Design of an Anaerobic Digester in Quebec, Canada

by

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ABSTRACT

In response to the future Quebec, Canada regulations prohibiting landfilling of organic matter by 2020, EBI, a waste management company located near Montreal is considering constructing an anaerobic digester. This thesis focuses on designing a scalable prototype based on the waste types available from the existing facilities of the company and the Montreal area. Based on an extended literature review and a feedstock analysis realized for this project, the study covers the elements composing an anaerobic digestion facility, the design criteria and calculations as well as a preliminary cost assessment and scalability strategy to help EBI realize the project.

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This thesis is dedicated to my grandfather, Victor Haï Hayat z"l, I miss you and I hope I make you proud.

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1 THE COMPANY AND PROJECT BACKGROUND

1.1 INTRODUCTION

Covering almost 1.4 billion square kilometers,[1] Quebec is the largest province of Canada located in the eastern part of the country. Its land area is the equivalent of about seventy times the size of Massachusetts,[2] but the population is only over 8 million people.[3] Quebec faces similar challenges to the rest of North America in terms of consumption lifestyle resulting in high production of waste per capita – 746 kilogram per capita and a total of 5.4 million tons of waste needed to be eliminated from the entire province in 2011.[4] The provincial government is aware of the problem and has set up regulations to reduce the quantity of eliminated material.

One of the objectives of the regulations is relatively ambitious: landfill of putrescible organic matter will be prohibited by 2020.[5] However, as of 2012 only about 5 % of the households have access to organic waste collection and very few services exist for institutional, commercial and industrial sectors.[6] Two main solutions are envisioned to fulfill the future regulation: composting and anaerobic digestion, though incineration and micro-fuel cells are also options. In Chapter 1, the company EBI is initially described with an evaluation of the environmental, economic and social constraints specific to Quebec. Then, the three organic waste management options competing in the province are covered which are landfilling, composting and anaerobic digestion. Incineration and micro-fuel cells are possible options. However, incineration is covered in the introduction as it is commonly used in Europe but micro-fuel cells are not considered applicable in this case. The overview includes a description of the processes, the factors of influence, a historic review and current units in operations. Based on the information provided, the organic waste management methods are compared and analyzed. The chapter concludes with recommendations on the optimal option.

The aim of this project is to assess the viability of treating organic matter in Quebec from the company EBI's standpoint. This thesis initially includes an overview of methods listed above with an emphasis on anaerobic digestion and a focus on the design of the anaerobic digester. The

[1] Statistics Canada, 2012a
[2] World Atlas
[3] Statistics Canada
[4] Recyc-Québec 2013, 14–15
[5] Direction des matières résiduelles et des lieux contaminés, Service des matières résiduelles 2012, VII
[6] Direction des matières résiduelles et des lieux contaminés, Service des matières résiduelles 2012, VIII– IX

feedstock analysis and the life cycle analysis (LCA) are covered in two other theses.[7] Note that Chapter 1 and Chapter 2 were co-authored.

1.2 INFORMATION ON EBI

EBI is a family business founded in 1960 in Canada with the mission to integrate waste management. The company collects and transports all the wastes of municipal, commercial and industrial sectors, sorts them and disposes of them in the best possible manner using very performing and up to date infrastructures.

Given all the different facilities already owned by the company, constructing an anaerobic digester is of high interest. As illustrated in Figure 1, the site contains many interconnected plants such as a landfill, a wastewater treatment plant, a composting platform, a biogas purification plant and more. Therefore, constructing an anaerobic digester enables the company to push integration of waste management further. This project aims at helping the company get an additional amount of biogas to its natural gas plant.[8]

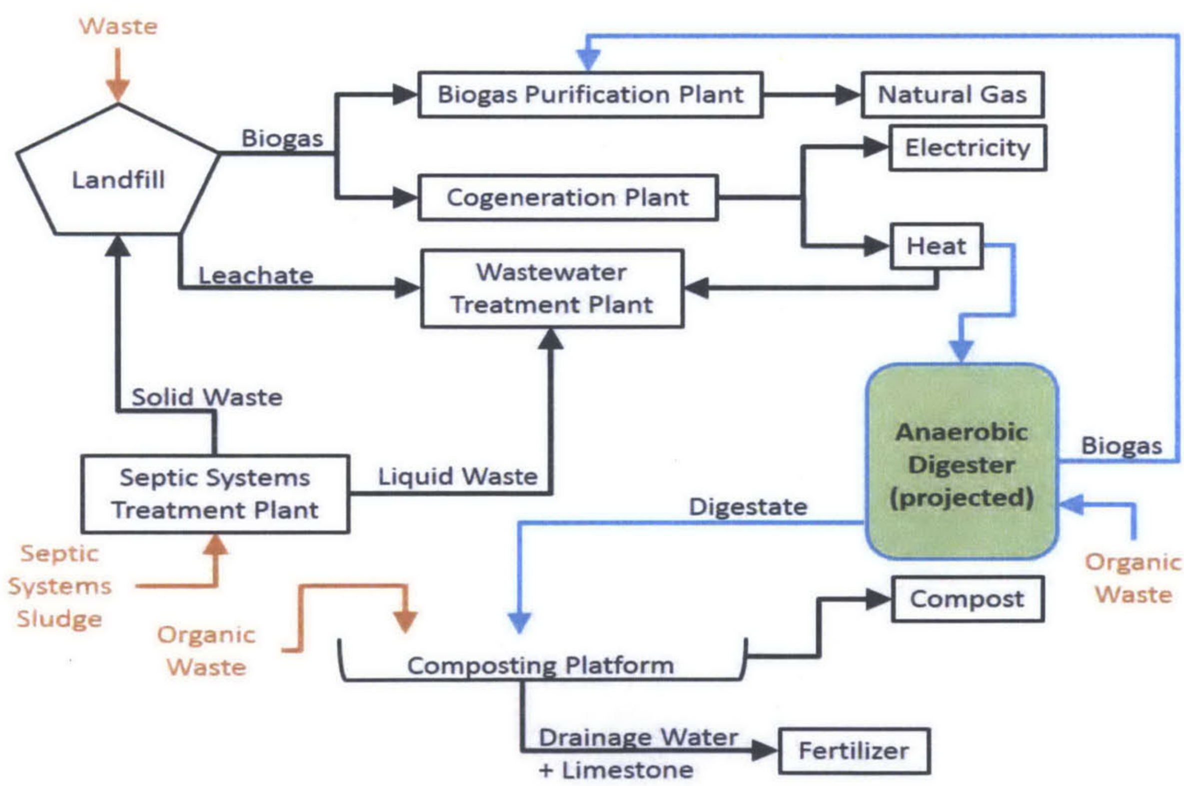

Figure 1: Schematic diagram of the projected anaerobic digester in the existing infrastructures

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[7] Sylvestre, 2014 and Wilson, 2014

[8] Groupe EBI, 2010

Fulfilling the regulation explained earlier for Quebec by 2020 is another reason for EBI to start to explore anaerobic digestion. Moreover, as mentioned previously, this projected plant has the potential to increase the usage of its existing facilities. Additionally, the present infrastructures of the company and the electricity situation in Quebec bring the potential for the digester to run on green energy and to produce energy, heat as well as fertilizer. Finally, EBI currently receives sludge from food industries that is thickened with wood chips and used to produce compost, which is a costly and ineffective process. It is relevant for the company to explore whether anaerobic digestion is more suitable and profitable to treat that kind of material.

The anaerobic digester represents a source of revenue for the company. In order for the project to be interesting for EBI, the investment has to be as low as possible combined with the highest potential biogas production.

1.3 QUEBEC'S SPECIFIC ASPECTS

The province of Quebec has several particularities needing consideration in the evaluation of the management of organic waste. These elements are split into environmental, economic and social aspects and explained below.

1.3.1 Environmental aspect

Quebec's territory is distinct; it is very large but most of the population lives in its South portion, mostly along the Saint-Lawrence River. The largest city is Montreal and has territorial constraints by the fact that it is located on an island. The entire metropolitan area counts over 3.5 million people.[9]

Obviously, Quebec is a Nordic area with a relatively cold climate. Temperature may vary from 30°C during the summer to -30°C during the winter. It is an important component to incorporate in the analysis of the management of organic waste. Just like in a refrigerator, the bacteria responsible of the transformation of the matter stop working at cold temperatures. Heating has to be planned if a plant operating all year is desired.

1.3.2 Economic aspect

The province has a unique economic landscape. In the 1960s, the provincial government decided to develop hydroelectricity in the northern part of the territory where many rivers flow and few people live. As a result, 96% of the electricity currently comes from hydropower, which is a

[9] Population by Aboriginal group, by census metropolitan area 2006 Census", Statistics Canada, http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/demo64a-eng.htm, viewed on 10/20/2013.

renewable energy.[10] In addition, electricity produced in large hydropower plants has a significantly low cost making Quebec the place where electricity is the cheapest in North America.[11] Figure 2 illustrates a comparison of the price of electricity in various cities in North America. Moreover, electricity production, transmission and distribution are a monopoly owned by Hydro-Quebec, which has the government of Quebec as its only shareholder.

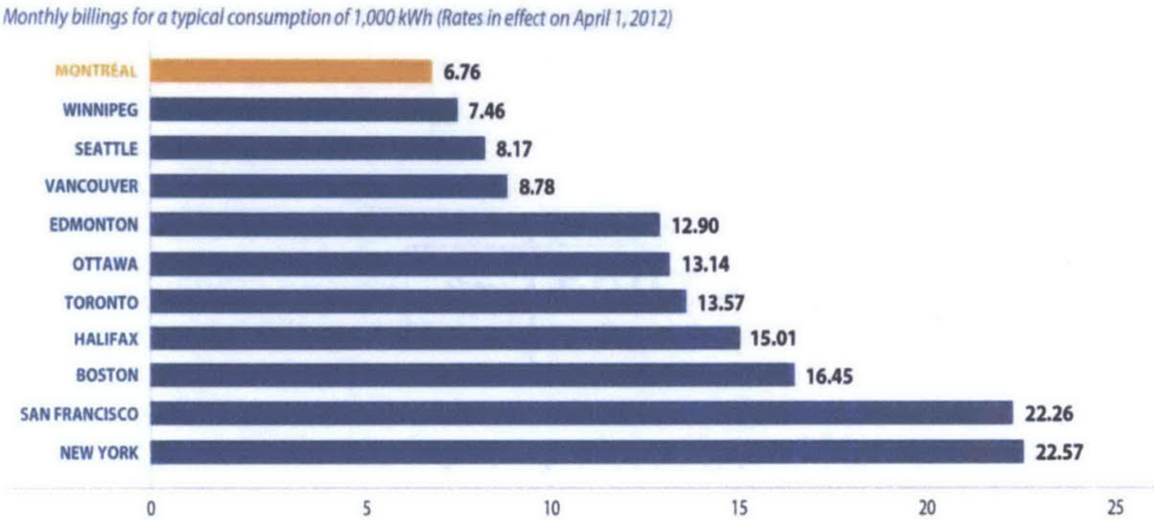

Figure 2: Average prices for residential customers in North American cities (¢/kWh)[12]

1.3.3 Social aspect

As shown by the political decisions of Quebec's government, the population is getting more concerned by environment. The province aspires to reduce its ecological impact on the planet and the proper management of organic waste is one way to reach this goal.[13] However, its implementation has to be done with respect to people in order to make it successful.

[10] "Electricity Generation", Hydro-Québec, http://www.hydroquebec.com/about-hydro-quebec/our-energy/hydropower/pdf/presentation-generation-comments-june-2013-en.pdf, viewed on 10/30/2013, p. 11.

[11] Hydro-Quebec, 15

[12] "Electricity Generation", Hydro-Québec, http://www.hydroquebec.com/about-hydro-quebec/our-energy/hydropower/pdf/presentation-generation-comments-june-2013-en.pdf, viewed on 10/30/2013, p. 15.

[13] Ministère du Développement durable, Environnement et Parcs du Québec. Banissement des matières organiques de l'élimination au Québec : état des lieux et prospectives, 2012, Direction des matières résiduelles et des lieux contaminés, Service des matières résiduelles, p. VII.

2 WASTE MANAGEMENT OPTIONS

2.1 LANDFILL

2.1.1 Process

Landfills can be used as the sole waste treatment option, or used in conjunction with other options as discussed later. It is considered the status quo method. Anaerobic processes, a result of the depletion of oxygen in pockets of the waste, are the primary form of waste degradation in landfills.[14] Organic waste breaks down to release methane and carbon dioxide, while inorganic waste variably breaks down. For instance, sulfate produces a metal sulfide, which can then produce hydrogen sulfide under acidic conditions, a hazardous material. Liners, both natural and synthetic, are used in landfills to prevent the escape of hazardous materials.[15]

The two main concerns of landfills are the production of leachate and landfill gas. Leachate is collected via these liners and must be treated. Landfill gas, also known as biogas, is produced from the anaerobic processes and must be controlled to avoid health and environmental risks.[16] Biogas has to be collected and burned or used for energy production.

2.1.2 Factors influencing the process

The major factor influencing waste degradation in a landfill is the type of waste that is deposited in it. While the aerobic aspect is influenced by the amount of oxygen, the anaerobic processes are responsible for most of the degradation. Generally, the factors influencing a landfill are similar to those of an anaerobic digester, which is discussed in depth later.

2.1.3 Historic review

Though disposal via landfill has been the primary waste management since humans' beginnings, formal landfills have come into play in the past two hundred years.[17] Until the 1970s, the perspective of "dilute and attenuate" was used, allowing the leachate to be diluted by groundwater and attenuated as it travels down the layers of the landfill.[18] Containment has

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[14] Harrison, 1995, p. 51.
[15] Harrison, 1995, p. 57.
[16] Harrison, 1995, p. 60.
[17] Harrison, 1995, p. 43.
[18] Harrison, 1995, p. 45.

become the objective after this time, in which leachate is collected and treated, unless it is stored until better technology is developed for the treatment.[19]

In the 1980s, sustainable landfills became more common with the idea of pre-treating the leachate before storage.[20] Landfills are designed to anticipate an eventual failure and put measures into place to limit the risk of releasing leachate in the environment. More landfills are now increasingly sustainable by being integrated with other types of waste management as well as being linked with energy recovery.

2.1.4 Current operations

Landfills are in operation worldwide, being the oldest and most common method of waste management. The United States (US) alone has over 2,000 landfills in operation, with waste to landfills consisting of over 50% of the waste generated, at least from 2008 and before.[21] EBI has four main cells of landfills on its land. BFI Canada has been in operation in Quebec as well for the past 25 years.[22] Their landfills operate with energy recovery, much like EBI. Many other companies manage landfills all around Quebec.

2.2 AEROBIC DIGESTION (COMPOSTING)

2.2.1 Biological process

The process of composting is characterized by the degradation of organic matter by a consortium of microorganisms with oxygen. Its main environmental advantage is to produce carbon dioxide instead of methane, which contributes less to global warming. Feedstock may come from any of the agricultural, residential, commercial, institutional or industrial sectors. According to Luc Turcotte, from EBI, maturation of the material takes up to six months. After that period, a material rich in nutrients like phosphorus, nitrogen and potassium is produced.[23] It can be used in agriculture or gardening as a fertilizer. To ensure a proper content of several components like nutrients, trace elements and pathogens, the compost produced has to be analyzed.[24]

During the process, heavily contaminated wastewater is produced which has to be collected and treated before it is released in the environment. It may also be mixed with limestone to increase the typical low pH of the wastewater to facilitate its use as a fertilizer in agriculture.

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[19] Harrison, 1995, p. 48.
[20] Harrison, 1995, p. 49.
[21] EPA, 2009
[22] BFI Canada 2012
[23] Direction des matières résiduelles et des lieux contaminés 2011, 2
[24] Direction des matières résiduelles et des lieux contaminés 2011, 3

Considerable odors are also released when composting. Depending on the neighbors and the winds, measures to control odors may be necessary.

2.2.2 Factors influencing the process

Aerobic digestion depends on numerous aspects, which mainly are the feedstock, temperature, pH, aeration and moisture content.[25] Feedstock, also called substrate, is fundamental to the digestion. Nutrient content and particle size dictate the process of aerobic digestion.[26] A high nutrient content with a high surface area fosters digestion by bacteria. Carbon, nitrogen, phosphorus and potassium are the principal elements processed by microorganisms.[27] In addition, the ratio of organic carbon to nitrogen is important to calibrate because bacteria need specific quantities of both.[28]

Composting produces high quantities of heat. Temperature can increase up to 90°C in certain cases. Even if pathogens and viruses are mostly eliminated at high temperature, very little digestion occurs above 70°C. The optimal temperature range for composting is between 30°C and 45°C.[29] Some methods exist to monitor and control temperature in a composting process. Heat extracted can even be used in other infrastructures.

The pH varies throughout digestion and is hard to control; nonetheless it remains an important factor. It tends to acidify at the beginning because acid is produced and increase towards the end. The most efficient range is between 5.5 and 8.0, but in general bacteria prefer a neutral pH.

As initially mentioned, aerobic digestion is characterized by the presence of oxygen. Therefore, aeration needs to be provided to the system to prevent degradation from becoming anaerobic. Pile turning is a direct but inefficient way to aerate; ventilation provides guaranteed results.[30] A lot of research and development has been done on this aspect to optimize systems.[31] Ventilation can also provide temperature and moisture control. A positive correlation between temperature and oxygen demand exists.[32]

Balancing moisture content is crucial to the process. Indeed, microorganisms stop degrading organic matter under low humidity conditions. On the other hand, too high water content does not allow air to penetrate the substrate. During transformation, it is possible to monitor moisture

[25] Diaz et al. 2007, 49–56
[26] Diaz et al. 2007, 49–50
[27] Diaz et al., 2007, p. 50
[28] Diaz et al., 2007, p. 51
[29] Diaz et al., 2007, p. 53
[30] Diaz et al., 2007, p. 55
[31] Diaz et al., 2007, p. 54
[32] Diaz et al., 2007, p. 55.

content and add water if needed. At the end of the degradation, humidity of the compost has to be lower, approximately at 30%, to make sure it is biologically stable.[33]

2.2.3 Historic review of composting

Prior to 1950, there was only a very basic understanding of the composting process, but no real large-scale practical application existed.[34] According to Golueke, Sir Albert Howard developed one of the first composting systems intended for hygiene purposes for sewage water in India in the early 20th century.[35]

During the 1950s and early 1960s, research investigated composting as a way to enhance the quality of soils and a pilot scale experiment was made at University of California. Europe performed research more aimed towards survival of pathogens and their potential impacts on health. During that period, high hopes existed that composting would be an economically viable waste management solution. However, poor implementation of the process brought results below expectations.[36]

A significant increase in research on composting occurred in the 1970s.[37] The process was well understood and further study was conducted on specific aspects of it. Still, its development was slowed by unfavorable economic returns. The 1980s saw three large-scale projects fail in the US mostly due to poor siting and incorrect design, which resulted in odor problems.[38]

2.2.4 Current operating composting infrastructure

Many composting infrastructures are in operation worldwide. The present section is a brief overview of these projects with specific attention to Canada and the US.

EBI currently operates a platform used to transform organic matter into compost.[39] Most of the inputs are leaves, grass, wood chips and several residues from food industries. Even though the facility is located in a low population density area, odors are monitored and appropriate guidelines are usually met. However, the compost produced has a relatively poor quality due to the presence of non-organic contaminants like plastic residues, which reduces its value. Another similar open-air composting facility is operated by the city of Guelph in Ontario, Canada where odor emissions became a problem.[40] Due to complaints from neighbors, the plant had to stop

[33] Diaz et al., 2007, p. 57
[34] Bertoldi, 1996, p. 5
[35] Golueke, 2009, p. 28
[36] Golueke, 2009, p. 28
[37] Bertoldi, 1996, p. 9
[38] Bertoldi, 1996, p. 10
[39] Dépôt Rive-Nord 2010
[40] City of Guelph 2012

receiving organic waste for a certain period of time and a plan on odor management had to be developed before being allowed to treat material again.[41]

In Western Europe, specifically in Germany, successful covered composting plants exist both in rural and in urban areas, which relies on a strategic location.[42] A covered plant is located in Brampton in Ontario, Canada. It appears to be successfully operating with a 60,000 tons per year capacity.[43] Moving to a larger scale, Edmonton, Alberta has a plant treating municipal organic waste along with sewage sludge with a capacity of 200,000 and 25,000 tons per year respectively.[44] Also with an annual capacity of over 200,000 tons, a privately owned composting plant is located in Wilmington, Delaware. The treatment is partially indoor and covered during outdoor maturing.[45]

2.3 INCINERATION

2.3.1 Process

Incineration involves the combustion of waste to reduce its overall volume being landfilled. There are four steps to incineration: drying, pyrolysis, gasification, and combustion.[46] Drying removes a majority of the water vapor from the waste, while pyrolysis is for more specific types of waste, such as plastics, rubber, sewage sludge or wood, thermally decomposing these wastes. Gasification produces carbon monoxide, hydrogen and methane, which are flammable gases that under combustion produce carbon dioxide and water vapor.[47]

Dust, HCl, HF, SO_2, NO_2, Hg, dioxins and furans make up the majority of the emissions from incineration, as well as fly and bottom ash. Dust must be removed from the flue gas, with nearly a 100% removal rate required by regulations.[48] All of the emissions must be removed with at least a 95% removal rate, and an addition of scrubbing processes may be needed to neutralize acid gas.[49] Bottom ash and fly ash are separated out, either for use in construction as a replacement material in such goods as concrete or to be further treated to remove volatile metals.[50]

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41 City of Guelph
42 Diaz et al., 2007, p. 95
43 BioCycle 2010
44 City of Edmonton 2014
45 Environmental Protection 2011
46 Buekens, 2012, p. ix.
47 Buekens, 2012, p. x.
48 Buekens, 2012, p. xiii.
49 Buekens, 2012, p. xv.
50 Buekens,, 2012, p. xi.

2.3.2 Factors influencing process

Temperature is a major factor during incineration, reaching between 750°C and 1200°C where the higher temperatures are for hazardous waste.[51] Residence time is also a factor, at only a few seconds compared to days in other types of waste management. The third main factor, turbulence, fosters the interaction of oxygen with the combustible materials to increase the reaction rate.

2.3.3 Historic review

Incineration always includes an aspect of energy recovery, primarily in the form of heat.[52] Traditionally, it has been one of the three major options for waste management, which are landfill, composting, and incineration. It mainly aims at the reduction of the waste volume, especially in areas where land is highly valued for other purposes. Global regulations restricting landfilling of certain wastes appeared in the 1970s due to an increasing knowledge of the hazards of some materials.[53] Severe acute respiratory syndrome (SARS) is one of these hazards, known to result from incineration, especially of hospital waste.[54]

2.3.4 Current operations

Many areas worldwide incinerate waste to this day. In Europe, incineration of waste has been on the rise since the mid-1990s, going from 13% to 21% of waste incinerated.[55] China incinerates about 16% of its waste, while less than 5% of waste is incinerated in Canada, where this study takes place. [56,57]

2.4 ANAEROBIC DIGESTER

2.4.1 Biological process

Anaerobic digestion is the degradation of organic matter by a consortium of bacteria in the absence of oxygen. Just like composting, this process can be used to transform organic matter from virtually any sector. The main difference from composting is that methane is produced during the reaction, which has a good energy potential. This process is slow because the microorganisms need a large amount of energy in the form of heat and nutrients to degrade

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[51] Buekens,, 2012, p. xi.
[52] Buekens, 2012, p. xvi.
[53] Buekens, 2012, p. 1.
[54] Buekens, 2012, p. 2.
[55] GAIA, 2013
[56] Zhou & Chen, 2012
[57] Statistics Canada, 2012b

organic matter.[58] Degradation can be divided into four main steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis.[59] They are briefly explained below.

In simple terms, hydrolysis is the degradation of large molecules into smaller compounds, hydrogen, and acetic acid. During the second step, acidogenesis, the smaller molecules from hydrolysis are transformed into volatile fatty acids, hydrogen, and acetic acid.[60] Next, acetogenesis implies the complete transformation of volatile fatty acids into carbon dioxide, hydrogen, and acetic acid. Finally, hydrogen and acetic acid are both converted into methane during methanogenesis.[61]

2.4.2 Factors influencing the process

The quantity of biogas produced depends on numerous factors including concentration of microorganisms, type of feedstock, specific surface area of material, reactor type and its operation, light, pH and temperature.[62]

Bacteria responsible for degrading organic matter have a time of generation ranging from under twenty minutes to sixteen days.[63] For this reason, feedstock has to stay long enough in the digester to give time for microorganisms to be generated and degrade organic matter. A way to increase concentration of bacteria is to recycle biomass in the reactor. The type of feedstock used is fundamental to degradation. Microorganisms need various nutrients to pursue an efficient transformation. Lack of an element can compromise the process. Some feedstock can produce intermediate products like fatty acids that inhibit reaction. Also, the form of the input is important in the rate of the reaction; a higher surface area eases degradation.[64]

Three main types of reactors exist and impact the process, explained in greater details in the design section. They differ in the continuity of the system and it's mixing. Moreover, retention time influences the reaction because bacteria need to degrade organic matter, which is relatively slow, as mentioned above. Light acts as an inhibiter for microorganisms doing the transformation so it has to be avoided.[65] Furthermore, the optimal pH range for the degradation of organic matter is between 6.7 and 7.5.[66] Temperature determines the types of bacteria generated. The general principle is that higher temperature has an increased transformation rate. Psychrophilic digestion

[58] Tchobanoglous, Burton, & Stensel, p. 571–572.
[59] Cheng, 2010, p. 154
[60] Cheng, 2010, p. 154
[61] Cheng, 2010, p. 154
[62] Deublein & Steinhauser, 2011, pp. 112–127
[63] Deublein & Steinhauser, 2011, p. 113
[64] Deublein & Steinhauser, 2011, p. 115
[65] Deublein & Steinhauser, 2011, p. 123
[66] Deublein & Steinhauser, 2011, p. 125

is in the range of 10°C to 25°C and is known as a cheap and inefficient process.[67] Moderate temperatures of about 30°C to 37°C characterize the mesophilic process. This type of system is an interesting balance between rate of performance, initial investment, ease of implementation and stability.[68] Thermophilic digestion typically happens between 50°C and 65°C. The advantages of this degradation are the high rate of reaction and the removal of most pathogens and viruses. However, it is more sensitive to temperature variations, hard to start and requires high initial and operational costs.[69]

2.4.3 Historic review of anaerobic digesters

According to Cheng, the first anaerobic digester intended to produce energy was built in France in 1860. The first unit in the US was made in 1926. As the cheap price of fossil fuels limited the interest in the technology, North America and Europe did little work towards the development of anaerobic digesters until the oil-crisis in the US in the 1970s gave a second burst to anaerobic digestion, which only lasted during the crisis.[70]

Today, interest in all types of organic waste digestion is burgeoning due to the high price of fossil fuels and increasing environmental concerns. It is reported by Cheng that over 4,000 anaerobic digestion plants were in operation in Europe in 2005 producing the equivalent of 2.3 million tons of petroleum annually.[71]

2.4.4 Current operating anaerobic digesters

Numerous plants are operational in North America. A few are discussed in the following paragraph.

A facility with 35,000 tons per year capacity is located in Oakland, California reporting operating costs of about 40 to 55 US dollars (USD) per ton.[72] Biogas is used to produce electricity to fulfill the plant's needs and the surplus is sold to the local utilities. Water is partially removed from the digestate and it is either used as a fertilizer in agriculture or as a daily cover in a local landfill.[73] The city of Toronto, Ontario owns two anaerobic digestion plants, newly renovated in one case and newly constructed in the other.[74] Their summed capacity is

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[67] Cheng, 2010, p. 157
[68] Cheng, 2010, p. 158
[69] Cheng, 2010, p. 161
[70] Cheng, 2010, pp. 152–153
[71] Cheng, 2010, p. 153
[72] ILSR, 2010, pp. 5–6.
[73] ILSR, 2010, p. 5
[74] City of Toronto 2014

110,000 tons annually and the city plans to expand to 180,000 tons per year.[75] They treat municipal organic waste collected through a large municipal initiative.[76] Based on analysis from the city of Toronto, operational costs used to be 90 Canadian dollars (CAD) per ton but are estimated to decrease to 69 CAD per ton with the new plants.[77] Very recently, a large-scale organic waste digester started to operate in London, Ontario.[78] It has an annual capacity of about 65,000 wet tons and an electricity production of approximately 2.8 MW. The project is economically viable, but strict constraints have to be met. According to Alex MacFarlane from Harvest Power, the company owning the digester, electricity has to be sold at over 0.13 CAD per kWh and the company has to charge over 45 CAD per ton to collect the feedstock. The same company operates a large composting facility in Richmond, British Columbia where the first commercial high-solids anaerobic digester was installed in parallel with a composting facility. The anaerobic digester can transform 30,000 tons per year.[79]

2.5 COMPARISON OF THE METHODS

Once the organic waste treatments available to EBI are explained as well as the constraints that apply to Quebec, it is important to compare them in order to make the optimal selection. Regarding landfilling, it is the cheapest and the most common option. However, the regulation prohibiting landfilling of putrescible organic waste by 2020 in Quebec indicates to EBI that an alternative has to be sought. The two other realistic avenues are composting and anaerobic digestion. Table 1 is a brief summary of the main aspects involved in these organic waste treatments.

Table 1: Quantified aspects of composting and anaerobic digestion

Aspects	Composting	Anaerobic Digestion
Investment	~450 CAD/T[80]	300-900 CAD/T[81]
Maturation	Up to 6 months	15-60 days
Operating cost	~80 CAD/T	45-70 CAD/T[82]
Output value	Low	High

[75] ILSR, 2010, p. 7
[76] City of Toronto 2014
[77] ILSR, 2010, p. 8.
[78] "Anaerobic Digest," 2013
[79] Harvest Power, 2013
[80] Office of the City Auditor, Edmonton Composting Facility Review, Edmonton, 2003, p. 1.
[81] Institute for Local Self-Reliance, Update on Anaerobic Digester Projects Using Food Wastes in North America, United States, 2010, Division of Sustainability City of Atlanta, Georgia, p. 8.
[82] Institute for Local Self-Reliance, Update on Anaerobic Digester Projects Using Food Wastes in North America, United States, 2010, Division of Sustainability City of Atlanta, Georgia, p. 8.

Note that incineration was only briefly introduced and therefore not taken into account in this table. Also, it is important to note that the investment cost for composting solely comes from the facility in Edmonton and might not be representative of all composting plants. In the case of anaerobic digestion, a high variability is observed. In both methods, the investment needed is specific to each project and a realistic range of values is hard to provide. It is influenced by all the design factors explained previously.

There is a clear gap between maturation times for the two treatments. Anaerobic digestion is much faster. A composting plant needs a lot of storage to allow the material to mature during several months, which is costly.

Again, the operating costs present a great variability because they are specific to each project. But the two methods are of the same order and a clear difference cannot be established.

The output value favors anaerobic digestion because of the production of biogas. Both methods produce fertilizer and heat, which are useful, but have limited applications. However, biogas produced by anaerobic digestion represents a remarkable asset with a wide range of possible uses.

From the information summarized, no monetary advantage can be concluded for either treatment process. Nonetheless, maturation time and the value of the outputs are superior for anaerobic digestion compared with composting.

2.6 ANALYSIS

The current analysis critiques the information previously covered by raising uncertainties observed in the two methods and evaluating the barriers to success.

2.6.1 Uncertainties

The two different ways to treat organic matter rely on biological degradation done by different consortia of bacteria. They present numerous uncertainties, which may substantially alter the economic viability of projects. In the two cases, feedstock has a major influence on the outputs. Although industrial food waste may be relatively constant over the course of a year, household organic waste significantly changes from season to season, which impacts the performance of the process. Moreover, especially for composting, the presence of non-organic contaminants in the waste may reduce the retail value of the fertilizer produced. If originating from household organic waste, the compost depends on the good will of people to sort properly their organic matter, which is virtually impossible. Plastic bags or any other non-organic contaminants are always found.

Furthermore, anaerobic digestion's viability relies on the market price of other energies, which is hardly predictable but has a direct impact on revenues. Competing against natural gas is not simple because prices in North America are extremely low due to the extraction of shale gas in the United States. If this trend continues, it can possibly reduce the interest towards biogas.

On the economic side, the comparison presented before reflects the great range of investment and operating costs, which cannot be used to determine if a method is preferable. The economics are specific to each project and are barely comparable. For this reason, no monetary advantage is considered to any method.

Another uncertainty is the political position, which can imply favorable or non-favorable decisions. The renewable aspect of the two methods is definitely a great asset, but if it is too costly, odors are emitted or trucking causes noise or congestion, strict measures may be enforced.

From a plant size perspective, it is hard to determine if one large plant is preferable to many smaller ones. The first option certainly presents economies of scale during construction and operation, but the second option brings flexibility. Instead of building a large unit that will be used at its full capacity after a long period, building smaller plants over time has the capability to adapt to demand. Economies of scale have to be balanced against flexibility to identify which option is preferable for a given project. On the chemical side, it is unclear whether digestion is superior in one way or the other and it relies on the specific design of each facility.

From a technical point of view, it is hard to compare quantities of wastewater and heat produced by the two studied treatments. The amount of leachate depends on the difference of water content in the substrate between the beginning and the end of the treatment plus any water added to facilitate degradation. It may be assumed that open-air composting plants involve more wastewater treatment because of storm water. However, it is hard to handle leachate produced in a covered composting plant with an anaerobic digestion plant. The same difficulty applies to production of heat. These two factors may be highly variable and specific to each project.

2.6.2 Barriers to success

Currently in Quebec, the main barrier to success to treat organic matter is the lack of infrastructure to collect it. In order to achieve the ambitious goal of not landfilling organic waste by 2020, the government has to greatly incentivize cities and private companies to collaborate in the management of organic waste.

Also, the particular territorial limits of greater Montreal may cause problems to implement local treatment of organic matter. It may lead to the transportation of organic waste outside the metropolitan area to treat it, which represents accrued operating costs. The capability to efficiently control odors has the potential to counter the problem of installing an organic waste treatment plant in an urban area.

An additional barrier to success is the high competition the outputs face. The fertilizer produced is on the same market as chemical fertilizers, which are more expensive but more efficient. In the case of biogas, it competes against fossil fuels being cheap and abundant sources of energy.

Finally, another obstacle is the monopoly situation in the electricity sector. Companies are only allowed to sell electricity to Hydro-Quebec. Being an advantage on one side because cheap renewable electricity is provided, it limits the potential applications of biogas on the other side.

2.7 RECOMMENDATIONS

It is recommended that EBI favor anaerobic digestion over composting under certain conditions. First, the company needs to have a strong market evaluation of feedstock availability with great quality and in important quantities in the area of the plant. Second, the initial capital expenses have to be within the company's capabilities. Some non-organic contaminants in the substrate may have a considerable impact on methane production, which may involve pretreatment. Anaerobic digestion is favored over composting mostly because of the methane production. Even if it is a system initially harder to set up, it is a key factor in a society with growing energy needs

Now that an insight into all the possible waste management options has been given, the next chapter will focus on anaerobic digester unit.

3 DIGESTER UNIT

The next step is the design of the anaerobic digester. As explained earlier, the feedstock characteristics and the output are key to the design of the digester because the composition and amount of the material has a direct influence on the type of reactors and the digesters dimensions.[83] To design an anaerobic digester, characteristics such as dry matter content or even pathogenic risk are fundamental elements; the chemical and biological composition of the substrate even determines the construction materials needed to avoid corrosion.[84]

One of the key elements that needs to be understood is that the following design is for a prototype. This prototype allows the company to have a better understanding of the results such a facility would have as well as an idea of the investment required to construct it. This should help the company decide whether a larger scale digester is the right investment.

The digester is the heart of the plant; it is where the microbial activity takes place and the organic matter is transformed.[85] The plant design is a main step in the development of a digester; it contains the choice of the technology, the determination of dimensions and the plant layout. The final goal is to achieve an efficient installation, which allows for an optimal use of the available resources and has a progressive impact on the natural and social environment of the plant.

A common plant design is usually divided into six components: transportation, storage and pre-treatment, digestion unit, gas storage, pipework and armature, and finally gas transformation. This chapter focuses on the development of the digester unit.[86] Still, all the components will be explained here.

The digester unit is composed of many systems; each one of their functions and characteristics is explained below.

3.1 TRANSPORTATION SYSTEM

Prior to entering to the facility the waste has to be brought on site. The different transportation options are dependent on the substrate characteristics such as its location or its type. Considering the Group EBI's infrastructures, the substrate could be provided in two different ways. It could be waste collected from Montréal and its surroundings as is done now for the existing composting facilities. The waste would be transported to the site by trucks owned by the

[83] Wellinger, Murphy, & Baxter, 2013
[84] Riffat, 2012
[85] Wellinger, Murphy, & Baxter, 2013
[86] Wellinger, Murphy, & Baxter, 2013

company. The other possibility is to use waste that is produced on site, where transportation would also be needed but to a lesser extent.

The substrate can be liquid or solid. The phase has a considerable impact on the way the substrate should be transported.

EBI owns approximately 160 trucks, which are either tank trucks or garbage trucks. The tank trucks can be used to transport the substrate if it is liquid. These trucks commonly have a tank volume of 10000 to 15000 L. On the other hand, garbage trucks are also available and could be used if the substrate is solid. The volume of garbage trucks is 10 to 15 tons.[87]

Even though this part has been covered in the feedstock analysis, it is important to keep in mind the distance a truck travels when transporting the substrate, which should be as short as possible.

Due to the high number of trucks owned by EBI, availability is not a major issue. The company owns trucks operating on diesel or natural gas. The price of the use per hour for those is respectively $45 and $35, which is also an important factor. Both types are illustrated in Figure 3 and 4 below.

Figure 3: Garbage truck from site[88]

[87] "Groupe EBI" 2010
[88] "Groupe EBI" 2010

Figure 4: Tank truck from site[89]

Figure 5: Household waste[90]

3.2 PRETREATMENT FACILITY

Often substrates contain many undesired components especially in the case of household waste, which is usually made of a large quantity of plastic, glass and non-organic elements. It is usually composed of out of date food, rejected food batch from the food industry as well as kitchen or vegetables waste delivered both with and without packaging as illustrated in Figure 5.

Those elements have a direct impact on the process. They can inhibit the methane production considerably. There are many ways to deal with this issue. The most logical way would be selecting only organic waste. However, this is highly dependent on the stock availability. Another alternative would be to pre-treat the substrate and reduce the quantity of undesired

[89] "Groupe EBI" 2010
[90] EBI site visit, 2014

elements. This process is considered to be very expensive and should be avoided. Nonetheless, as stated previously, the stock availability can sometimes require pretreatment. The most common way to pre-treat is to add a hammer mill to the process that separates those elements from the substrate. Removing by hand cannot be taken into consideration due to the project scale as well as the liquidity of the feedstock. When using a separation hammer mill, the organic matter is reduced to a particle size of 3 to 6 mm and is collected into the storage tank. In order to keep the substrate liquid for it to be pumped, the separation hammer mill needs process water for the treatment of relative dry material. The process water consists mainly of rain and cleaning water and is fed according to the hammer mill requirement. A hammer mill representation can be found in Figure 6.

Pretreatment is also used to increase the biodegradability of different substrates. There are several pretreatment techniques available and usually these methods are divided into four categories: biological, chemical, mechanical and thermal treatment.

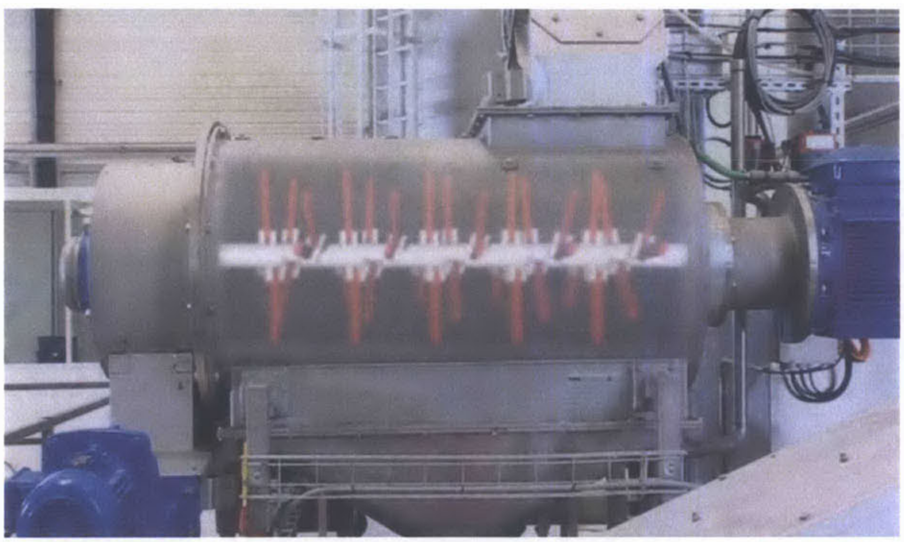

Figure 6: Hammer mill[91]

As an example, if the substrate comes from straw or wheat silage, it would be rich in lignocellulose, which is known to be extremely resistant to digestion. Therefore, a suitable pretreatment should aim to destroy the lignocellulosic structure, which releases the sugars contained in the biomass, making them available for the bacteria.

[91] Mabarex, 2014

Many technologies are available to destroy lignocellulosic structures such as the steam explosion and the extrusion. The steam explosion method combines high heating (240 C°) with high pressure (33 bar). The substrate is exposed to these conditions for 5 to 30 minutes, which hydrolyzes the glycosidic bonds present in the substrate. It is then cooled down, which causes the water to "explode" and opens the lignocellulose structure, enabling the biomass inside to be consumed by the bacteria. This has an impact on the substrate quality. In fact, the homogeneity of the substrate increases, together with an increase of the methane yield and the biogas production. In addition the anaerobic digest rate increases, which implies smaller reactors and lower investments.[92]

Another possibility is the extrusion method. In this pretreatment technique, the substrate is mechanically crushed through a double screw extruder. The lignocellulose becomes fibrous. The result is an increase of the substrates surface area. This surface area is directly and positively correlated to the enzymatic hydrolysis.[93] The advantages of this technology are the same as those of the steam technology discussed previously.

These two techniques should be used in the specific case of lignocellulose presence; many others are available dependent on the substrate characteristics.

3.3 FEEDING SYSTEM

The next process is the feeding system.[94] As shown in Figure 7, this system brings the substrate from the storage to the digester; it makes the transition from aerobic to anaerobic conditions. The sophistication of such a system is mostly dependent on the budget.[95] For example, it may possibly not only transport the substrate, but also include a mixing unit, milling, weighing or even feed-in control with full automation.

[92] Borgström, 2011
[93] Grethlein, 1985
[94] Wellinger, Murphy, & Baxter, 2013
[95] Schafer, Uhte, and Newman 2006

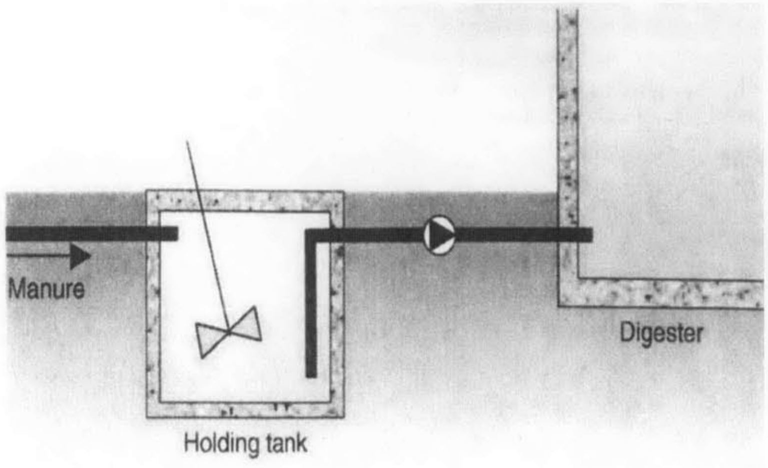

Figure 7: Feeding system[96]

It is important to remember that the feeding system, like any part of the digestion unit, is dependent on the feedstock, but also on the reactor type, which is explained later on.

There are two ways of designing a feeding system, which are by batch and by continuous flow.

In the case of batch systems the feeding is done in a discontinuous manner and wheel loaders generally do it. It is only done in the case of solid substrates. [97] Regarding the continuous systems, it is either continuously or semi continuously fed with different options for liquid and solid feedstock. If the substrate undergoes pre-treatment and its physical characteristics are altered, changes in the feeding unit can be required. [98]

In the case of liquid substrate, mixing has to be done before it enters the digester pre-pumping and it needs to be thoroughly mixed.[99]

In the case of a solid substrate, mixing is performed in the holding tank. However, an adapted pump is needed due to the material fluidity. One way of doing so is to feed the system separately through the sidewall or the ceiling of the digester. The advantage of such feeding is the avoidance of risks of clogging in the pumps and the possibility of changing the total solid concentration inside the digester. Interesting ways such as chute or flushing systems were used in

[96] Wellinger, Murphy, & Baxter, 2013
[97] Riffat, 2012
[98] Khanal, 2009
[99] Zupancic & Grilc, 2012

the past due to their low cost but they commonly involved temperature drop in the digester, perturbation in the system or odor emissions.[100]

Nowadays, two main systems are normally employed, which are the screw or piston system.

The screw conveyor system presented in Figure 8 goes through the ceiling or another part of the wall where the hydraulic pressure is not present. The disadvantage of this technique is that it causes abrasion due to long fiber substrate or impurities present in the feedstock.[101]

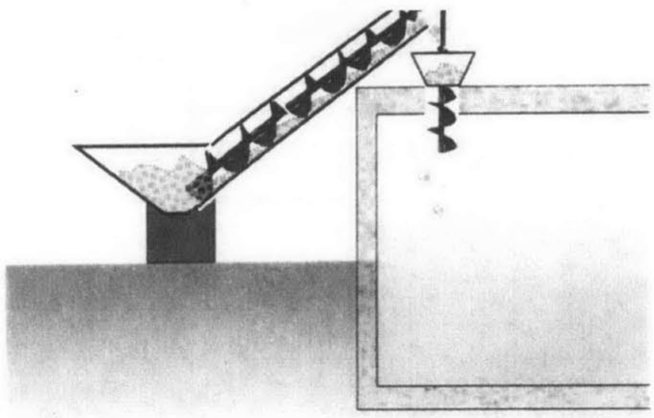

Figure 8: Screw conveyor feeding system[102]

The piston system, illustrated in Figure 9, involves having the substrate pressed through a delivery cylinder and into the digester. It is commonly located at the bottom of the digester using a hydraulic actuator. The disadvantage of this system is the compaction of the substrate by the piston force, which can make it less accessible to microorganisms.[103]

[100] Wellinger, Murphy, & Baxter, 2013
[101] Wellinger, Murphy, & Baxter, 2013
[102] Wellinger, Murphy, & Baxter, 2013
[103] Wellinger, Murphy, & Baxter, 2013

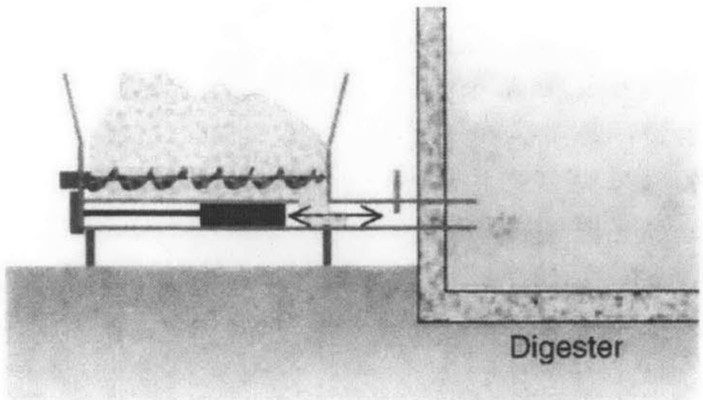

Figure 9: Piston feeding system[104]

In addition, the feeding system significantly influences the fermentation process. If sudden high loads, or abrupt changes in feedstock composition disturb the bacterial consortium, it results in a reduction of the gas production. Commonly, the optimal feeding is done in small doses with homogeneous mixing.

Next, the volume of the intermediate substrate storage has to be considered with a typical value of one to three days. The conveyance capacity has to be adapted to the substrate volume and the desired feed-in frequency. Automated storage systems also exist, which allows feeding during weekends and holidays.[105]

3.4 Reactor type

The forth part of the process, which is usually considered the most important part of the unit, is the reactor type.

The design of the reactors is determined on one hand by the feedstock characteristics as explained previously.[106] On the other hand, it is dependent on the feeding mode, which can be batch or continuous, and the mixing type, which is plug-flow or continuously stirred tank reactor (CSTR).

In the case of a batch reactor, the feedstock is exclusively solid, and since there is no mixing, the impurities or fibrous substrate do not disturb the process. Commonly, the microorganisms are distributed through water sprinkling from the digester ceiling, and wood chips and branches are integrated into the system in order to help efficient water penetration. The biogas production follows a pattern of an increase until it reaches a peak, where it starts decreasing and finally stops.

[104] Wellinger, Murphy, & Baxter, 2013
[105] Wellinger, Murphy, & Baxter, 2013
[106] Khanal, 2009

The ceasing point usually occurs when half of the stock is removed and it is common to keep it for the next batch. The retention time in the case of a batch reactor is 50% higher than in other types of reactor; the system is quite simple, and the energy consumption is low because of the high solid content. Another interesting asset of this method is the fact that undesired content such as metals in the substrate do not encroach on any of the moving parts due to the solid content. On the other hand, this method does not maximize the methane production.[107]

Regarding the continuous reactor type, two options are available: plug-flow and CSTR.

For the plug-flow system, the feedstock should have a high solid content. The entering substrate pushes the material through the digester, meaning there is minimal mixing, though some mixing is inevitable due to friction. Plug flow can only be achieved when the substrate mix has a dry matter content of 20%.[108]

In the case of the CSTR system, the dry matter content is usually under 15% and typically between 2-12% while under mixing. Commonly, the sludge retention time, which is the average time the liquid sludge is held in the digestion process, is around the same value as the hydraulic retention time. Also, its organic loading, which is defined as the weight of organic matter per day applied over a surface area, has a value of 1-4 kg VDM/ (day $\times$ m^3) where VDM represent the volatile dry matter. A CSTR system can be done in two steps but usually the majority, about 80%, of the biogas is produced in the first tank.[109]

In some plants with more than one digester tank, plug-flow digesters and CSTRs can be combined and substrates can go through one or both of them if their dry matter content and degradation rate fit the conditions.

3.5 Phase Number and Reactors Temperature Determination

The fifth part of the design of the digester unit is the number of phases. The main difference between a two-phase system and a one-phase system is that, in the case of a one-phase system, all the bacterial degradation happens in the same tank. It has the advantage of involving a low investment cost and a simple processing. The disadvantage lies in the fact that during the hydrolytic phase, the easily degradable substances produce large amounts of acids that inhibit the methane formation. On the other hand, a two-phase system separates the hydrolysis stage from the process since they are done in different tanks. In this case, the pH, temperature or retention time can be optimized for each phase. On the positive side, this system leads to a better

[107] Wellinger, Murphy, & Baxter, 2013
[108] Riffat, 2012
[109] Wellinger, Murphy, & Baxter, 2013

degradation kinetics and it has satisfying results in the case of high contents of sugar, starch or proteins.[110]

Temperature is an important factor because it has a big impact on many characteristics. As presented in Figure 10, there are different types of microorganisms growing at specific temperature ranges: the psychrophilic, which is from 10-25°C; the mesophilic, which is from 25-40°C and finally the thermophilic, which is from 45-58°C. Choosing a certain range has major impacts on the digester.[111]

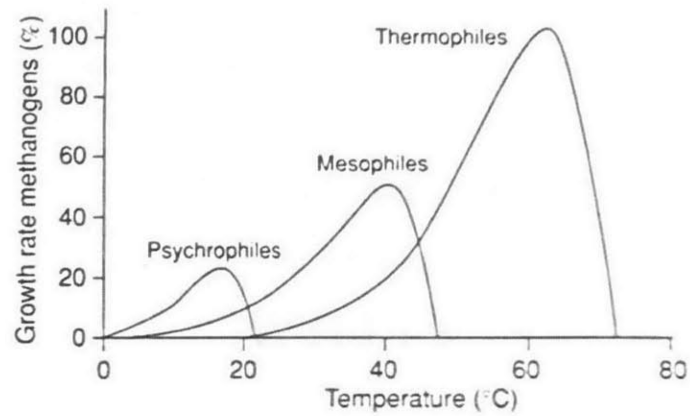

Figure 10: Relative growth rates of methanogens at different temperature ranges[112]

The first characteristic affected is the degradation rate. A high temperature allows a faster degradation of the organic matter. The second characteristic is the hygienization effect because higher temperature enhances inactivation of pathogens during the digestion. Using a thermophilic digestion can in some cases a feedstock pre treatment by hygienization. Another factor affected is the process stability where a higher temperature accentuates the sensitivity of the process to changes in temperature, pH and feeding rate. The increase of temperature favors the transformation of ammonium (NH_4^+) to ammonia (NH_3), which increases the risk of microbial inhibition.[113]

Finally, the last characteristic affected is the energy consumption, which tends to increase with temperature.

[110] Schafer et al, 2002
[111] Khanal, 2009
[112] Khanal, 2009
[113] Wellinger, Murphy, & Baxter, 2013

A large-scale anaerobic digester using psychrophilic temperature is not recommended. It is usually used in biogas plants without heating systems such as family size infrastructures. It is also used in developing countries. The degradation in those kinds of digesters is very slow. Typically, reactors at mesophilic temperatures are used due to their moderate energy demand and their satisfying retention time.

Plants can contain both a thermophilic and a mesophilic reactor, combined such that the substrate goes through the most appropriate one or sometimes both, depending on the pathogen risk and the degradation rate.[114]

3.6 REACTOR VOLUME DETERMINATION

The next part is the determination of the reactor volume. This step is adapted and linked to the amount of feedstock and the degradation rate. This process involves optimization of two key concepts, which are to give the microorganisms enough time to degrade and to control the concentration of organic matter. Overfeeding the digester has to be avoided because it can possibly inhibit the entire process.[115]

To define this element, two parameters are formulated: the organic-loading rate (OLR), which is the amount of volatile dry matter (VDM), and the hydraulic retention time (HRT).[116]

OLR is defined as:

$$OLR = \frac{Substrate\ input\ \left(\frac{kg}{day}\right) * DM(\%) * VDM(\%\ of\ DM)}{Digester\ volume\ (m^3)}$$

The OLR has units of $\frac{Kg\ VDM}{Day * m^3}$

HRT is defined as the theoretical time the substrate stays in the digester. It is also called the mean retention time. It is a theoretical value since it deviates, especially in reactors like CSTR where shortcuts may occur.[117]

The HRT must be chosen to allow degradation without increasing the reactor size too much. The total HRT is always more than ten days.

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[114] Bolzonella, et al., 2009
[115] Riffat, 2012
[116] Wellinger, Murphy, & Baxter, 2013
[117] Khanal, 2009

The HRT is defined as:

$$HRT = \frac{Net\ digester\ volume\ (m^3)}{Substrate\ input\ (m^3/day)}$$

The gas storage has to be taken into account when calculating the net digester volume.

When designing the digester, it is important to have targeted the kind of material and the protection, such as anticorrosion, needed to construct such a unit. An anaerobic digester is usually made out of concrete and steel. Reinforced concrete is used due to the high tensile strength of steel and the high compression strength of concrete.

Commonly, an appropriate concrete quality is made out of blast fumance cement with low lime content. This helps prevent corrosion and leaks in the digester. It is usually built with a small part in the ground but it can also completely be at ground level.[118]

Usually, the steel parts directly in contact with the corrosive fluid are required to be of stainless steel. If there are no risks of corrosion, glad-coated or galvanized steel are suitable.

Another important element of the design of the digester is protection. All the vulnerable parts of the reactor have to be protected by coating or liners in order to avoid corrosion; the substrate can contain aggressive substances such as ammonia, organic acids or microbes. These substances can disintegrate concrete or plastic.[119]

The zone of contact with biogas also requires protection. A plastic layer is generally used because it resists the small deformations or hairline cracks. Nonetheless, it is important to keep in mind that this material needs to be resistant to temperature variances and humidity.

Coating also has to be considered. Bitumen, polyurethane, polystyrene or epoxy are usually the materials used and they are applied by painting, spraying or by spatula. It must form a thick and completely covering layer.[120]

3.7 Insulation and Heating System

Another step of the design is the choice of the insulation and heating in the tank. Keeping a constant temperature in the reactor is essential for a stable digestion process. Therefore, it is common for a digester to be insulated and heated in order to compensate for heat losses. Another

[118] Wellinger, Murphy, & Baxter, 2013
[119] Cwalina, 2008
[120] Wellinger, Murphy, & Baxter, 2013

solution is to preheat the feedstock, which sometimes helps to avoid temperature fluctuation. Commonly, insulation layers are placed inside or outside the sidewalls and they are composed of wools such as glass, rock, or plastic. Organic materials such as cotton, coconut fiber or flax are also used but they are considered expensive.[121]

One of the goals is to optimize the thickness of the insulation layer with savings due to reduction of heat loss. The target values of heat transfer are:

0.3 W/m^2K for a mesophilic reactor

0.2 W/m^2K for a thermophilic reactor

Note that psychrophilic reactors are usually not used at this scale.

Optimization generally results in a thickness layer of 10 to 18 cm.

One of the common techniques to generate heat in the digester is passing hot water through pipes that are placed on the inside of the digester wall. The required heating power is mostly dependent on the digester temperature, volume, geometry and insulation.

To estimate the required power, three components are usually taken into consideration:[122]

The power for substrate heating:

$$P = R \times C \times \Delta T$$

R = feeding rate expressed in kg/s
C = specific heat, which in the case of water would be 4.186 J/(kg*K)
ΔT = temperature difference between the substrate entering and the digester in K

3.8 AGITATION SYSTEM

The agitation of the substrate is essential in the design for distribution purposes. Sometimes, it also helps to reduce the formation of floating materials or removing bubbles in the system. The agitation process is usually done at different intervals, which have a length and a frequency that are specific to each plant. Generally, intervals are initially long and frequent.

Three kinds of agitators exist: mechanical agitators, hydraulic agitators and pneumatic agitators.

Mechanical agitators, schematized in Figure 11, are usually paddles or propellers that create mixing by a rotational movement. Propellers are sometimes used in the case of liquid substrate

[121] Wellinger, Murphy, & Baxter, 2013
[122] Wellinger, Murphy, & Baxter, 2013

and paddles with high dry matter content. The three most common types of mechanical agitators are the rod mixer, which is used in CSTR digesters and when a low rotation per minute is desired; the submersible propeller agitator, which is also used in the case of CSTR digester until a temperature of 40°C; and the paddle agitator, which is commonly used in plug-flows with high solid concentrations. The main disadvantage of such agitators is their sensitivity to abrasion in the case of low solid content feedstock.[123]

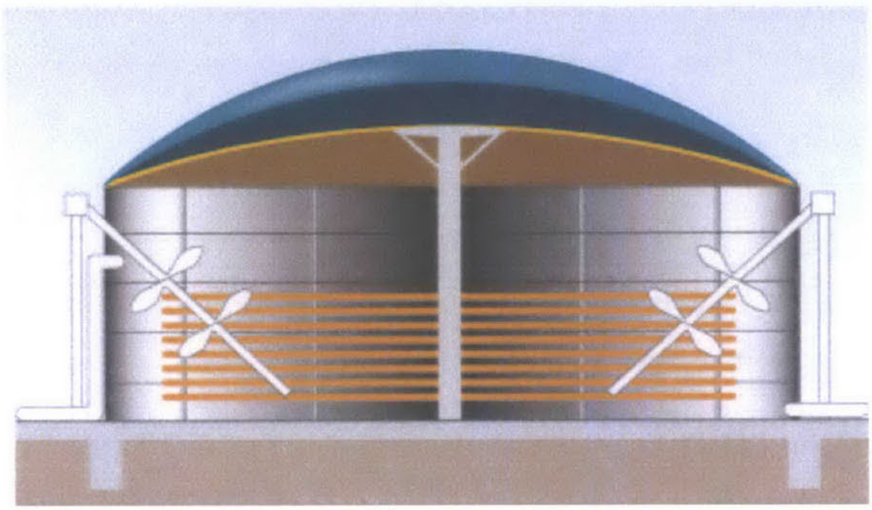

Figure 11: Mechanical agitation system[124]

As observed in Figure 12, hydraulic agitators are systems where a strong hydraulic current mixes the material. In this case a powerful pump is needed in order to withdraw the substrate from the digester and to return it via pressure through a nozzle, which can be done by the feeding system. The main disadvantage of this method is the high risk of clogging by too dense or fibrous substrates.[125]

123 Wellinger, Murphy, & Baxter, 2013
124 Çalli, 2013
125 Çalli, 2013

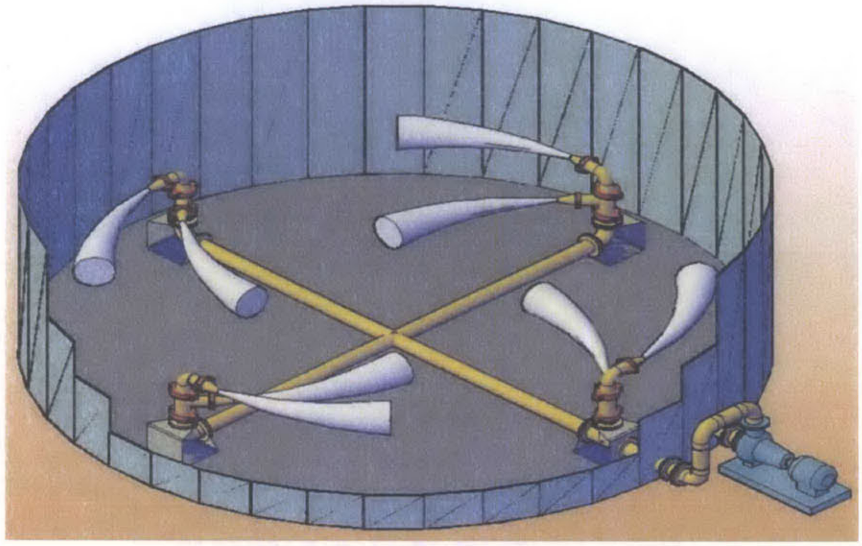

Figure 12: Hydraulic agitation system[126]

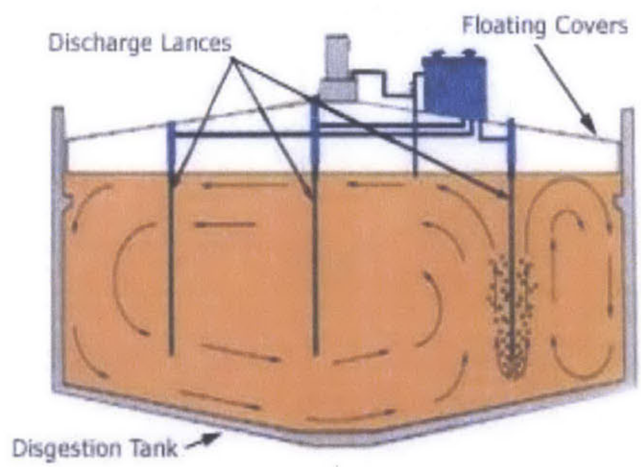

Figure 13: Pneumatic agitation system[127]

In the case of the pneumatic agitation systems as illustrated in Figure 13, gas is injected under pressure at the bottom of the digester and rising gas bubbles create a vertical movement in the tank, which mixes the material. This technique is efficient in the case of liquid substrates since the material is lighter.[128]

[126] Çalli, 2013
[127] Çalli, 2013
[128] Çalli, 2013

Last, it is important to know that fluctuations and peaks in biogas production commonly occur. Therefore, biogas needs to be temporarily gathered and stored before it goes into the transformation unit. Biogas storage needs to be addressed because it is usual to have a capacity of two to three days inside the digester. Storage is sometimes achieved by the addition of flexible membranes on the digester roof. The membrane needs to be resistant to pressure temperature variation or even UV radiation in the digester. Generally, the membranes are made of ethyl propylene dienemonomer (EPPM) and extend when the biogas production rate is greater than the storage capacity unit that follows the digester. Moreover, double membranes made of soft PVC may be used and an air blower between the two layers constantly inflates the outer membrane, protecting the inner membrane, which inflates and deflates with the gas volume.[129]

[129] Wellinger, Murphy, & Baxter, 2013

4 INSIDE THE DIGESTER

4.1 BACKGROUND

Prior to discussing the design of the digester, it is important to have a good understanding of the chemical process happening in anaerobic digestion. The biogas produced in digestion under anaerobic conditions is produced by at least three different groups of microorganisms: acidogenic bacteria, acetogenic bacteria and methanogenic archaea. [130] The process is summarized in four main steps, which are the hydrolysis, fermentation, anaerobic oxidation and methanogenesis, each having a major impact on the biogas produced and its quality. During each phase, those various microorganisms and a range of enzymes work symbiotically.

4.2 INSIDE THE DIGESTER

The first step, hydrolysis, is the process where complex organic materials such as carbohydrates, proteins or fat are degraded to smaller compounds such as simple sugars, amino acids, saccharides or fatty acids. The hydrolytic enzymes are usually the cellulases, amylases, lipases, and proteases that are secreted by the acidogenic bacteria, complete this entire process. The composition of the substrate has a major effect on the rate at which the organic matter is degraded. For example, when a substrate is rich in cellulose like straw or maize stalks, this step becomes limiting due to the resistance of cellulose to degradation.[131] The hydrolysis process is dependent on many of the substrate characteristics such as the particle size, the pH or even the production of enzymes.

The next step is the fermentation. During this phase the bacteria uses the produced compounds (i.e.: fatty acids, amino acids or sugars) as an energy source. This is then followed by the creation of alcohols, chain of fatty acids such as acetate, hydrogen gas or carbon dioxide.[132] This process is dependent on the interspecies hydrogen transfer, the pH and the hydraulic retention time.

Following that, the anaerobic oxidation process occurs. Long chain fatty acids and alcohol are oxidized by proton reducing acetogenic bacteria to acetic acid, H2 and CO2. One of the issues of

[130] Hans-Joachim, Winter, and Jordening, 2006
[131] Hans-Joachim, Winter, and Jordening, 2006
[132] Hans-Joachim, Winter, and Jordening, 2006

this step is the sensibility of acetogenic bacteria to high hydrogen pressure and their slow growing rate. This system is, however, balanced by the hydrogenotrophic methane forming archaea, which decreases the hydrogen pressure that the acetogenic bacteria increase.

The final step is the methanogenesis; it is the most important step in terms of methane production. The methane produced by methanogenic archaea uses acetate, carbon dioxide and hydrogen as carbon and energy sources.[133] Almost 65%-70% of the methane produced in the anaerobic digester comes from acetate. The methanogenesis is extremely dependent on the temperature, loading rate and pH fluctuations. It can also be inhibited by a number of organic and inorganic compounds. This process is summarized in Figure 14.

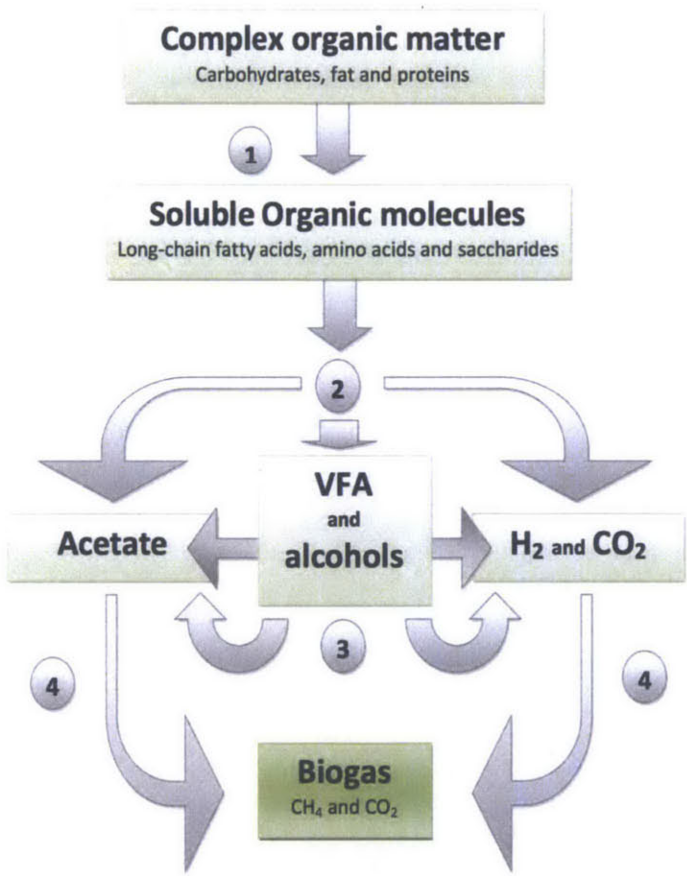

Figure 14: Illustration of the biogas process including the four steps: (1) Hydrolysis, (2) Fermentation, (3) Anaerobic oxidation and (4) Methanogenesis.[134]

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[133] Hans-Joachim, Winter, and Jordening, 2006

[134] Borgström, 2011

4.3 DESIGN CONSIDERATIONS

In order to ensure that the above processes are completed properly, stable process conditions must be established. The supply of nutrients and essential trace elements to the microorganisms involved in the processes is thereby a key factor.

In terms of nutrients, Liebig's law of the minimum governs the fermentation process. It states that if there is a deficiency in only one of the nutrients then the potential yield is not achieved, as this nutrient is a limiting factor.

The reaction cycle occurring inside the digester has major effects on the methane production. Therefore, it can have a considerable impact on the digester design. As stated earlier many of the steps are dependent on basic design criteria such as the temperature and the loading rate for the methanogenesis or the pH value and the retention time for the fermentation. These four steps must be performed in an optimal way to ensure the best methane production possible, which is the essence of this project.

As an example, if during the methanogenesis undesirable conditions occur in the bioreactor for the methanogenetic archaea, the hydrogen pressure drastically increases resulting in a negative effect on the acetogenic bacteria. This could lead to an accumulation of fermentation products such as the organic acid and could be followed by a pH drop.

This scenario may also occur if there has been an overload of substrate enabling the methanogens to consume all the hydrogen form. If such an event occurs, a couple of days are needed for the digester to return to its normal state.

5 DESIGN PROCEDURE

5.1 FEEDSTOCK ANALYSIS & STORAGE DETERMINATION

The characteristics of the feedstock mix are a key factor in designing a digester. Four mixes were selected for this project.[135] These mixes are used for the design that follows.

The mixes are combinations of liquid yeast, grease trap waste, food waste, poultry manure, whey permeate, waste activated sludge and dewatered septic systems sludge. The selected mixes are summarized in Table 2.

All these mixes could be used for the design of the digester. However, the solution decided upon was mix 3 and one of the following sections focuses on this mix.[136] This decision was based on a multi-criteria analysis as the mix generates high revenues joined with interesting suitability and digestibility. The six components of the feedstock are transported to the site and are kept in six different storage areas. Note that the mixes are numbered in a different manner than in the feed stock analysis study.

In order to have a better control over each substrate before mixing, each will be stored in a separated tank. The volume of each tank, being part of the general balance of the system, is determined below and included in the system diagram Figure 20.

The food waste is brought to site as illustrated in Figure 5 and will go through pre-treatment as explained in chapter 3, and will then be stored. The dosage of each component creates the final mix, which is introduced into the next step of the system.

There are various reasons that justify the choice to separate each component of the final mix in its own tank. For example, one tank could combine three of the components mixed together and if there happens to be a lack of one of the components for specific reasons, the mix could go completely wrong and have undesired effects on the methane production process. Also, having each component in its own tank enables the operator to adapt the dosage if needed.

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[135] Sylvestre, 2014
[136] Sylvestre, 2014

Table 2: Feedstock mixes

Mix	Type of Feedstock	Quantity (ton/year)
1. Food Waste, Dewatered Septic Systems Sludge and Grease Trap Waste	Food Waste	1,000
	Dewatered Septic Systems Sludge	200
	Grease Trap Waste	50
	Liquid Yeast	50
	Total Mix 1	1,300
2. Food Waste, Dewatered Septic Systems Sludge, Poultry Manure and Grease Trap Waste	Food Waste	1,000
	Dewatered Septic Systems Sludge	200
	Poultry Manure	100
	Grease Trap Waste	50
	Liquid Yeast	50
	Total Mix 2	1,400
3. Food Waste, Dewatered Septic Systems Sludge, Poultry Manure, Wasted Activated Sludge and Grease Trap Waste	Food Waste	1,000
	Dewatered Septic Systems Sludge	200
	Poultry Manure	100
	Wasted Activated Sludge	100
	Grease Trap Waste	50
	Liquid Yeast	50
	Total Mix 3	1,500
4. Food Waste, Dewatered Septic Systems Sludge, Poultry Manure, Wasted Activated Sludge, Grease Trap Waste and Whey Permeate	Food Waste	1,000
	Dewatered Septic Systems Sludge	200
	Poultry Manure	100
	Wasted Activated Sludge	100
	Grease Trap Waste	50
	Liquid Yeast	50
	Whey Permeate	10
	Total Mix 4	1,510

To calculate the volume of each storage tank, the density of each component is assumed to be around 1100 kg/m^3 as each mix has a solid content lower than 15% and has a density comparable to water.[137]

It is important to consider that each of the components is brought to site during the year at different rates. For example, the dewatered septic systems sludge is brought at different times within the year. As this project aims for a prototype, the amounts needed are always available. However, when scaling the project to full size, the substrate availability has to be taken into account.

The calculations lead to the amount stored:

$$\text{Mass}\left(\frac{\text{kg}}{\text{day}}\right) = \text{Mass}\left(\frac{\text{tons}}{\text{year}}\right) * \left(1000\frac{\text{kg}}{\text{ton}}\right)/365\left(\frac{\text{days}}{\text{year}}\right)$$

Note that the food waste arrives at the site and will go through pretreatment. Therefore there is a 10% loss of mass before going inside the digester.[138]

$$\text{Food waste mass after pretreatment}\left(\frac{\text{kg}}{\text{day}}\right) = 0.9 * \text{Mass}\left(\frac{\text{kg}}{\text{day}}\right)$$

Therefore, a certain amount of mass is assumed to be available and ready to be stocked per day for each component. Then, all mass was increase by a safety factor of 50%.

Using the assumption of $\rho = 1100\ (\frac{\text{kg}}{\text{m}^3})$:

$$\text{Volume}\ (\text{m}^3) = (\text{Mass real}\left(\frac{\text{kg}}{\text{day}}\right))/\ (\rho\left(\frac{\text{kg}}{\text{m}^3}\right))$$

Finally, in order to have realistic dimensions for construction purposes, each calculated volume was increased to a round number.

[137] Sylvestre, 2014
[138] Levis, Barlaz, Themelis, & Ulloa, 2010

All the results are illustrated in Table 3.

Table 3: Volume determination

Waste type	Mass (tons/year)	Mass (kg/day)	Mass assuming 50% more (kg/day)	Volume (m^3)	Final volume (m^3)
Liquid Yeast	50	137	205	0.19	0.25
Grease Trap Waste	50	137	205	0.19	0.25
Food Waste	1000	2740	4110	3.74	3.75
Poultry Manure	100	274	411	0.37	0.4
Dewatered Septic Systems Sludge	200	548	822	0.75	0.8
Wasted Activated Sludge	100	274	411	0.37	0.4

Assuming each storage unit is cylindrical, the volume is calculated by the following equation:

$$\text{Volume } (m^3) = \text{height } (m) * (\pi * R^2)(m^2)$$

Given the volume, the height and the diameter can be calculated as illustrated in Table 4.

Table 4: Dimension determination

	Height (m)	Diameter (m)
Liquid Yeast	0,35	1
Grease Trap Waste	0.35	1
Food Waste	0.8	2.5
Poultry Manure	0.6	1
Dewatered Septic Systems Sludge	0.5	1.5
Wasted Activated Sludge	0.6	1

Note that in this case, the storage dimensions selection does not follow any specific rules other than satisfying the volume needed.

The six storage units each contain a component of the final mix. This mix is created when all components are mixed together in the hydrolyzer, which is explained in the following section.

All the components are pumped, but it is important to understand that the system contains many pipes connecting each storage system to the tank. The pipework is approximated in the financial report. The inlet (feed) and outlet (discharge) pipes lead straight into the hydrolyzer at a steep angle. For liquid substrate, the pipe diameter should be 8-15 cm, while fibrous substrate requires a diameter of 20-30 cm. The inlet and the outlet pipe mostly consist of plastic or concrete.[139]

Every component is introduced in the hydrolyzer at a certain rate by a feeding system. The feeding systems can have a considerable impact on the process, as they influence the fermentation process. It is even more the case for a hydrolyzer as the steps consist in enhancing the fermentation. For example, if there are sudden high loads or abrupt changes, the bacteria consortium will be affected. This could lead to a reduction of the methane production. When designing the feeding system the feedstock and the hydrolyzer shape are the main parameters. Also it is important to keep in mind that all of the components that have a solid content play a

[139] Metcalf and Eddy 2002

determining role in the feeding system determination. If the solid content is lower than 15% then a simple pumping system will be sufficient; however if the solid content is higher than 15%, then a high dry matter method might be needed to introduce the component. As explained earlier, the feeding system makes the transition from aerobic to anaerobic conditions and its sophistication is budget dependent. The hydrolyzer type was decided to be a continuously stirred tank with a cylindrical shape.

Table 5: Solid content of each component

	Solid content (%)
Liquid Yeast	16%
Grease Trap Waste	15%
Food Waste	7%
Poultry Manure	18%
Dewatered Septic Systems Sludge	32%
Wasted Activated Sludge	5%

As shown in Table 5, three of the components have a solid content higher than 15 % and therefore a high solid content method is needed to introduce them into the system. As explained in chapter 3, in the case of a solid substrate, an adapted technique is needed due to the material fluidity. One way of doing so is to feed the system separately through the sidewall or the ceiling of the digester. The main advantage of such feeding is the avoidance of risks of clogging in the pumps and the possibility of changing the total solid concentration inside the digester. The most efficient method in our case is the screw conveyor feeding system, as the piston method reduces the substrate accessibility to the microorganism due to compaction. A screw conveyor is represented in Figure 15.

Figure 15: Screw Conveyor feeding two digesters.[140]

The two other components can be introduced in the system by a regular pump. The type of pump should be chosen depending on the flow of substrate it needs to pump on a daily basis.

5.2 DIGESTER UNIT DESIGN

5.2.1 Phase method determination & hydrolyzer characteristics

As discussed previously, the digester could go through either a single stage or two stages.

The single phased anaerobic digester is now considered the traditional process; it has been used for the past 80 years. It is cheap, simple and sufficiently efficient. It is characterized as a high rate process dependent on factors such as substrate's heating, secondary mixing and thickening.

[140] Maschinenbau, 2014

The sludge needs to be heated to achieve optimal results. An example of single stage anaerobic digester system can be found in Figure 16.

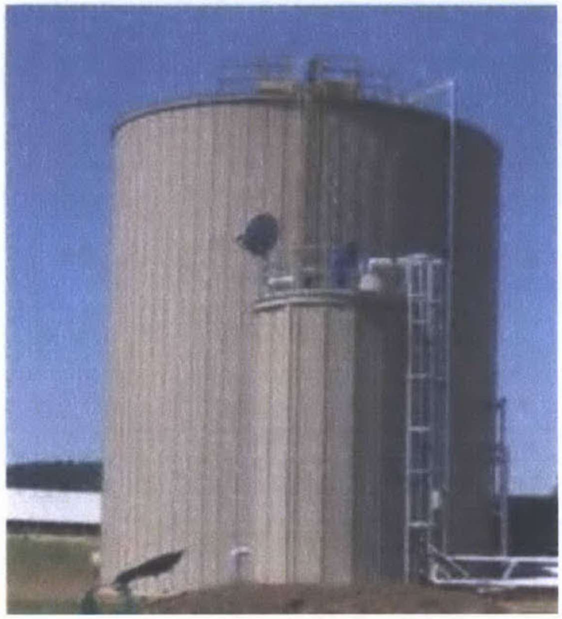

Figure 16: One phase anaerobic digester.[141]

Two-phase anaerobic digestion processes are proposed in the literature as a different approach with great efficiency enhancements in two categories: improved biodegradation rates and yields, and overall energy productivity. These enhancements are the result of the splitting of two main steps in the digestion process discussed previously: the hydrolysis and the methanogenesis. Splitting those processes affects the overall reaction rate, maximizes the biogas yields, improves the chemical oxygen demand reduction and gives better control of the processes. It also provides a better substrate conversion and an increase in the energy recovery. More importantly, this could provide stability to the process overall, avoiding overloading or inhibition of the methanogenic population by controlling the overall feeding or pH increase.

Two-phased anaerobic digestions could be done in multiple ways such as temperature-phased digestion, acid-gas phased digestion or staged thermophilic digestion. All these solutions will provide with different results depending on the desired enhanced parameters, such as a reduction

[141] Lazarus, 2013

in the energy needed, an increase in the methane production or the lowest retention time. Using a hydrolyzer also reduces the HRT of the digester by a considerable factor, as most of the fermentation process will not happen within the digester. A two-phase anaerobic digester is illustrated in Figure 17.

Figure 17: Two-phases anaerobic digester.[142]

On the other hand, splitting the system would require a higher investment. It also requires an increase in the land area for the project.

However in EBI's case, land is not a constraint. In terms of investment cost the control provided and the increase in efficiency are considerable enough to assume the two-stage is the most appropriate solution for a larger scale solution. Therefore, as the design of this smaller scale digester is a representation of what a considerably larger digester will produce, the two stages is the solution adopted.

The first tank in a two-phase system could take several forms. A simple way would be to have a reception tank where all the components are mixed together before entering the digester unit. Another method, which is the one that was chosen, is having a hydrolyzer. Typically, a hydrolyzer has a retention time of 3 to 5 days[143] with an OLR of 6 to 7 $\frac{Kg\,VDM}{day*\,m^3}$. It is in thermophilic conditions, meaning it has a set temperature of 55 C°. As explained previously, the

[142] Marshall, 2005
[143] Lemonde, 2014

purpose of this tank is to breakdown the molecules by enhancing the fermentation process, which happens faster at high temperature, meaning that it improves by a considerable factor the biodegradability of the substrate.[144] Also, while in the hydrolyzer, most of the pathogens within the substrate are destroyed due to the high temperature. The pathogens need to be destroyed for the biomass to be used as a fertilizer and it should satisfy the safety regulations of the country the digester is in. As the hydrolyzer design is dependent on the mass balance of the system, the final dimensions and flow are calculated as follows.

The flow in the hydrolyzer can be calculated as the sum of the flows from each component in the storage units.

$$Q_{\text{hydrolyzer}} = \sum_{i=1}^{5} Q_i = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6$$

Where each Q is summarized in Table 6

Table 6: Hydrolyzer flow calculation

Waste type	Mass assuming 50% more (kg/day)	Q (m^3/day)
Liquid Yeast (1)	205	0.19
Grease Trap Waste (2)	205	0.19
Food Waste (3)	4110	3.74
Poultry Manure (4)	411	0.37
Dewatered Septic Systems Sludge (5)	822	0.75
Wasted Activated Sludge (6)	411	0.37

144 Çalli, 2013

Therefore, the $Q_{hydrolyzer} = 0.19 + 0.19 + 3.74 + 0.37 + 0.75 + 0.37 = 5.61$ (m^3/day).

Assuming a retention time of 4 days, the volume of the hydrolyzer has to hold at least 4 times the Q since the system is continuous. Therefore, it should be at least 4*5.61 = 22.5 m^3. This is illustrated in Figure 18.

Note that the inflow of the food waste going in the hydrolyzer is smaller than 4110 m^3/day since 10% of the mass is lost during the pretreatment process.

Thus, a volume of 22.5 m^3 is assumed in order to standardize the dimensions. The final values are represented in Table 7.

Table 7: Hydrolyzer dimensions

Volume (m^3)	Height (m)	Diameter (m)
23	3.1	3.1

Note that Figure 18 is provided just to illustrate the total volume. However, in reality the digester first goes through the startup, which is covered in section 5.2.5.

5.2.1 Reactor shape determination

As previously explained the reactor determination is a critical part of the design. Retention time is usually the main design criteria; 15 to 25 days are recommended. One might also consider adding storage tank if stock availability requires.

Most anaerobic digestion tanks are cylindrical or egg shaped in Europe. In the United States the most common shape used is a shallow vertical cylinder as illustrated in Figure 19. In the following we will go through the advantages and disadvantages of each shape, which will lead to a final decision.

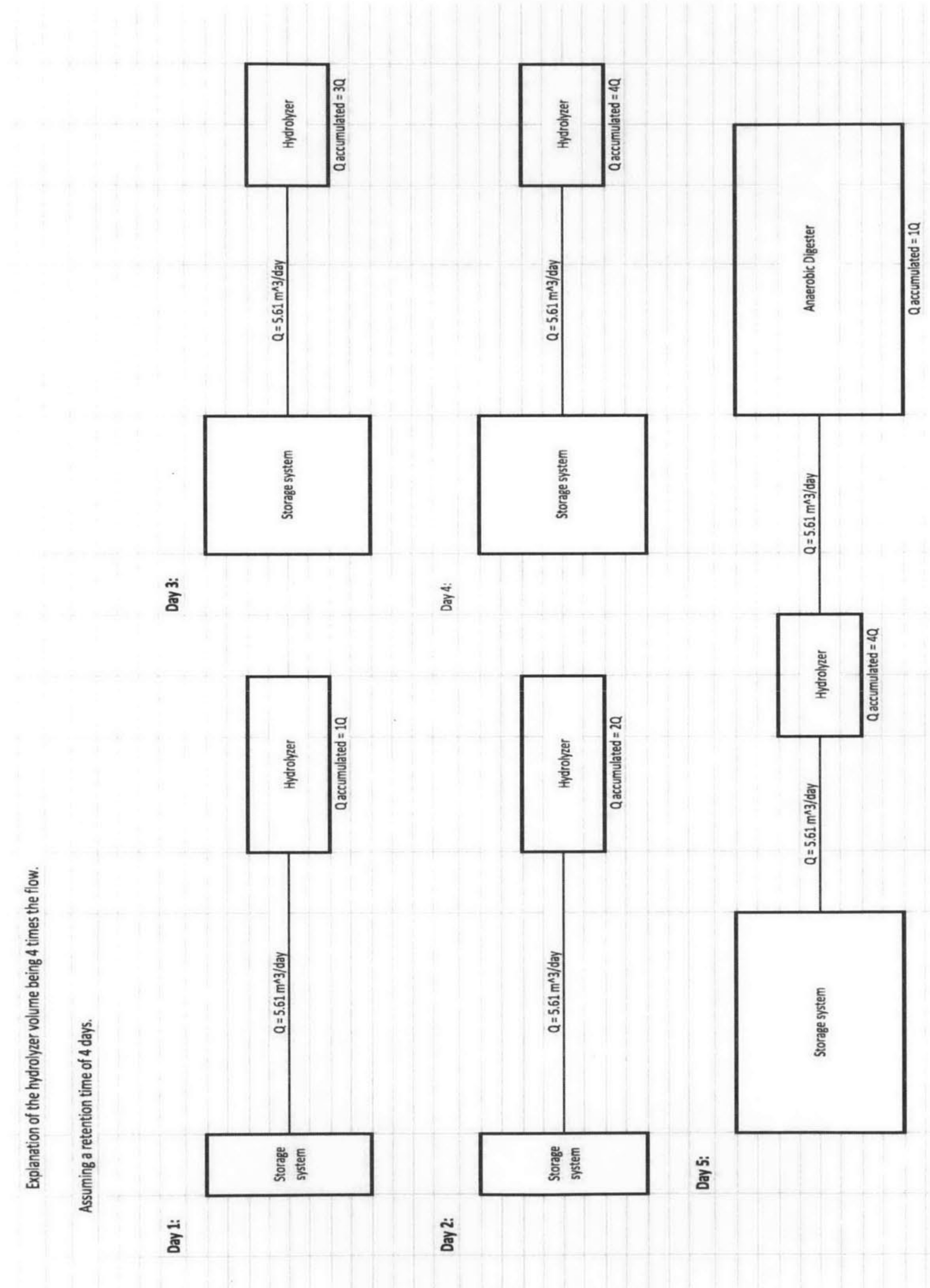

Figure 18: Hydrolyzer flow design

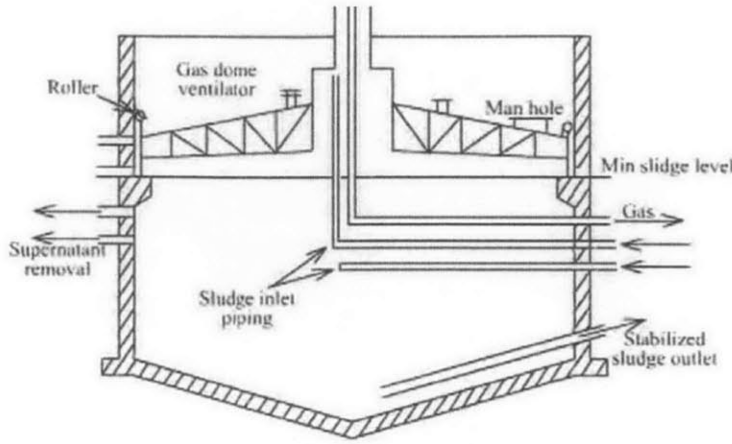

Figure 19: Example of cylindrical anaerobic digester.[145]

Cylindrical tanks are generally in a range of 6 - 38 meters in diameter. For mixing purposes, the tank depth should be greater than 7.5 meters at the sidewalls, which would increase the mixing difficulties, but less than 15 meters. At the bottom of the tank, the floor is usually conical having the bottom sloping to the center. The slope will usually range from 1 vertical for 6 horizontal to 1 vertical for 8 horizontal. One of the decisions made for the design was to have a 1 to 1 ratio between the diameter and the height of the digester.[146] There are many advantages of such a shape, such as the fact that the shape allows a large gas storage volume as well as the possibility of equipping such a shape with gasholder covers. Finally the construction techniques that can be applied when building such a digester are conventional. However, such a design also has disadvantages. The main one would be the inefficiency of the mixing system in the dead spaces, which are created by the shape, as well as the formation of scum and foam created by the large surface area. Finally, the cleaning required for removal of grit and scum accumulation could lead to having the digester out of service for a few hours.

Eggs shaped tanks are designed to considerably enhance the mixing and eliminate the cleaning needed from foam and scum formation. Typically the sides of such tanks will have a steep cone at the bottom to minimize the accumulation. There are also many other advantages, such as the

[145] NPTEL, 2013
[146] Lemonde, 2014

lower operating and maintenance cost or the smaller footprint leading to a reduced land area require. Nonetheless it will also have considerable disadvantages such as a small gas storage, which requires external gas storage or greater foundation design requirements. It will also have high construction costs and the difficult access to top mounted equipment, which would require a high stair tower or an elevator.[147]

One of the key inconveniences in opting for an egg shaped design is the lack of contractors with the capacity to build such a digester in North America. Therefore, for simplicity purposes and to have the ability to store the gas in large quantity, a cylindrical design is chosen. However this will imply having a consistent cleaning system to reduce the foam and scum accumulation. Nowadays, cylindrical digesters are the preferred models. The dimensioning of the digester is explained in the next chapter.[148]

The next important step is to determine the type of cover to allow gas collection. Even though it was briefly explained earlier, to finalize our design we need to choose which cover is the most adaptable to the digester. There are three types usually used: floating, fixed and membrane cover. Typically, floating covers fit on the digester's content surface allowing the digester's volume to change without allowing air intrusion. If air would enter the system, an explosive and very dangerous solution would be created. Floating covers could be used either for a single stage digester or in the second stage of a two-stage digester. Fixed covers are used to provide free space between the liquid surface and the roof of the digester. They are not commonly used, as they require having gas storage for the liquid volume to be changed as well as the need of a gas meter to measure gas produced due to the possibility of losing some gas if the storage is not provided. Finally the last cover available is the membrane cover. It consists of a support structure for a small center gas dome and flexible air membrane. It is made of flexible polyester fabric. It is particularly helpful due to the extension capacity of the membrane. However, the price of such a membrane is fairly high.

Therefore our final cover choice will be a floating cover due to its high utility and low investment cost.

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[147] Metcalf and Eddy, 2002
[148] Metcalf and Eddy, 2002

In the case of the reactor itself, pipework is also needed. As for the hydrolyzer, the pipework is approximated in the financial report. The inlet (feed) and outlet (discharge) pipes lead straight into the digester at a steep angle. For liquid substrate, the pipe diameter should be 8-15 cm, as the substrate is considered liquid. The inlet and the outlet pipe mostly consist of concrete in this case.[149]

A second feeding system is needed to get the mix to the digester unit. It is determined depending on the digester characteristics. As for the hydrolyzer, the determination of the feeding system has a considerable impact on the digestion process, as it will influence the fermentation process within it. Even though most of the fermentation was done within the hydrolyzer, some still occurs in the digester.

When determining the digester feeding system, the mix and the digester shape are the main parameters. The mix has a 14% solid content and the reactor type is decided to be a continuously stirred tank with a cylindrical shape. Regarding the feeding mode and mixing, feeding by batch is mostly used when the feedstock is greater than or equal to 20%. Therefore, in this case a continuous feeding mode is the optimal solution. It was also determined that the inflow of substrate will be continuous. Therefore, as the mixing is already done before entering the digester, a regular pump can feed the substrate as it is already homogeneously mixed. Finally, when determining which pump should be used, the flow entering the digester is an important factor.

Mixing is an important part of the process. There are many mechanisms that could be used for the continuous mixing such as by gas injection or mechanical pumping. However, as the project is about a smaller scale digester and the budget is limited, the most efficient mechanism is using a low speed turbine. This gives good efficiency results, although bearing failure could occur.

There are as two different mixing types: plug flow or continuously stirred tank reactor (CSTR). There are also two main types of feeding mode: by batch or continuous.

In general, a CSTR allows avoiding sludge accumulation, which will mean having a sludge retention time, which is the time required to achieve a certain amount of volatile solid

[149] Çalli, 2013

destruction, of zero days. However, if the feedstock contains sand there might be a need to clean the bottom of the tank. In fact, having no sludge accumulation is a considerable advantage, but the mixing type decision is mostly dependent on the solid content. The plug flow type is only used when the solid content is at least 20%. As every feedstock chosen has a solid content smaller than 15% the CSTR mode is the optimal decision.[150]

5.2.2 Temperature and alkalinity determination

Temperature is one of the most important parameters when designing a digester. It not only influences the metabolic activities of the microbial population but also has a considerable influence on parameters such as the biological settling of the tank, the rate of digestion or the gas transfer rates. Interestingly, the rate of digestion is different in every stage inside the digester such as in the hydrolysis or the methanogenesis. Note that, the temperature design establishes the minimal sludge retention time value.

Mesophilic digesters are considered to be the most cost effective investment. They satisfy the needs, perform well and are very popular among contractors. The energy needed to heat the system is also not excessive. Therefore it is assumed to be the best solution for this digester. Nonetheless, a combination of mesophilic and thermophilic digestion could potentially have better results and should be investigated for a larger scale digester. The temperature choice is also dependent on the energy consumption accessible. Typically, as explained before, the temperature that should be used is between 30 to 37C° the optimal temperature being 35C°[151]. However, if energy consumption needs to be lowered, a temperature of 32 degrees in the digester would have satisfying results. Also, the weather has an impact, as the heat loss needs to be compensated. Another very important step when designing an anaerobic digester is the capacity to maintain the tank at the temperature assumed for stability purposes. Most of the bacteria are thermosensitive especially methane formers where a change of 1C°/day may affect digestion performance.[152]

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[150] Sylvestre, 2014
[151] Lemonde, 2014
[152] Metcalf and Eddy, 2002

In general, alkalinity is not a concern in the digester design as it is more related to the reactions within the digester. However, determining the alkalinity of the system is part of the design as it is proportional to the solid feed concentration within the digester. It is defined as the sum of calcium, magnesium and ammonium bicarbonates concentrations present in the system. It is consumed by the carbon dioxide produced during the fermentation and the methanogenesis phases of the process. Therefore, the carbon dioxide concentration in the digester is directly correlated to the alkalinity. Typically a digester has an alkalinity of 2000 to 5000 mg/L and some additives such as lime or sodium carbonate can be added to provide control over the alkalinity. The alkalinity of this digester is assumed to be 3500 ml/l, which is a common and easily reachable value.

5.2.3 Unit layout

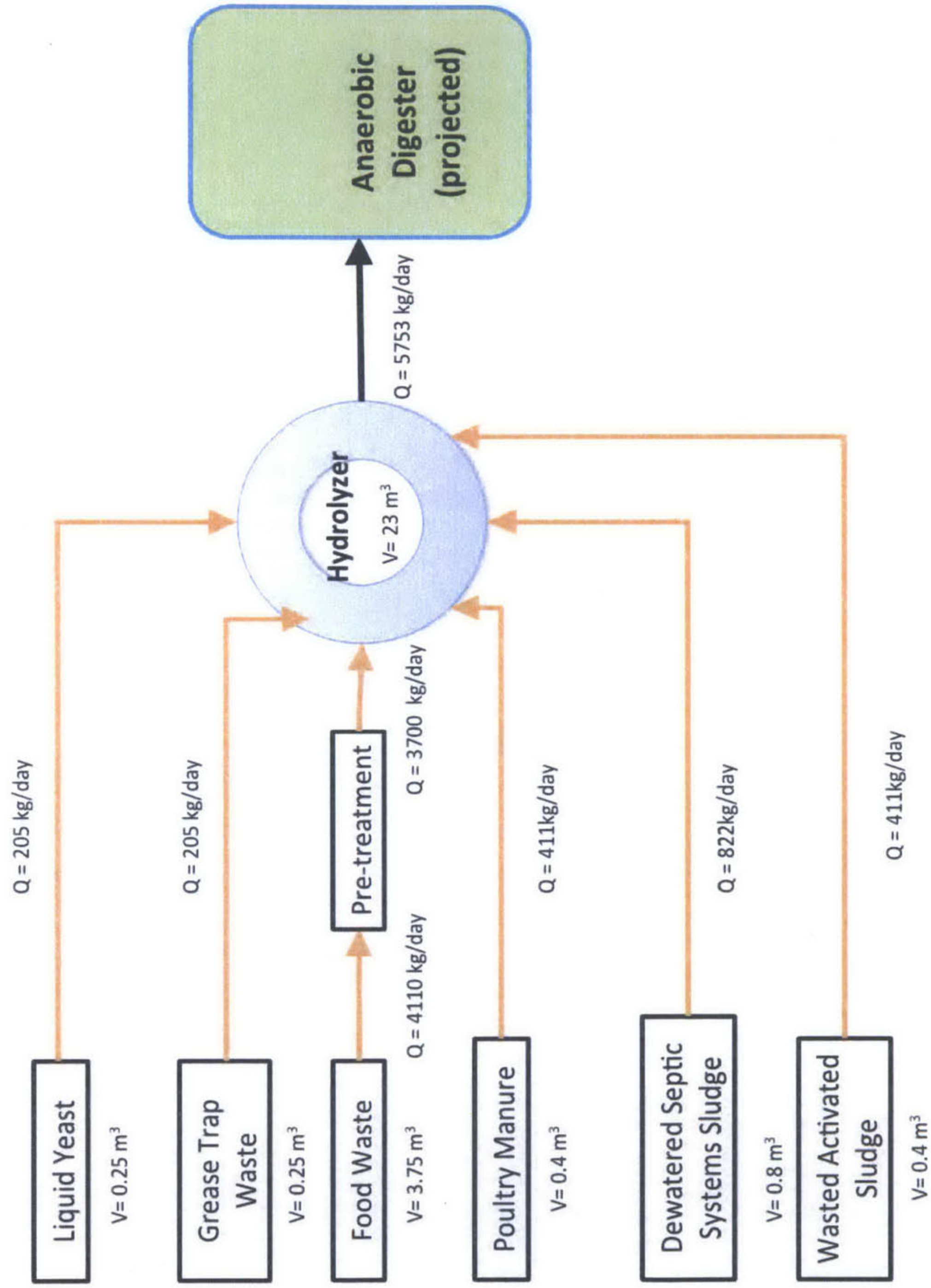

Figure 20: Hydrolyzer and storages layout

Figure 20 illustrate the system's layout prior to entering the anaerobic digester.

5.2.4 Startup step of a digester

The startup of the anaerobic digester is worth mentioning. The treatment of the organic waste is done by a consortium of bacteria, but none are present when feedstock is initially inserted in the digester. According to Gerardi, the startup operation has to be done gradually and may have a duration of approximately a month for a well-designed unit. This should be scalable depending on the digester's size. Monitoring and control of pH and alkalinity are very important for this stage; pH has to range between 6.8 and 7.2 during that period. If need be, it is also possible to seed bacteria in the digester to accelerate the startup. Gerardi suggests primary wastewater sludge or cow manure, which both present interesting bacterial assets. This initiating process is done when the biogas produced contains an acceptable fraction of methane and the conditions in the anaerobic digester are stable. [153]

Typically, in determining OLR, the digester is fed at a starting low OLR and its value is increased gradually until it reaches the desired value. It is common to increase the OLR by 0.5 $\frac{Kg\ VDM}{day * m^3}$. Starting the process with a high OLR could lead to a disaster in terms of bacteria consortium, meaning bacteria will not grow and the digester will be out of service. When reaching the desired value, the consortium of bacteria is formed the startup process is complete, a steady state is reached.

Once the startup of the unit is completed, a close monitoring of the internal environment is still necessary. Regular measurements of numerous parameters are useful to understand and control efficiently the operations: temperature, pH, alkalinity, total solids, volatile solids, C/N ratio, the evolution of COD during digestion, secondary products like volatile fatty acids, hydrogen and ammonia, metals and biogas production and composition.[154] Indeed, analyses have a cost, but the capacity to continuously optimize the anaerobic digester represents a great potential. To implement such an optimization, a proper framework is needed to understand the internal environment of the unit and perform adjustments on a continuous basis.

Note that the startup step should also be done for the hydrolyzer.

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[153] Gerardi 2003, 81–84

[154] Wellinger, Murphy, and Baxter 2013, 231

5.3 DESIGN CHARACTERISTICS FOR THE CHOSEN MIX

The next step is the dimensioning of the reactor. The mix chosen by the multi-criteria analysis is 4.[155] It is the most stable solution with high digestibility, suitability as well as a high diversion of waste. Also, this combination generates high revenues joined with interesting suitability and digestibility. The composition of the mix is illustrated in Table 8.

Table 8: Chosen mix

3. Food Waste, Dewatered Septic Systems Sludge, Poultry Manure, Wasted Activated Sludge and Grease Trap Waste	Food Waste	1000 (ton/year)
	Dewatered Septic Systems Sludge	200 (ton/year)
	Poultry Manure	100 (ton/year)
	Wasted Activated Sludgc	100 (ton/year)
	Grease Trap Waste	50 (ton/year)
	Liquid Yeast	50 (ton/year)
	Total Mix 3	1500(ton/year)

Other mixes could be suitable when it comes to design but mix 3 gives the best results. It is important to understand that the availability of each component is key to this design. When taking the prototype to a higher scale, stock availability should be ensured.

5.3.1 Solid content and density determination

The solid content was stated to be 14% earlier. However, it is important to understand how it was calculated. Table 9 illustrates the volatile solids percentage and Mass input of each waste type.

Table 9: Solid content composition

Waste type	Volatile Solids (%)	Mass (ton/year)
Liquid Yeast	$VS_1 = 18$	$X_1 = 50$
Grease Trap Waste	$VS_2 = 15$	$X_2 = 50$
Food Waste	$VS_3 = 10$	$X_3 = 1000$
Poultry Manure	$VS_4 = 19$	$X_4 = 100$
Dewatered Septic Systems Sludge	$VS_5 = 38$	$X_5 = 200$
Wasted Activated Sludge	$VS_6 = 5$	$X_6 = 100$

[155] Sylvestre, 2014

The solid content was calculated by doing a weighted average considering each component:

$$\textit{Solid content}\ (\%) = \frac{X_1 * VS_1 + X_2 * VS_2 + X_3 * VS_3 + X_4 * VS_4 + X_5 * VS_5 + X_6 * VS_6}{X_1 + X_2 + X_3 + X_4 + X_5 + X_6}$$

Therefore the solid content found was 14%, which means the substrate is a liquid substrate. The solid content is dependent on the mass input of component. If the inputs are changed for any reason then the solid content could vary. As explained before, only under a certain value of the solid content can a regular pump be the best technique to pump. Therefore, the solid content should be maintained fewer than 15%.

The density is also a key concept in the volume calculation. Because the substrate is a mix of different components with varying densities it was assumed for the purpose of this project that the density should be slightly above the density of water as it has a solid content lower than 15%. Therefore it was assumed to be:

$$\rho = 1100\ \frac{kg}{m^3}$$

This assumption is reasonable. However, as the density influences the reactor's volume by a considerable factor, a more detailed analysis and calculation of the density could improve the accuracy of the result.

The organic-loading rate (OLR) was defined as the weight of organic matter per day applied over a surface area. The design is dependent on the OLR as it is used to find the hydraulic retention time. The method used in this project is to set the OLR to a certain acceptable value such as 5 $\frac{Kg\ VDM}{day * m^3}$ and determine the appropriate HRT.

5.3.2 Volume and hydraulic retention times determination

Following the determination of the OLR, the volume can be calculated. The mix characteristics are illustrated in Table 10.

The volume can be calculated by using the following equation:

$$\textit{Digester volume}\ (m^3) = \frac{\textit{Substrate input}\ \left(\frac{kg}{day}\right) * DM(\%) * VDM(\%\ of\ DM)}{\text{OLR}((\text{kg VDM})/(\text{day} * m^3))}$$

Table 10: Chosen mix characteristics

Mass (ton/year)	1500
Mass (kg/day)	4110
pH	6.2
Dry Matter (%)	14
Volatile Solids (% of DM)	78
Density (kg/ m^3)	1100
OLR ((kg VDM)/(day* m^3))	5

This leads to a volume of 90 m^3. A safety factor is always of use in these cases as the substrate could stay more time within the digester or the flow could change. Therefore a 20% safety factor was assumed leading to a volume of:

$$Digester\ volume\ (m^3) = Real\ Digester\ volume\ (m^3) * 1.2 = 108\ \mathrm{m}^3$$

Following the reactor's volume determination, the HRT can be calculated:

$$Hydraulic\ Retention\ Time\ (days) = \frac{real\ digester\ volume(m^3) * Density\ of\ solution\left(\frac{kg}{m^3}\right)}{Mass\ input\ \left(\frac{Kg}{days}\right) *}$$

Therefore, the hydraulic retention time is 25 days. However, it is important to remember the hydrolyzer is part of the system enhancing fermentation. A good assumption is a reduction of time from the digester of 7 to 10 days. For conservatism, a reduction of time of 7 days is assumed leading to an HRT within the reactor equal to 18 days.

5.3.3 Comments on chosen solution

The design of the reactor is summarized in Table 11.

Table 11: Design summary

Dry Matter (%)	OLR((kg VDM)/(day*m³))	Volume (m³)	Real Volume (m³)	HRT (days)
14	5	90	108	18

The next step is to design the dimensions of this digester. As for the hydrolyzer a 1 to 1 ratio between the diameter and the height is assumed.

Given the volume of the reactor and the shape assumed cylindrical, the dimensions can be calculated:

$$V_{Cylindrical}\,(m^3) = \pi * Radius\,(m)^2 * \text{Height (m)}$$

Finally the dimensions calculated are shown in Table 12.

Table 12: Reactor dimensions

Final volume (m³)	Height (m)	Diameter (m)
108	5.2	5.2

5.3.4 Unit layout & after the digestion process

When sketching the second part of the unit layout including the anaerobic digester, it is important to take into account the next step, which is the gas and fertilizer storage. As explained before, parts of the incoming substrate are in the gas state and others in the solid state, typically with 5% gas and 95% of solids. The gas produced is the biogas and should be stocked in the appropriate storage facilities. The solid part is the fertilizer, if it satisfies the regulations, and should be stocked until it is sold for agricultural purposes. A representation of the digester can be found in Figure 21.

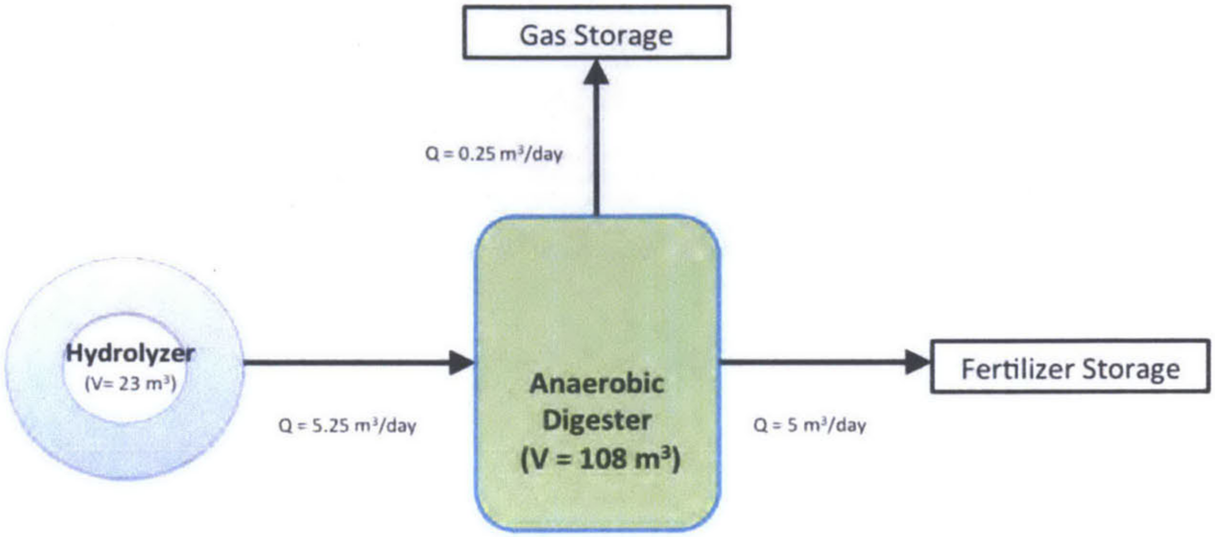

Figure 21: Anaerobic digester representation

6 DESIGN FINALIZATION

6.1 DIGESTER UNIT SUMMARY

Figure 22 represents the life cycle of the substrate within the digester unit from collection to its final form.

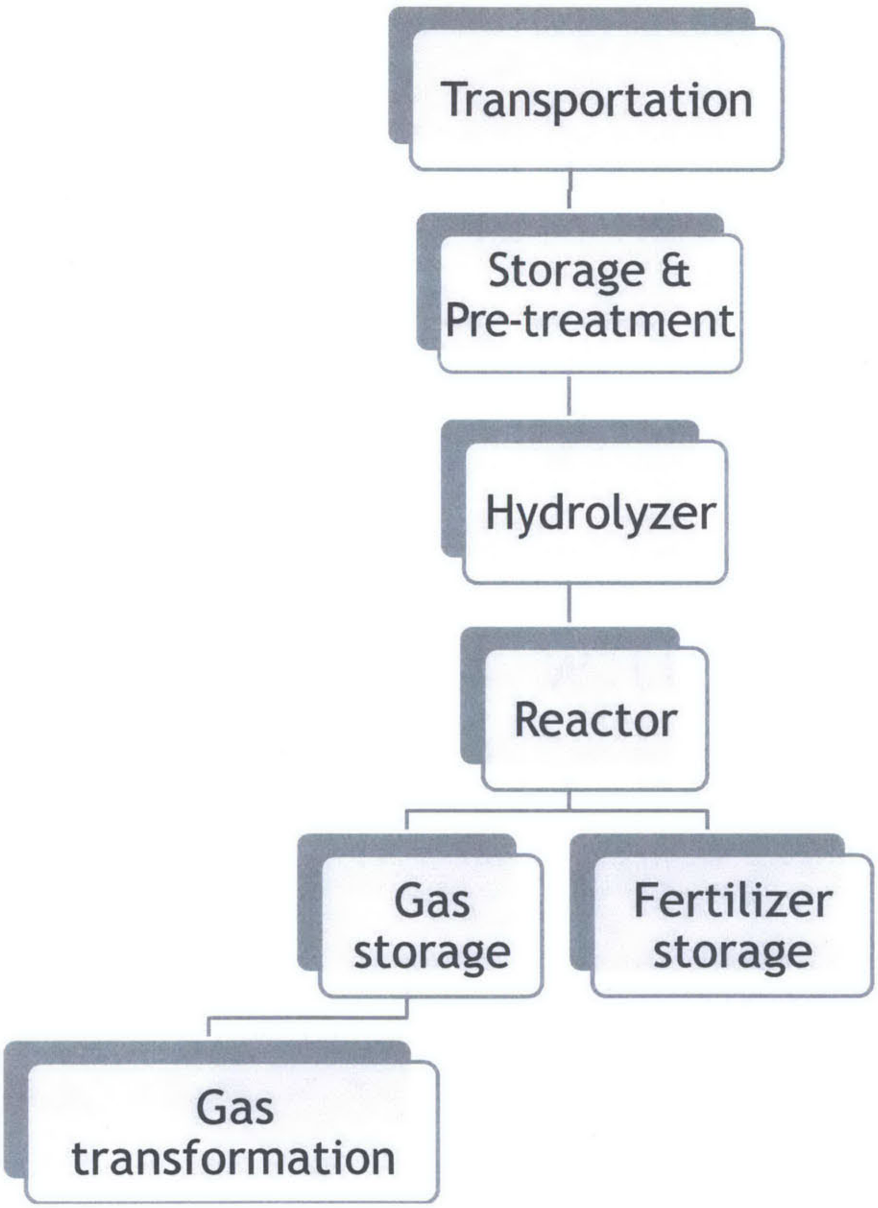

Figure 22: Substrate life cycle in the system

Before showing a final infrastructure layout it is important to recall all the important calculations done in the previous sections.

Table 13 illustrates the volume calculated for each waste type tank. Note that the dimensions are not calculated, as there are no specific rules for the design of these storage tanks.

Table 13: Storage summary

Waste type	Final volume (m^3)
Liquid Yeast	0.25
Grease Trap Waste	0.25
Food Waste	3.75
Poultry Manure	0.4
Dewatered Septic Systems Sludge	0.8
Wasted Activated Sludge	0.4

Table 14 shows the final dimensions of the anaerobic reactor and hydrolyzer.

Table 14: Reactor dimensions summary

	Volume (m^3)	Height (m)	Diameter (m)
Hydrolyzer	23	3.1	3.1
CSTR	108	5.2	5.2

The final infrastructure layout is illustrated in Figure 23.

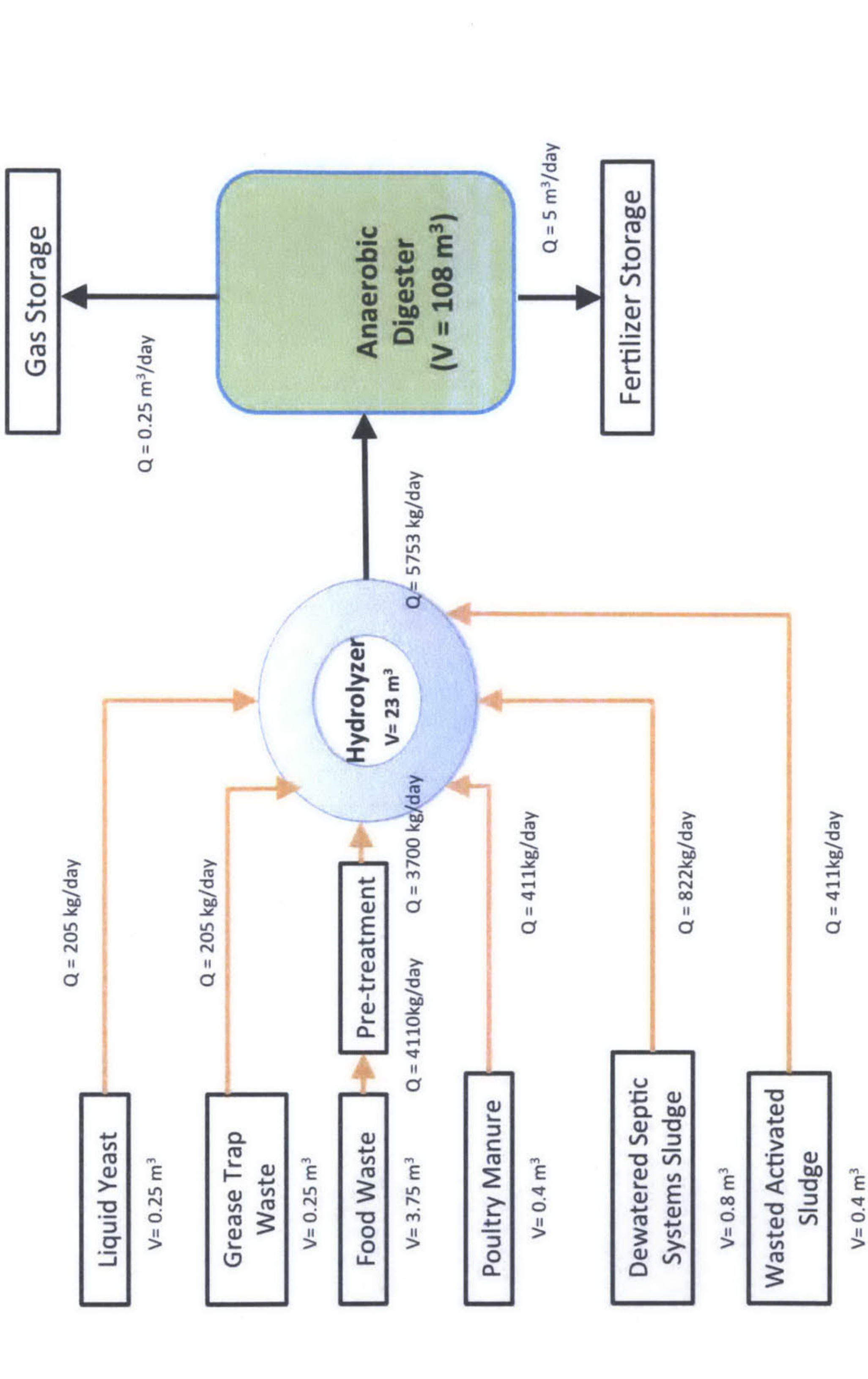

Figure 23: Final infrastructure layout

Note that the system is also made of other elements such as the pipes or the pumps but those are considered secondary.

6.2 CHOICE EVALUATION

In this thesis, many critical choices and assumptions were made which have a considerable impact on the systems design. It is important to recall that this project aims to build a prototype that can be scaled for the company's needs. Therefore one of the main assumptions was that scalability could simply be done by increasing the calculated design with the needed factor.[156]

However, making this assumption has an impact on the scaled infrastructure. For example, the mix chosen was mix 3 and it is made of 6 different waste types. Not all of the wastes are available all year and the dosage of each component in the mix is key to the digester efficiency. Disturbing the system could lead to a reduced gas and fertilizer production. Therefore, bigger storage systems might be needed to store enough of the waste for the entire year. This could be the case for the dewatered septic systems sludge. Another assumption made that can be changed when scaling the digester is the land availability. It was explained earlier that land is not a constraint at EBI site. However, in a more general manner, real life project dimensions may not fit the given area and would need to be adapted.[157]

Concerning the choice of the mix itself, mix 3 was chosen based on the multi-criteria analysis done for this project.[158] Nonetheless, if this feedstock happens for some reason to not be the optimal mix, the design would have to be adapted.

Assumptions were also made when designing the digester. First the digester dimensions were calculated using a rule of thumb giving a one to one ratio between the height and the diameter. This was chosen for design simplicity as well as efficiency but it is plausible that other dimension decisions could have the same or a better result. Also, the digester was chosen to be cylindrical, but other shapes have specific advantages as well.

When calculating the gas and fertilizer outcomes, it was assumed that 95% of the flow was going to become fertilizer and 5% biogas.[159] This is a general rule of thumb that could change depending on the actual components. However, due to the lack of details on how the feedstock mixes from a chemical perspective, this assumption is considered acceptable.

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[156] Lemonde, 2014
[157] "Groupe EBI," 2010
[158] Sylvestre, 2014
[159] Lemonde, 2014

Finally, all the safety factors for the hydrolyzer and digester design were considered in order for the design to be more conservative design. If the price happens to be too high, reducing those factors could decrease the investment needed.

6.3 Risk management analysis

In all engineering projects, a risk analysis must be performed. This helps to understand every party's concerns in the project, what are needs of the project and sometimes, it helps to accelerate the paperwork of the project by giving an understanding of the major concerns and help solving them accordingly.

6.3.1 Stakeholders

When performing a large-scale project, many parties are usually involved. In the case of the addition of the anaerobic digester to EBI's current facilities, the main stakeholder is EBI. The Government of Quebec and its cities are considered the two stakeholders from the public sector since the government of Quebec wants to forbid landfilling of organic matter by 2020 and the cities are concerned as the waste is collected within them. The last stakeholders are EBI's clients. Other stakeholders such as the gas and fertilizer users could be considered; however, they only play a role in increasing EBI's revenue. Therefore, they do not play an important role in the risk analysis.

6.3.2 Strategic Issues

The four major strategic issues in a project are economy, environment, function and society. Stating most of the issues helps the different stakeholders understand their position on each issue and helps identify a possible conflict of interest. The economic aspect regarding the design is related to profitability and investment costs. Concerning the environmental aspect, contamination of the environment and environmental impacts are critical. The fertilizer and gas produced by the digester represent the functional aspect of the project. Finally, an understanding of the community perception of the project is needed for it to be successful. Below, each of the main strategic issues is explained.

a. Profitability

As for any company, profitability is the reason for such a project. One of the most probable requirements for this project to be sustainable is to have the 2020 regulations happen. If they were to be postponed or abandoned, landfilling, being the cheapest option, would be used and the investment would not meet expectations. None of the other stakeholders would make an economic profit from this project.

b. Investment Cost

In terms of investment cost, the company is affected as they look to have the lowest possible investment while meeting the required efficiency. The project cost will affect the city since it is providing work to contractors. The government of Quebec could be considered indirectly related, as it will impact the economy. Finally the clients will not have any connection to the investment cost.

c. Contamination

All stakeholders are concerned by any type of environmental contamination. None would benefit from a spill or leakage of any sort. The government of Quebec could continuously check that no contamination is released to the environment and could punish the company if contaminants are released.

d. Environmental Impact

The main part of this project is to create fertilizer and biogas from the different waste types brought to site. The company's mission is to manage waste and the first main commitment of the company is to do it without harming the environment. The digestion of the feedstock should aim to reduce the environmental impact of the substrate treated. The government as well as the cities have a key role in reducing the environmental impact done by the waste and could want to help the company accomplish that. For the clients, the company is offering them a service that helps them manage their waste produced; if it reduces the environmental impact at an admissible price, the clients could have a greater interest in working with the company.

e. Feedstock Quality

The criteria defining the quality of the feedstock as described in the multi-criteria analysis are suitability, availability, digestibility, purity and inhibitors. Only one of the waste type of the chosen mix needed pretreatment. However, if the quality of the components of the mix is compromised then the digester could be damaged. Therefore, it is a critical point for the company. It is also for the client as they have committed to a pure waste. On the other hand, this aspect of the project does not concern the government of Quebec and the cities.

f. Feedstock Availability

Availability of the feedstock plays a key role for the company, as the digester is dependent on the mix it was designed for, which is composed of different waste types. Some of those will not be available all year round, but the quantity needed for each one should be provided and stored to ensure the digesters production. The second main stakeholder in this case is the client if they decide to work with the company. As the digester could be damaged if the mix is not provided in proper quality or quantity, the client must deliver the volume they committed to. This aspect of the project does not concern the government of Quebec and the cities.

g. Perception of the Community

Finally, the perception of the community is an important factor for every stakeholder of the project. From the company's perspective, the project needs to be well perceived. It is also the case for the government of Quebec and the cities as they look to show their population an improvement in reduction of the environmental impact. For the some clients such as restaurants, having an environmentally friendly waste management solution could help their brand and, for example, increase their customers' base.

6.3.3 Sources of Risk and their Criticality

The main sources of and their criticality are identified in this section, and an understanding of the impact those risk is explained.

a. Odor Emissions

When a project concerns waste management, odor emission is one of the primary concerns. First, it can make the work environment difficult for the workers. In addition, if the odor propagates to surrounding communities it could be detrimental to society. This could result in the population lobbying to terminate the project. EBI has experienced such events in the past, which resulted in terminating the reception of malodorous waste like poultry manure. Anaerobic digestion is an indoor process, and therefore odor emission propagation is less likely to occur, but it needs to be planned for.

b. Spill in the Environment

Most of the material in the anaerobic digestion process is organic, with only the industrial waste needing to go through pre-treatment. Even though organic material has a smaller impact if spilled, contamination of the environment should never occur. This would not only degrade the surroundings but could also generate community discontent. If the community engages against the project, termination could be the end result. Furthermore, if sites happen to become contaminated EBI will have to finance the site cleaning. Such a process can be very costly and should by all means be avoided.

c. Increased Transportation Costs/Co2 emissions

The waste has to be transported from surrounding areas to the infrastructures. Increasing the transportation system of the company will have two impacts: increase the transportation cost and impact the environmental. We can consider that the transportation costs increase due to an increase in the trucks needed, but it will not have a big economical impact. However, if for example the actual transportation cost for the trucks increase, then the company would have to balance this cost with their price for each ton treated. The increase in truck number also impacts the environment as it increases the CO2 produced by the company.

d. Poor Design for Weather Conditions

When designing the digester, it was assumed that the contractor could provide materials that are adequate to the temperature in the region. This is a safe assumption as it is common to build for extreme conditions in Quebec. It is known that the temperature in Quebec can go down to around -30 C° in winter. Therefore, as the digester requires a temperature of 35 C° to efficiently grow the bacteria and produce both fertilizer and gas, the materials used must satisfy the temperature requirement. If not, equipment heating the system, as explained earlier, needs to be purchased. It is important to keep in mind that such equipment is expensive but for efficiency in the bacteria growth the temperature within the digester must be achieved.

e. Gas and Fertilizer Quality

Apart from the waste management service provided by EBI when constructing an anaerobic digester, biogas and fertilizer are produced. The biogas will go through a treatment before being commercialized and the fertilizer will be commercialized to the agricultural market. Those two products are very valuable to the company and represent a source of assets. They must meet the country requirements and their quality plays an essential role in this. Therefore, a quality check should be performed on a monthly basis to ensure that the fertilizer can be used.

6.4 Conclusion & Recommendations

This thesis provides an overview of an anaerobic digester unit. It is important to consider that most of the project is based on literature review as well as interviews with professionals from the industry. As explained earlier, the thesis focuses on building a small-scale prototype for the project EBI targets in the short-term. However, it is important to look at the bigger scale application and possible outcomes EBI can derive from this project.

The company desires to make a controlled investment of less than 1 million dollars in anaerobic digestion. The company desires to make a controlled investment of less than 1 million dollars in anaerobic digestion. While a detailed analysis of the costs was not performed, approximations could be used, such as how 1 m^3 of digester costs around $1000.[160] The price of other items should also be considered, such as the cost of 7 pumps (which is likely to be one of the more expensive components of the system), 6 storage tanks and piping. The overall price of the facility should be close to the desired investment. When comparing the project's investment to the cost of operating anaerobic digesters in Canada, most of the annual capacities ranged from 1,000 to

[160] Lemonde 2014

2,000 tons per year. The prototype is the first step for such project, as it will help the company understand the needs for a much larger one. In the case of anaerobic digester, scalability can be done by multiplying the prototype's calculations and results by a certain factor, which is simply the ratio of sizes. However, there is one main issue that needs to be checked when scaling. Not all of the waste types used in mix 3 are available at the same quantity and at the same time of the year as detailed in the feedstock study.[161] Therefore, when scaling the digester it is important to realize that the design will be dependent on the waste availability and it needs to satisfy the dosage of the solution. Lab tests on the prototype will help EBI understand if the mix chosen meet their expectations. When processing the prototype or the digester, such an infrastructure needs to go through a startup. The startup is done gradually and can have a duration of a month and be monitored and controlled at a certain pH and alkalinity.[162] If the startup fails, rehabilitating the digester could take a considerable amount of time and would therefore cost the company a considerable amount of money.

In addition, a small-scale project is the best way for EBI to ensure the results and understand the possible problems the company might face if they invest in a larger infrastructure. They might benefit from it in many aspects, such as ensuring the mix components are pure and do not need to go through pre-treatment or help them manage dosages. Furthermore, the risk taken by EBI when building a prototype is lessened by a considerable factor. The investment cost will be smaller and they can use this time to test the different feedstock to ensure their client's wastes are optimal for the digester.

It is important to realize that many aspects of the project have not been completely covered in this thesis. It could be interesting to look into the possibilities of making the proposed design more sophisticated with the new available equipment in order to automate the infrastructure while staying in the investment cost range. Also, the different materials needed to satisfy the weather conditions are not defined as it was assumed that the contractors know how to work best for the region condition. However, investigating the possible materials that would be used and trying to ameliorate the design in a more environmentally friendly manner should be considered. For example, in those conditions it is crucial to keep the material dry as freezing could be followed by a thermal shock and result in cracks.[163] In addition, an analysis of the heat and energy loss in the process as well as a technique to recover could be of great use. Most of it would be recovered using the cogeneration plant and be reused in the digester itself, but, looking for materials with a better temperature impermeability could save the company a considerable amount of money and reduce the negative environmental impact of the unit. Finally, comparing

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[161] Sylvestre, 2014

[162] Gerardi, The Microbiology of Anaerobic Digesters, 81–84.

[163] International Masonry Institute, 2010

the use of anaerobic digestion as well as the technique used in other countries could be very beneficial. This could for instance, help build a better infrastructure as the design usually differs with the specific needs of the region, and could help understand what conditions are best for anaerobic digestion as a waste management method.

As of now, large-scale anaerobic digestion is not a common waste management solution in Quebec. This provides the company with a serious competitive advantage in the market and using the proposed design is the first step in the realization of the project. However, more projects are converging to this solution, since it is one of the most cost-efficient solutions to the 2020 regulations. Quebec is one of the first regions in North America that has decided to undertake a very strict policy about landfilling of organic matter but it is for sure not the last.[164] Organic matter needs to be treated and useful products can be created in the process. Therefore, it is safe to say that many other parts of the world will follow the precedent of Quebec.

[164] Gouvernement du Quebec 2012

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