{\% i,f}$ = Moisture content (initial, final)

to amount to 102 900 kg/day (see Appendix A.7). The water removed is not sent to the lagoon, however. A portion is recycled as dilution water of the incoming food waste (only half of the necessary dilution water, i.e. 36 000 kg, in order to avoid long term accumulation of salts (Cluff, 2003)), while the other part (66 900 kg) may be sent to the sewers or a septic bed.

Removing the water from the sludge is done with a dewatering unit. Veolia Water Solutions and Technologies currently markets the Gravi-Tek™ Sludge Thickening System (2008). The table below shows typical performances available from this machine:

Technical Data

Effective Belt Width (mm)	500	650	1000	1500	2000	3000
Overall Length (m)	4.40	4.40	4.40	4.40	4.40	4.40
Overall Width (m)	1.25	1.40	1.75	2.25	2.75	3.25
Overall Height (no hood) (m)	1.50	1.50	1.50	1.50	1.50	1.70
Overall Height (inc hood) (m)	1.85	1.85	1.85	1.85	1.85	2.05
Installed Power (kw)	0.75	0.75	1.1	1.1	1.5	2.2
Wash Water (m^3) at 6 bar	2.5	3.3	5.0	7.5	10.0	15.0
Overall Weight (unladen) (kg)	1,900	2,000	2,400	2,800	3,200	4,000
Overall Weight (wet) (kg)	2,600	2,800	3,400	4,100	4,700	5,500

Sludge Type % Dry	Input % Dry Solids	Throughput (m^3/hr) per metre width	Output Solids
Municipal Primary	1 to 4	20 to 40	6 - 10%
Municipal Biological	0.3 to 2	40 to 60	5 - 8%
Industrial Biological	0.3 to 2	30 to 50	4 - 8%
Waterworks	0.2 to 1	15 to 30	4 - 7%

Fig. 10: Technical specifications of dewatering machinery

Source: Veolia Water Solutions and Technologies.

From this table, the throughput (capacity) of machine needed for our plant needs may be determined using the following equation

$$C = V / t_{op}$$

where,

V = Volume to treat
C = Capacity of machine
t_{op} = Operating time

Arbitrarily choosing an operating time of 4 hrs, the required capacity (C) of the dewatering machine was thus calculated to be 34.3 m^3/hr (see Appendix A.9). According to the table, a belt width of approximately 1000 mm would thus be needed.

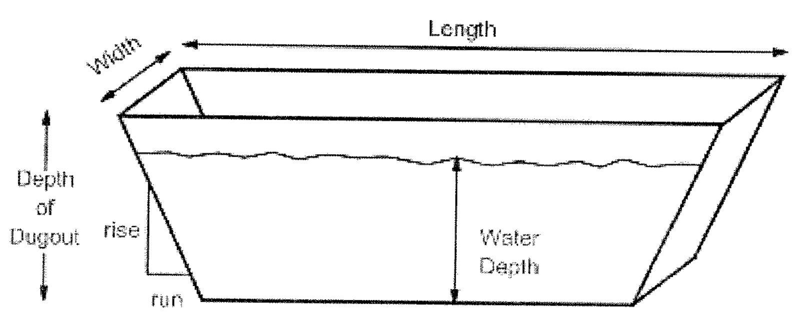
Lagoon dimensions

The quantity of sludge sent to the lagoon is the thus calculated as

Sludge to lagoon = (total sludge) - (water removed)

which was calculated to be 34 300 kg/day, and the consequent volume of the lagoon is determined to be 12 862 m^3, using the equation (see Appendix A.7):

$$V_{lagoon} = \text{(sludge sent to lagoon daily)} * \text{(storage period)} * \text{(Safety factor)}$$



<u>Fig. 11:</u> Schematic of lagoon for sludge storage
Source: Alberta Agriculture and Rural Development.

The final design of the lagoon must also include a free board height as a safety precaution, for the lagoon is not covered, and rainfall and evaporation will affect the water level of the lagoon. The weather data of the area must thus be considered. The mean annual precipitation and evaporation for the area are 950mm and 600mm respectively (The Weather Network, 2008). The difference in height of the two is of 350 mm. Given that the storage period is for 300 days, a proportional value of 0.3 m is added to the depth of the lagoon. Another 0.3 m is also added on top of this as the minimum required freeboard for a lagoon. The size selected was of 135m by 50 m top dimensions with a liquid depth of 2.4 m and free board of 0.6 m, for a total lagoon depth of 3 m (see Appendix A.8).

Electric and heat generation

For the purpose of this project, the use of a cogeneration system that recovers the energy in form of electricity and heat has been chosen. The selected system is the GE™ J312GS engine. This combustion engine, manufactured by General Electric™, can use the biogas directly, not solely methane, for combustion. The specifications of this system are given by the table below.

Biogas		1,200 rpm | 60 Hz					1,500 rpm | 50 Hz					1,800 rpm | 60 Hz				
NOx <	Type	Pel (kW)[1]	ηel (%)	Pth (kW)[2]	ηth (%)	ηtot (%)	Pel (kW)[1]	ηel (%)	Pth (kW)[2]	ηth (%)	ηtot (%)	Pel (kW)[1]	ηel (%)	Pth (kW)[2]	ηth (%)	ηtot (%)
500 mg/Nm³	312						526	40.4	566	43.5	83.9	540	37.2	682	47.0	84.2
	312						625	39.7	702	44.7	84.4	633	38.1	765	46.0	84.1
	316						835	39.9	934	44.6	84.5	848	38.2	1,020	46.0	84.2
	320						1,064	40.8	1,104	42.4	83.2	1,060	39.0	1,258	46.3	85.3
250 mg/Nm³	312											633	36.7	811	47.0	83.7
	316											848	36.9	1,081	47.0	83.9
	320											1,060	36.9	1,367	47.6	84.5

Fig. 12: Specifications of the GE™ J312GS biogas engine, by General Electric™

Source: GE Energy

Using these specifications, the total energy yield may be found. The yield will depend on the amount of biogas that passes through the system, which thus depends on the volume of biogas produced by the digestion. The electric potential was calculated to equal 14.1 MWh, using the given formula (see Appendix A.10):

$$E_p = V_d u \eta \qquad \textbf{(a)}$$

where,

E_p = Electric potential
V_d = Daily volume of biogas
u = Energy content of Biogas
η = Efficiency of conversion

Given the efficiency of approximately 38 % and the potential electric production of 14.1 MWh for the given flow of biogas through the co-generator, the consequent steady electric output (interpolated) of the co-generator is approximately 588 kW. Because of the co-generation, this system not only yields electric power, but also yields heat. The heat generation potential is found using the same above equation, but using the associated *thermal* efficiency from the table. The heat production is calculated as 710 kW (see Appendix A.11). The table below demonstrates the potential yield of this system for this design.

	daily	*weekly*	*monthly*	*annually*
Biogas (m^3)	6 140	43 000	184 300	2 242 200
Electric Output (kW)	588			
Electric Production (MWh)	14.1	98.5	422.1	5 135.6
Heat Output (kW)	710			
Heat Production (MWh)	17.0	119.3	511.2	6 220.0

Table 5: Electric and heat outputs for GE™ J312GS co-generation unit

Mass and Energy Considerations

Daily Mass Balance

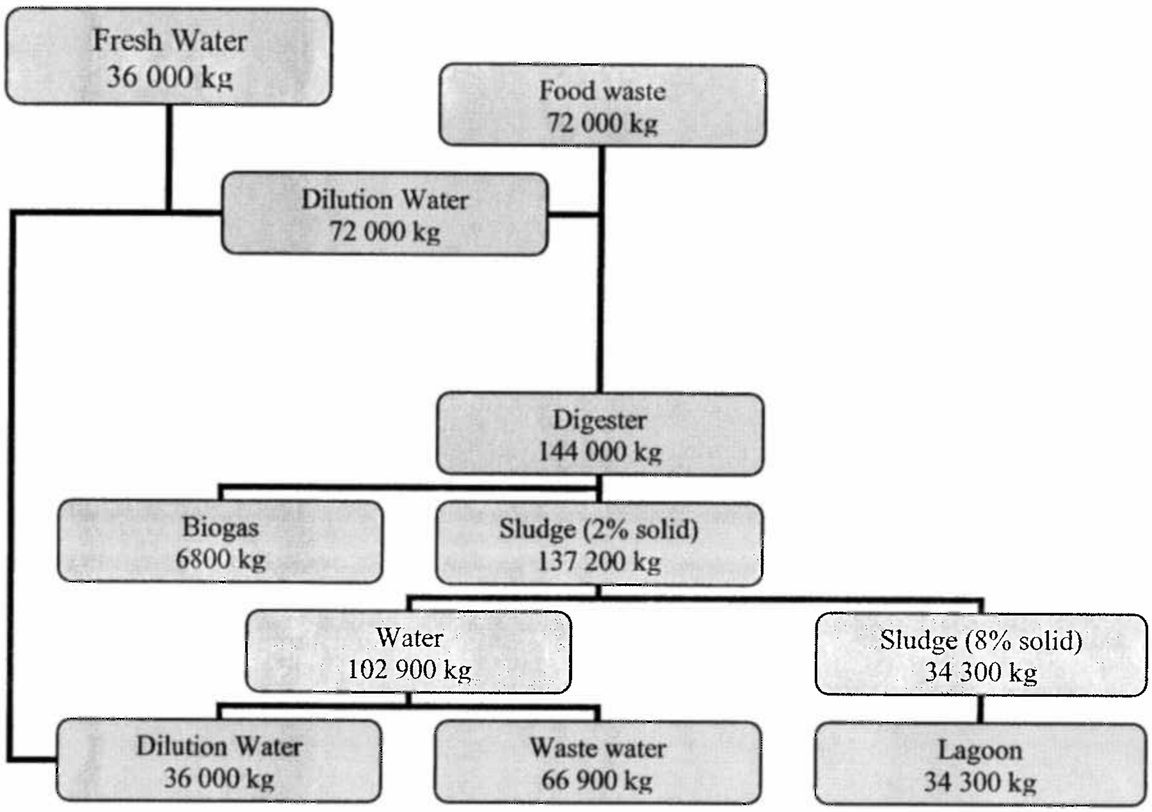


Fig.13: Flowchart of daily mass balance of the complete designed system

This flowchart is a visual schematic representing the values previously calculated and discussed.

Daily Energy Balance

Average January day (-9°C)

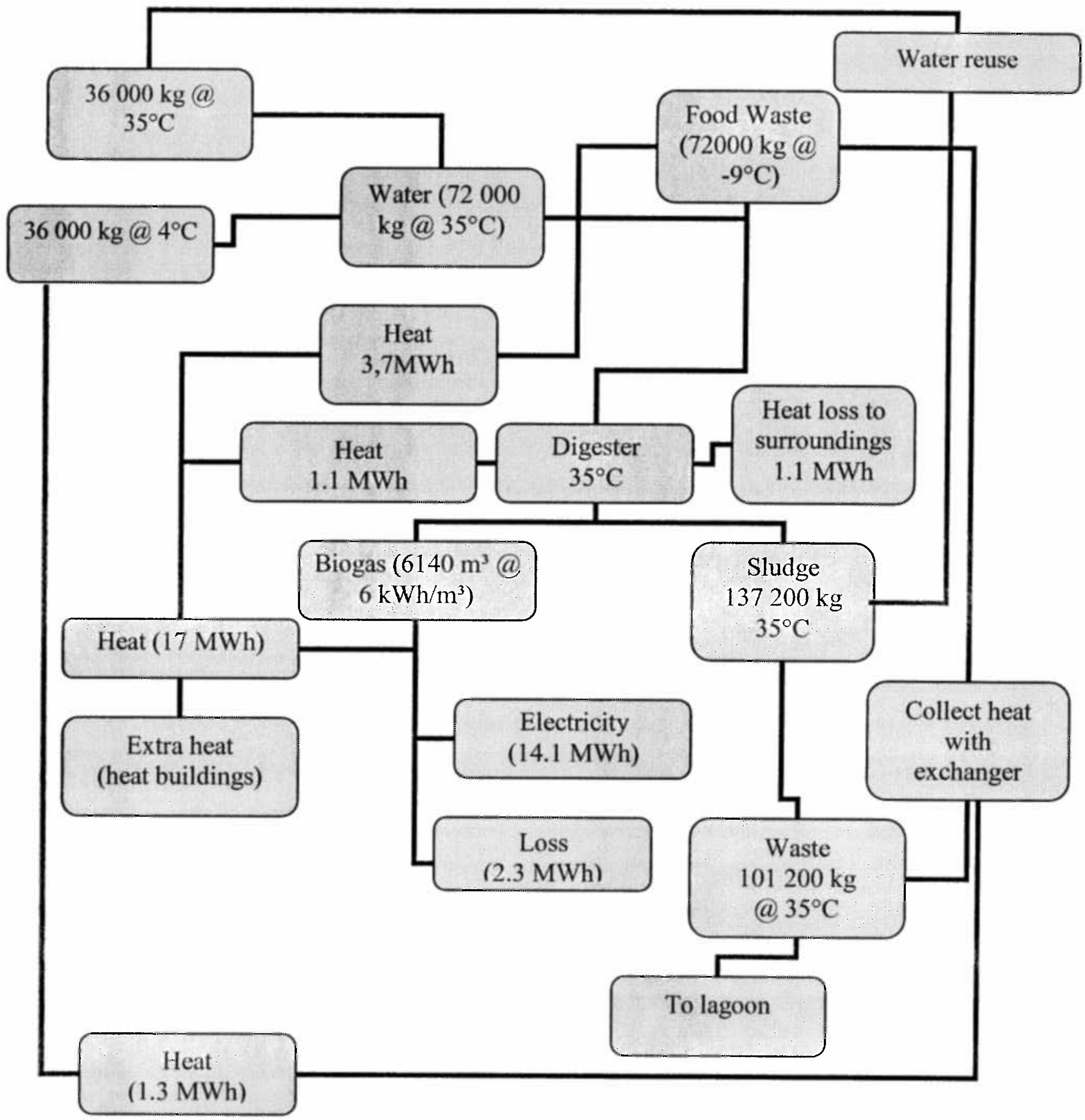


Fig. 14: Flowchart of daily energy balance of the complete designed system

The above energy balance demonstrates various heat needs and how these needs can be filled. Initially, there are two mass inputs into the digester; food waste and water. The water is added to dilute the food waste to get the appropriate organic loading rate. As aforementioned, half the water is extracted from the sludge and the other half is fresh. The reuse water should be at a temperature close to that of the digester (35°C). The food waste and the fresh water will need to be heated before entering the digester in order to keep the digester at a constant temperature. The food waste would be at the outside temperature while the fresh water is assumed to be at 4 °C. The energy to heat the fresh water can come from the heat generated from the biogas combustion or heat extracted from the exiting sludge by the help of heat exchangers. The energy needed to heat the water can be calculated by the formula:

$$E = \Delta T m C_p \qquad \text{(b)}$$

where,

E = Energy
T = Temperature difference
m = Mass
C_p = Specific Heat

Using this formula for both the water and the food waste will determine the amount of energy required to ensure that the inputs entering the digesters do not cool it down and reduce its performances. The other major source of heat loss will be released from the digester to the surroundings. If the interior of the digester is maintained at 35°C, and the external temperature is less, there will always be a temperature gradient that will cause some energy to transfer to the surroundings. This quantity of energy can be determined with principles of heat transfer. The equations in this Energy Balance section are all taken from Kreith and Bohn (2001).

An analogous electrical circuit can be made of this scenario, where the top branch represents the energy loss by the roof, while the middle branch represents the heat loss from the wall and the lower branch the energy from the floor.

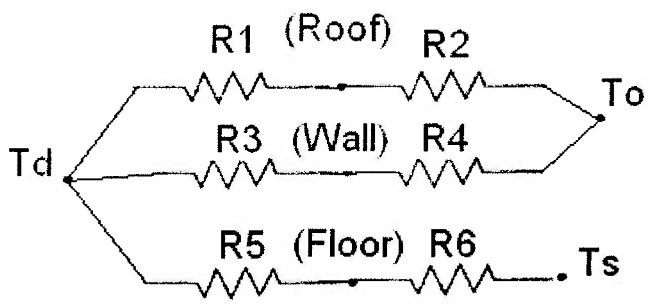


Fig.15: Circuit diagram representing path of heat loss through digester

where,

Td = temperature inside the digester
R1 = Conduction resistance of the roof
R2 = Convection resistance of the roof
R3 = Conduction resistance of the wall
R4 = Convection resistance of the wall
R5 = Conduction resistance of the floor
R6 = Conduction resistance of the soil.
Ts = Soil temperature
To = Outside temperature

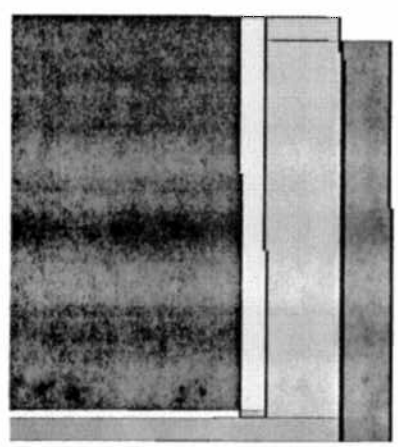


Fig.16: Cross-section of digester wall and floor

Above is a typical wall section of a digester. The yellow is the interior lining, the grey is the concrete structure, and the red is the insulation. The respective thicknesses are what influence the radius dimension for R3. The natural log (ln) is used because radial heat transfer is assumed. In the case of R1 and R2, 1-D heat flow is assumed. Therefore, the thickness is directly taken to calculate the resistance. A parallel is made to an electric circuit where the temperature difference between the interior of the digester and the exterior is the driving potential. The R's represents resistances slowing down the flow of energy caused by the potential. An increase in thickness increases the resistance, while an increase in thermal conductivity decreases it.

Equations used for the *conduction* resistance:

$$R1 = \frac{b_1}{k_1 \pi r^2} + \frac{b_2}{k_2 \pi r^2} \qquad R3 = \frac{ln(r_2/r_1)}{2\pi k_a L} + \frac{ln(r_3/r_2)}{2\pi k_b L} + \frac{ln(r_4/r_3)}{2\pi k_c L}$$

$$R5 = \frac{b_3}{k_3 \pi r^2} + \frac{b_4}{k_4 \pi r^2}$$

Equations used for *convection* resistance:

$$R2 = \frac{1}{h_c \pi r^2} \qquad R4 = \frac{1}{h_c 2\pi r L} \qquad R6 = \frac{1}{S k_{soil}}$$

where:

b = Thickness of layer
k = Thermal conductivity of layer
r = Radius of tank
r_x = Radius of layer
L = Height of tank
h_c = Convection heat transfer

Total energy loss from digester to surrounding area is calculated using the equations,

$$E = q_{ground} + q_{wall} + q_{roof}$$

$$E = \frac{T_d - T_s}{R5 + R6} + \frac{T_d - T_o}{\frac{1}{\frac{1}{R1+R2} + \frac{1}{R3+R4}}}$$

$$E = \frac{T_d - T_s}{\frac{b_3}{k_3 \pi r^2} + \frac{b_4}{k_4 \pi r^2} + \frac{1}{4 r k_{soil}}} + \frac{T_d - T_o}{\frac{1}{\frac{1}{\frac{b_1}{k_1 \pi r^2} + \frac{b_2}{k_2 \pi r^2} + \frac{1}{h_c \pi r^2}} + \frac{1}{\frac{ln(r_2/r_1)}{2\pi k_a L} + \frac{ln(r_3/r_2)}{2\pi k_b L} + \frac{ln(r_4/r_3)}{2\pi k_c L} + \frac{1}{h_c 2\pi r_o L}}}}$$

This energy that is lost from the digester must be replaced in order to keep a constant temperature. This is achieved with the heat generated by the co-generation unit. Therefore the heat input in the digester is the same as the amount lost to the surroundings. The goal is to have enough energy available (heat from biogas combustion and from sludge heat recuperation) to replace the heat loss to the surrounding, as well as heat the inputs. The energy available from the cogeneration unit was previously determined to be 14.1 MWh, from equation **(a)**. The energy available from the output sludge can be determined using the equation **(b)**, where T will depend on the heat collection method. The available heat from the output sludge can be collected using a counter flow heat exchanger. The general equation for this type of exchanger is:

$$q = UA\frac{\Delta T_a - \Delta T_b}{ln(\Delta T_a / \Delta T_b)} \qquad \text{(c)}$$

where,

q = energy transfer
U = Overall heat transfer coefficient
A = Surface Area
ΔT_a = Temperature difference between inlet temperatures
ΔT_b = Temperature difference between outlet temperatures

q is determined by equation **(b)** while U and A together are determined by the overall conductance and depend on the design of the heat exchangers. In this case, both inlet temperatures are known, as well as one desired outlet temperature. The volumes are also known for both fluids and therefore we can use the following equation to determine the missing temperature.

$$m_h c_{ph}(T_{h,in} - T_{h,out}) = m_c c_{pc}(T_{c,out} - T_{c,in})$$

Where: m = Flow rate of respective fluid (hot or cold)
c_{px} = Specific heat of respective fluid
T_x = Temperature of respective fluid at location (inlet or outlet)

By solving equation **(c)** for UA, a required heat exchanger conductance can be found. The heat exchanger can therefore be designed to get this conductance. The conductance of the heat exchanger can be determined with the following equation:

$$UA = \frac{1}{\frac{1}{h_i 2\pi r_i L} + \frac{L}{kA_k} + \frac{1}{h_o \pi r_o L}}$$

where:

UA = Conductance
h_x = Heat transfer coefficient of inner and outer surface
$r_{i,o}$ = Radius (inner, outer)
L = Length of pipe
k = Thermal conductivity of pipe
A_k = Area of pipe

A detailed spreadsheet containing the calculations and final figures for the above heat transfer section is found in Appendix A.12.

Economic Analysis

Discussion of tipping fees for disposal of organic waste

A tipping fee is a charge that is imposed upon a party for the unloading and disposal of their cargo. This is not only a common practice for waste disposal sites, but rather the standard. There are also different tipping fees for various types of waste, such as regular landfill waste, recycling, green waste, hazardous waste, etc. In 2000, California's average tipping fee for landfill waste was roughly $35/ton, and only $24/ton for green waste (California Integrated Waste Management Board, 2008).

As an incentive for collection companies to dispose of their waste at the anaerobic digester site instead of sending it directly to landfill, a lower tipping fee for the green waste could be implemented. If the anaerobic digester site were to charge $20/ton, versus $24/ton at the landfill site, this would save the collection company $105 000/yr in disposal costs, and create almost $526 000/yr income for the anaerobic digester site.

General discussion

In the overview of expenditures and returns below, the abovementioned tipping fees are not considered, for it is unclear as of yet what parties will be responsible for the various elements of the designed program (collection, digester construction, digester operation and maintenance, etc.). Therefore, a simple accounting of capital costs, yearly operation and maintenance costs, and potential yearly revenues is presented, without consideration of the source of financial support. For the calculation of yearly expenses and revenues that contribute to the yearly net return, however, it is assumed that the collection costs, being a significant amount ($ 3 612 000 /yr) will likely be absorbed by a combination of municipal funds as well as federal/provincial grants directed toward alternative energy initiatives.

	rate	units	capital	yearly	Reference
Collection					
contractor costs*	$ 5/household	60 200 hh		*$ 3 612 000*	(City of Chilliwack, 2008)
bin (cart) purchase (240 L / 0.45 m3)	$ 33/unit	60 200 units	$ 1 986 600		(BioCycle, 2005)
Digester					
Capital cost of digester	$ 5159/ kW	588 kW	$ 3 033 500		(California Energy Commission, 2007)
Operation and maintenance costs	$ 0.028/kWh	5.15 MWh		$ 144 200	(California Energy Commission, 2007)
Returns					
green waste tipping fees**					
electricity	0,10$/kWh	50 % of 5.15 MWH		$ 250 000	assumed Québec rate
sludge	Assume sold for cost of transportation				
heat	Can be directed (sold) to neighbouring homes or industry - situation unsure as of yet				
				$ 250 000	
			subtract	$ 144 000	
Net return				$ 106 000 /yr	
* assuming contractor costs will be covered by municipal taxes and government grants					
** tipping fees for the digester site are not considered in this economic analysis, but are a beneficial option, as discussed previously.					

Fig.17: Economic Analysis – overview of costs and returns

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Appendix

A.1 Calculation of population projection for 2021

Year	Population	Growth (%)
1991	84 500	---
1996	95 318	12.8
2001	102 100	7.1
2006	120 395	17.9
1991-2001	---	20.8
1996-2006	---	26.3
1991-2006	---	42.5

Source: Statistics Canada, 2006

As may be seen from the above table, the growth over the years has demonstrated cyclical behaviour. Thus, considering the recent boom in population over the previous 15 years (43 %), the predicted growth rate over the following 15 years will be slightly conservative in comparison (30 %).

The projected population of Vaudreuil-Soulanges for 2021 is thus:

(120 395) * (1.30) = **156 514** persons

For the purpose of further calculations, the 2021 population will be rounded to 156 500 persons.

According to Statistics Canada, the average number of people per household throughout Vaudreuil-Soulanges varies between 2 and 3 persons. The figure of 2.6 persons per household for 2006 was thus used, as it closely represent the mean. Accordingly, the expected number of households come 2021 is:

(156 500 persons) / (2.6 persons/hh) = **60 192** households

The rounded figure of 60 200 households will be employed for further calculations.

A.2 Calculation of design organic load

The 2004 national average for yearly residential solid waste production was **418 kg** per capita (Environment Canada, 2007); **40 %** of which is determined to be the organic fraction (Statistics Canada, 2005). Therefore,

$$(418 \text{ kg/cap/yr}) *(0.4)* (1/52) \text{ yr*wks}^{-1} = \mathbf{3.22\ kg}\text{/cap/wk of organic waste}$$

Using the projected population of Vaudreuil-Soulanges for the year 2021 (156 500 pp), the predicted amount of residential organic waste produced by the population would be as follows:

$$(\mathbf{3.22} \text{ kg/cap/wk}) * (156\ 500 \text{ cap}) = \mathbf{503\ 208\ kg}\text{/wk}$$
$$= 71\ 887 \text{ kg/day}$$

Therefore, the design organic waste loading rate used for further calculations will be 72 000 kg/day.

Thus the approximate weekly amount of organic waste produced per household would be:

$$(3.22 \text{ kg/cap/wk}) * (2.6 \text{ cap/hh}) = \mathbf{8.37\ kg}\text{/hh/wk}$$

The number of truckloads required to collect the 503 208 kg produced per week by the population, assuming each truck has a capacity of 25 m^3:

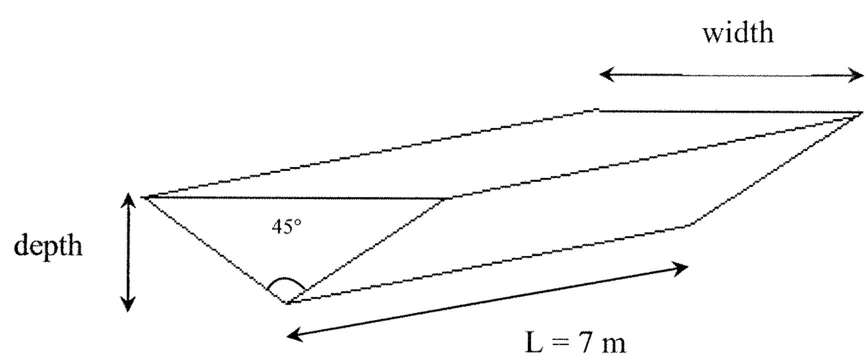
$(503\ 208\ kg) * (1\ m^3/\ 1000\ kg) * (1\ truckload/\ 25m^3) \approx$ *<u>20 truckloads</u>*

A.3 <u>Calculation of preparation storage areas</u>

In order to keep the digester running at capacity over weekend, an amount larger than the design organic waste loading rate must be collected each day. The daily *collection rate* is therefore:

(503 208 kg/wk) / (5 collection days/wk) = *<u>100 800 kg/day</u>*

In order to have a self cleaning dump pit, a side slope of 45° will be selected for both sides of the triangular prism pit. This slope creates a depth to overall width ratio of 2:1. A pit length of 7 m and a volume of 70 m^3 are both assumed values. The depth and width of the pit may then be calculated:



$$V = Length * depth * width/2$$
$$70\ m^3 = (7m) * (depth) * (width/2)$$
$$= (7m) * (depth)^2$$

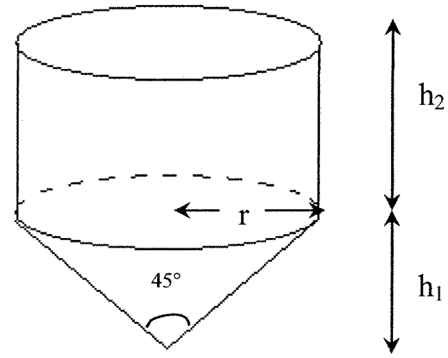
therefore, depth = 3.2 m

width = 2 * 3.2 m = 6.4 m

The size of the temporary storage tank is calculated using a safety factor of 1.2, and storage for 3 days. The size of the storage tank is therefore:

$$(100\ 800 \text{ kg/day}) * (3 \text{ days}) * (1.2) \approx 260\ 000 \text{ kg} \approx 260 \text{ m}^3$$

Dimensions of the tank can therefore be calculated assuming a hopper tank bottom with a slope of 45° and maintaining an overall height of < 7.5 m.



h_1 = height of the hopper section = r (due to 45° slope)
r = radius of tank
h_2 = height of top cylindrical section

$$V_{hopper} = [(\pi * h_1 * r^2) / 3] + (\pi * h_2 * r^2)$$
$$= 260 \text{ m}^3$$

assuming $h_1 = r = 4.5$ m,

then $h_2 = 2.6$ m

A.4 ***Calculation of useful digester volume***

$$V_d = W * Wd * DF * RT$$

where $DF = VS\ Content / (RT * Loading\ rate)$

$VS\ content = (TS\ fraction) * (VS/TS\ fraction) * (waste\ density)$

$= (15\ \%\ TS) * (90\%\ VS/TS) * (1000\ kg/m^3)$

$= 135\ kg\ VS/m^3$

therefore,

$DF = 135\ kg\ VS/m^3 / (28\ days * 2.4\ kg\ VS\ /m^3/day)$

$= 2$

and $V_d = 72\ 000\ kg/day * 1000\ kg/m^3 * 2 * 28\ days$

$= 4032\ m^3$

<u>*actual volume*</u>, $V_a = (V_d) * (Safety\ Factor)$

$= (4042\ m^3) * (1.5)$

$= \underline{6000\ m^3}$

A.5 <u>Calculation of digester dimensions</u>

$$V_{cyl} = (\pi) * (diameter/4)^2 * (height)$$

Digester interior *height* chosen arbitrarily to be <u>*5 m*</u>. Therefore, the interior diameter must be,

$$diameter = [(4 * V_{cyl}) / (\pi * height)]^{1/2}$$

$$= [(4 * 6000\ m^3) / (\pi * 5\ m)]^{1/2}$$

$$= \underline{40\ m}$$

A.6 Calculation of biogas production

$$V_{biogas} = FW * (1 - M_{\%}) * VS * F_B * BP$$

where V_{biogas} = Volume of biogas (@ STP: 0°C and 101.325 kPa)
FW = Food waste
$M_{\%}$ = Moisture content of waste
VS = Volatile Solid content
F_B = Biodegradability Factor
BP = Biogas potential

therefore,

$$V_{biogas} = (72\,000 \text{ kg/day}) * (1 - 0.85) * (0.9 \text{ kg VS/ kg TS}) * (0.8) * (790 \text{ L/kg VS})$$

$$= \underline{6140 \text{ m}^3\text{/day}}$$

	daily	weekly	monthly	annually
FW (tonnes)	72	504	2184	26204
Biogas (m^3)	6 140	43 000	184 300	2 242 200

Table 4: Biogas production for food waste input

A.7 Calculations of digestate (sludge) production and removal

$$Mass_{in} = Mass_{out}$$

hence:

$$FW + Water = Biogas + Sludge$$

$$72\,000 \text{ kg FW} + 72\,000 \text{ kg } H_20 = (6140 \text{ m}^3 * 1.112 \text{ kg/ m}^3) + \text{Sludge}$$

$$\text{Sludge} = 137\,172 \text{ kg/day}$$
$$\approx \underline{137\,200 \text{ kg/day}}$$

*** (1.112kg/m3 = density of biogas at STP: 0°C and 101.325 kPa)

An approximate solid content of the end product sludge can be computed from the equation:

$$S_{\%} = (1 - M_{\%})*(1 - VS)*(1 - F_B)$$

where, $S_{\%}$ = Final solid content

$M_{\%}$ = Moisture content of (waste + water) mixture
= [(0.85*72 000 kg) + 72 000 kg] / (72 000 kg + 72 000 kg)
= 0.925

VS = Volatile solid content of (waste + water) mixture
= (135 kg/m^3* 72 m^3) / (72 000 kg + 72 000 kg)
= 0.0675

F_B = Biodegradability Factor
= 0.8

therefore, $S_{\%} = (1 - M_{\%})*(1 - VS)*(1 - F_B)$
= (1-0.925)*(1-0.0675)*(1-0.8)
≈ <u>*2 %*</u>

According to Roos (2007), 8% total solids is the maximum desired solid content to have a sludge which can be pumped without too many complications. The amount of water to remove can be determined by the equation:

$$m_r = m(1 - \frac{M_{\%i}}{M_{\%f}})$$

where,

m_r = Water to remove
m = Quantity of sludge
$M_{\% i,f}$ = Moisture content (initial, final)

therefore,

m_r = 137 200 kg/day *(1-(0.02/0.08))

= <u>*102 900 kg/day*</u>

The quantity of sludge sent to the lagoon is the then,

Sludge to lagoon = (total sludge)-(water removed)

= (137 200kg – 102 900kg)/day

= *34 300 kg/day*

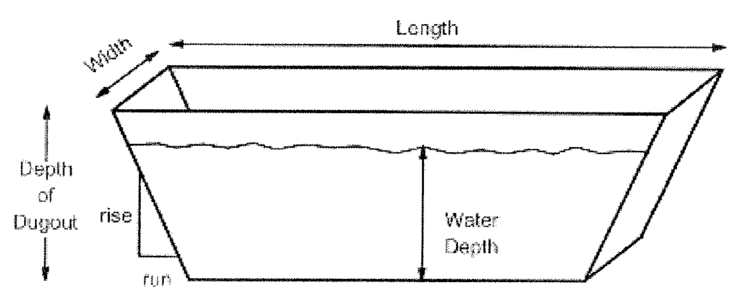
Thus, the necessary volume of the lagoon (storage period of 300 days) is calculated as:

V_L = (sludge sent to lagoon daily) * (storage period) * (Safety factor).

= 34.3 m^3 /day * 300 days * 1.25

= *12 862 m^3*

A.8 Calculation of lagoon dimensions



$$V_L = (d/6) \times (A_t + A_b + 4\ A_m)$$

where,

$A_t = L \times W$
$A_b = (L - 2 \times ES \times d)\ (W - 2 \times SS \times d)$
$A_m = (L - ES \times d)(\ W - SS \times d)$

and

V = Volume
d = depth of the dugout
A_t = Area of the top of the dugout
A_b = Area of the bottom of the dugout
A_m = Area of the midsection of the dugout
SS = slope of the sides of the dugout
ES = slope of the ends of the dugout
L = Length of the top of the dugout
W = Width of the top of the dugout

V_L = 12 862 m^3 and total depth (liquid + freeboard) determined as *d = 3 m*. Final calculations revealed a top surface length of *135 m* and width of *50 m*. These figures were found using the Dugout/lagoon volume calculator tool on the Alberta Agriculture and Rural Development website (2004), which employs the above equations.

A.9 Calculation of dewatering requirements

Throughput of the dewatering machine is calculated using the equation

$$C = V / t_{op}$$

where,

V = Volume to treat (total sludge)
C = Capacity (throughput) of machine
t_{op} = Operating time = 4 hrs (arbitrary)

therefore,

$$C = V / t_{op}$$
$$= (137.2\ m^3) / (4\ hrs)$$
$$= 34.3\ m^3/hr$$

A.10 *Calculation of electric and heat potential*

$$E_p = V_d u \eta \qquad \textbf{(a)}$$

where,

E_p = Electric production potential
V_d = Daily volume of biogas
u = Energy content of Biogas
η = Efficiency of conversion

The previously calculated volume of biogas produced by the digester is 6140 m^3/day. The heat content of biogas is taken as 6 kWh (Sasse, 1988) and the efficiency is chosen as ≈ 38 %, operating at 60 Hz and 1800 rpm.

Therefore,

$$E_p = V_d u \eta$$

$$E_p = 6140 \frac{m^3}{day} * 6kWh/m^3 * 0,38$$

$$\underline{E_p = 14,1MWh}$$

The heat generation potential is found using the same above equation, but using the associated thermal efficiency, given in the below table.

A.11 *Calculation of electric and heat output*

Given an efficiency of approximately 38 % and the potential electric production of 14.1 MWh for the given flow of biogas through the co-generator, the consequent steady electric output of the co-generator can be interpolated from the below table.

Biogas		1,200 rpm | 60 Hz					1,500 rpm | 50 Hz					1,800 rpm | 60 Hz				
NOx <	Type	Pel (kW)	ηel (%)	Pth (kW)	ηth (%)	ηtot (%)	Pel (kW)	ηel (%)	Pth (kW)	ηth (%)	ηtot (%)	Pel (kW)	ηel (%)	Pth (kW)	ηth (%)	ηtot (%)
500 mg/Nm³	312						526	40.4	566	43.5	83.9	540	37.2	682	47.0	84.2
	312						625	39.7	702	44.7	84.4	633	38.1	765	46.0	84.1
	316						835	39.9	934	44.6	84.5	848	38.2	1,020	46.0	84.2
	320						1,064	40.8	1,104	42.4	83.2	1,060	39.0	1,258	46.3	85.3
250 mg/Nm³	312											633	36.7	811	47.0	83.7
	316											848	36.9	1,081	47.0	83.9
	320											1,060	36.9	1,367	47.6	84.5

Fig. 12: Specifications of the GE™ J312GS biogas engine, by General Electric™

Source: GE Energy

If efficiency is 38 %, then the electric output is interpolated as approximately 588 kW. The associated thermal efficiency would therefore be 46.5 %, and the thermal output is approximately 710 kW. The electric and heat production are therefore calculated by multiplying the outputs by the hours in the desired time period. The table below summarizes the results.

	daily	*weekly*	*monthly*	*annually*
Biogas (m^3)	6 140	43 000	184 300	2 242 200
Electric Output (kW)	588			
Electric Production (MWh)	14.1	98.5	422.1	5 135.6
Heat Output (kW)	710			
Heat Production (MWh)	17.0	119.3	511.2	6 220.0

Table 5: Electric and heat outputs for GE™ J312GS co-generation unit

A.12 Calculations of heat transfer through digester wall and floor

All equations used are found in the Energy Balance section, taken from Kreith and Bohn (2001).

MONTH	January	February	March	April	May	Jube	July	August	September	October	November	December
Wind V	17	16	16	16	14	14	12	11	12	14	16	16
Tinfiniti	-8	-9	-1	6	13	18	21	19	15	8	2	-6
U infiniti	4.7	4.4	4.4	4.4	3.9	3.9	3.3	3.1	3.3	3.9	4.4	4.4
D	40	40	40	40	40	40	40	40	40	40	40	40
v	13	13	13	14	15	15.7	15.7	15.7	15	14	13.9	13
k	0.0237	0.0237	0.0237	0.0237	0.0242	0.0251	0.0251	0.0251	0.0247	0.0242	0.0237	0.0237
Pr	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
Re	14,529,915	13,675,214	13,675,214	12,698,413	10,370,370	9,907,997	8,492,569	7,784,855	8,888,889	11,111,111	12,789,768	13,675,214
C	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076
M	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Nu	6908.2	6621.1	6621.1	6286.4	5455.5	5284.1	4743.6	4463.3	4897.5	5725.4	6318.0	6621.1
h wall	4.1	3.9	3.9	3.7	3.3	3.3	3.0	2.8	3.0	3.5	3.7	3.9
h roof	1.83	1.78	1.78	1.84	1.79	1.83	1.69	1.62	1.65	1.73	1.84	1.78
Roof												
insul K	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157
Lining K	0.163	0.163	0.163	0.163	0.163	0.163	0.163	0.163	0.163	0.163	0.163	0.163
Lining Thick	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
insul thick	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
R1	0.001160188	0.001160188	0.001160188	0.001160188	0.001160188	0.001160188	0.001160188	0.001160188	0.001160188	0.001160188	0.001160188	0.001160188
R2	0.000434286	0.000447652	0.000447652	0.000431368	0.000445515	0.00043547	0.000470361	0.000491277	0.000481211	0.000461152	0.000432917	0.000447652
Wall												
lin K	0.163	0.163	0.163	0.163	0.163	0.163	0.163	0.163	0.163	0.163	0.163	0.163
stuct K	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
ins k	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157
lin thick	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
stuck thick	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
ins thick	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
L	5	5	5	5	5	5	5	5	5	5	5	5
R3	0.002544147	0.002544147	0.002544147	0.002544147	0.002544147	0.002544147	0.002544147	0.002544147	0.002544147	0.002544147	0.002544147	0.002544147
R4	0.000388838	0.000405694	0.000405694	0.000427296	0.000482203	0.000479996	0.000534688	0.000568267	0.000526273	0.000459468	0.000425157	0.000405694
Floor												
ins K	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
concrete K	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
ins thick	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Concrete thck	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
R5	0.001127348	0.001127348	0.001127348	0.001127348	0.001127348	0.001127348	0.001127348	0.001127348	0.001127348	0.001127348	0.001127348	0.001127348
soil K	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
R6	0.008928571	0.008928571	0.008928571	0.008928571	0.008928571	0.008928571	0.008928571	0.008928571	0.008928571	0.008928571	0.008928571	0.008928571
floor loss	2983	2983	2983	2983	2983	2983	2983	2983	2983	2983	2983	2983
roof loss	26968	27366	22390	18221	13701	10654	8586	9688	12185	16653	20714	25500
wall loss	14661	14916	12204	9760	7269	5621	4547	5141	6514	8989	11114	13899
Total Loss (W	44612	45265	37578	30964	23954	19259	16117	17812	21682	28625	34811	42382

MONTH	**January**	**February**	**March**	**April**	**May**
Wind V	17	16	16	16	14
Tinfiniti	-8	-9	-1	6	13
U infiniti	4.7	4.4	4.4	4.4	3.9
D	40	40	40	40	40
v	13	13	13	14	15
k	0.0237	0.0237	0.0237	0.0237	0.0242
Pr	0.71	0.71	0.71	0.71	0.71
Re	14,529,915	13,675,214	13,675,214	12,698,413	10,370,370
C	0.076	0.076	0.076	0.076	0.076
M	0.7	0.7	0.7	0.7	0.7
Nu	6908.2	6621.1	6621.1	6286.4	5455.5
h wall	4.1	3.9	3.9	3.7	3.3
h roof	1.83	1.78	1.78	1.84	1.79
Roof					
insul K	0.157	0.157	0.157	0.157	0.157
Lining K	0.163	0.163	0.163	0.163	0.163
Lining Thick	0.03	0.03	0.03	0.03	0.03
insul thick	0.2	0.2	0.2	0.2	0.2
R1	0.001160188	0.001160188	0.001160188	0.001160188	0.001160188
R2	0.000434286	0.000447652	0.000447652	0.000431368	0.000445515
Wall					
lin K	0.163	0.163	0.163	0.163	0.163
stuct K	1.8	1.8	1.8	1.8	1.8
ins k	0.157	0.157	0.157	0.157	0.157
lin thick	0.03	0.03	0.03	0.03	0.03
stuck thick	0.3	0.3	0.3	0.3	0.3
ins thick	0.2	0.2	0.2	0.2	0.2
L	5	5	5	5	5
R3	0.002544147	0.002544147	0.002544147	0.002544147	0.002544147
R4	0.000388838	0.000405694	0.000405694	0.000427296	0.000482203
Floor					
ins K	0.16	0.16	0.16	0.16	0.16
concrete K	1.8	1.8	1.8	1.8	1.8
ins thick	0.2	0.2	0.2	0.2	0.2
Concrete thck	0.3	0.3	0.3	0.3	0.3
R5	0.001127348	0.001127348	0.001127348	0.001127348	0.001127348
soil K	1.4	1.4	1.4	1.4	1.4
R6	0.008928571	0.008928571	0.008928571	0.008928571	0.008928571

floor loss	2983	2983	2983	2983	2983
roof loss	26968	27366	22390	18221	13701
wall loss	14661	14916	12204	9760	7269
Total Loss (W)	44612	45265	37578	30964	23954

June	July	August	September	October	November
14	12	11	12	14	16
18	21	19	15	8	2
3.9	3.3	3.1	3.3	3.9	4.4
40	40	40	40	40	40
15.7	15.7	15.7	15	14	13.9
0.0251	0.0251	0.0251	0.0247	0.0242	0.0237
0.71	0.71	0.71	0.71	0.71	0.71
9,907,997	8,492,569	7,784,855	8,888,889	11,111,111	12,789,768
0.076	0.076	0.076	0.076	0.076	0.076
0.7	0.7	0.7	0.7	0.7	0.7
5284.1	4743.6	4463.3	4897.5	5725.4	6318.0
3.3	3.0	2.8	3.0	3.5	3.7
1.83	1.69	1.62	1.65	1.73	1.84
0.157	0.157	0.157	0.157	0.157	0.157
0.163	0.163	0.163	0.163	0.163	0.163
0.03	0.03	0.03	0.03	0.03	0.03
0.2	0.2	0.2	0.2	0.2	0.2
0.001160188	0.001160188	0.001160188	0.001160188	0.001160188	0.001160188
0.00043547	0.000470361	0.000491277	0.000481211	0.000461152	0.000432917
0.163	0.163	0.163	0.163	0.163	0.163
1.8	1.8	1.8	1.8	1.8	1.8
0.157	0.157	0.157	0.157	0.157	0.157
0.03	0.03	0.03	0.03	0.03	0.03
0.3	0.3	0.3	0.3	0.3	0.3
0.2	0.2	0.2	0.2	0.2	0.2
5	5	5	5	5	5
0.002544147	0.002544147	0.002544147	0.002544147	0.002544147	0.002544147
0.000479996	0.000534688	0.000568267	0.000526273	0.000459468	0.000425157
0.16	0.16	0.16	0.16	0.16	0.16
1.8	1.8	1.8	1.8	1.8	1.8
0.2	0.2	0.2	0.2	0.2	0.2
0.3	0.3	0.3	0.3	0.3	0.3
0.001127348	0.001127348	0.001127348	0.001127348	0.001127348	0.001127348
1.4	1.4	1.4	1.4	1.4	1.4
0.008928571	0.008928571	0.008928571	0.008928571	0.008928571	0.008928571

2983	2983	2983	2983	2983	2983
10654	8586	9688	12185	16653	20714
5621	4547	5141	6514	8989	11114
19259	16117	17812	21682	28625	34811

December

16
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4.4
40
13
0.0237

0.71
13,675,214

0.076
0.7

6621.1
3.9
1.78

0.157
0.163
0.03
0.2
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0.000447652

0.163
1.8
0.157
0.03
0.3
0.2
5

0.002544147
0.000405694

0.16
1.8
0.2
0.3
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1.4
0.008928571