THE POTENTIAL OF ANAEROBIC DIGESTION TECHNOLOGY TO TREAT COFFEE WASTE IN HUATUSCO, MEXICO

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Abstract

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THE POTENTIAL OF ANAEROBIC DIGESTION TECHNOLOGY TO TREAT COFFEE WASTE IN HUATUSCO, MEXICO (85 pp).

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This research proposes a system that uses the waste generated by coffee processing to generate biogas and fertilizer, called AD-Coffee Waste System (AD-CWS). The biogas will be used to dry coffee beans and the fertilizer will be sold. Through this study it was proven that AD-CWS is feasibility. AD-CWS will not only eliminate coffee processing waste discharge into waterways, but it will also generate revenue through fertilizer and methane sales. At this time, further studies are needed to verify the biogas yield from coffee pulp at thermophilic temperatures (above 55°C) in order to properly forecast revenues. Enforcement of environmental laws in Mexico will result in fines to the coffee industry for discharging coffee waste into waterways, increasing coffee processing operating costs. AD-CWS can help the coffee industry comply with environmental regulations and avoid fines.

Approved:

Gerardine G. Botte

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To John and Jeannette

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Chapter 1 Introduction

Project Overview

Coffee is one of the most important crops in developing countries. The International Coffee Organization estimates that 6,985,680 tons of coffee beans were produced worldwide in 2004[1]. Coffee production provides livelihood to millions of people, but the organic waste generated threatens their environment. Developing countries are facing a serious problem in properly disposing of the waste produced by production of coffee. It is estimated that more than two million tons of coffee waste is generated yearly[2].

Mexico produced 232,020 tons of Arabica coffee beans and was the 7th leading producer of coffee in 2004[1]. As a result, Mexico faces the challenge of economically treating coffee waste to avoid soil and water pollution while staying competitive in the global coffee market. In fact all coffee producing countries face this challenge; however, Mexico needs to create solutions for coffee waste in order to endure the strong competitive forces from Brazil and Asian countries. Therefore, Anaerobic Digestion (AD) technology is worth evaluating as an alternative coffee waste disposal solution. Currently in Mexico, there are efforts to treat the coffee processing wastewater; however, cost of treatment is expensive[3]. The solid waste, i.e. coffee pulp, is not treated, but rather composted, potentially generating soil and water pollution. In Mexico, 13.2 million m^3 of wastewater from coffee processing is generated, equivalent to the sewage of a city of 5.6 millions inhabitants and 45,000 tons of chemical oxygen demand (COD)[3]. Wasser reported that 245 kg of coffee beans (1 quintal or sac) generate 6 to 8 kg of Chemical Oxygen Demand (COD) and 10 kg of total solids[3].

Using anaerobic digestion would enable coffee bean producers to sell the solid and liquid effluents as fertilizer. AD will enable the conversion of nitrogen present in the coffee waste to ammonium, and therefore creating an excellent fertilizer.

The aim of this study is to evaluate the economic feasibility of using AD to treat coffee waste. Essentially, this research proposes a system that uses the waste generated by coffee processing to generate biogas and fertilizer, called AD-Coffee Waste System (AD-CWS). The biogas will be used to dry coffee beans and the fertilizer will be sold.

AD-CWS is based upon the coffee production conditions in Huatusco, Mexico. Huatusco is located in the state of Veracruz, between Mexico City and Veracruz City in the Sierra Madre Oriental. The state of Veracruz is the second leading coffee producing region in Mexico[4], right after Chiapas. The district of Huatusco produces about 16% of the production of the Veracruz state[5].

The municipality of Huatusco is an active agricultural area, where coffee is the main commodity but also crops like plantains, sugar cane, and fruit trees, among others, are present. The region is localized between 18°55’ and 19°25’ north latitude and between 96°20’ and 97°15’ west longitude and at an altitude ranging from 470 m to 1,520 m above sea level[6]. The high altitude and 19.1ºC average temperature[7] make the region favorable to grow coffee. The coffee variety grown in Huatusco is Arabica coffee and it is processed using the wet processing method. However, despite being a productive region Huatusco is suffering from a lack of human capital, a situation similar to other regions of Mexico. Young people, mostly men, leave the region seeking better economic opportunities. A great majority migrate to USA, due to higher wages and great opportunities. Unfortunately, they leave a human capital vacuum in the region. Huatusco’s coffee industry faces challenges finding workers. Every year there are less people in the community involved in the coffee cultivation, harvesting and processing, therefore coffee growers bring people from other areas to work, that in most cases are not trained for the job as well as the people of the region. The possibility of installing a coffee waste treatment like AD-CWS will generate jobs and promote a technology transfer beneficial for the area. Also, since the impact on the environment will be reduced, the coffee beans may be able to be sold a higher price under an environmental label, which will bring much needed income to the community.

The AD-CWS is designed for a coffee processing plant similar to the coffee processing plant called *Solidaridad Cafetalera* which is part of the *Union Regional de Pequeños Productores de Café, Agropecuaria, Forestal y de la Agroindustria de Huatusco,* UR (Regional Union of Small Coffee producers, Agro-animal, Forestry and Agro-industry of Huatusco). The UR is a cooperative of small coffee farmers, and it has about 1,561 members. *Solidaridad Cafetalera*, (SC) is designed to handle between 50 to 100 tons of coffee cherries per day. For this study, AD-CWS will handle waste from 45 tons of coffee cherries a day, representing a medium size coffee processing plant. SC has been modified to reduce the amount of water used during the wet process. It uses only 0.5 L/kg of coffee cherry for pulping and 2 L/kg of coffee cherries for washing[8] and does not use water to separate green and mature coffee cherries. SC process flow is incorporated in AD-CWS is shown in Figure 1.1.

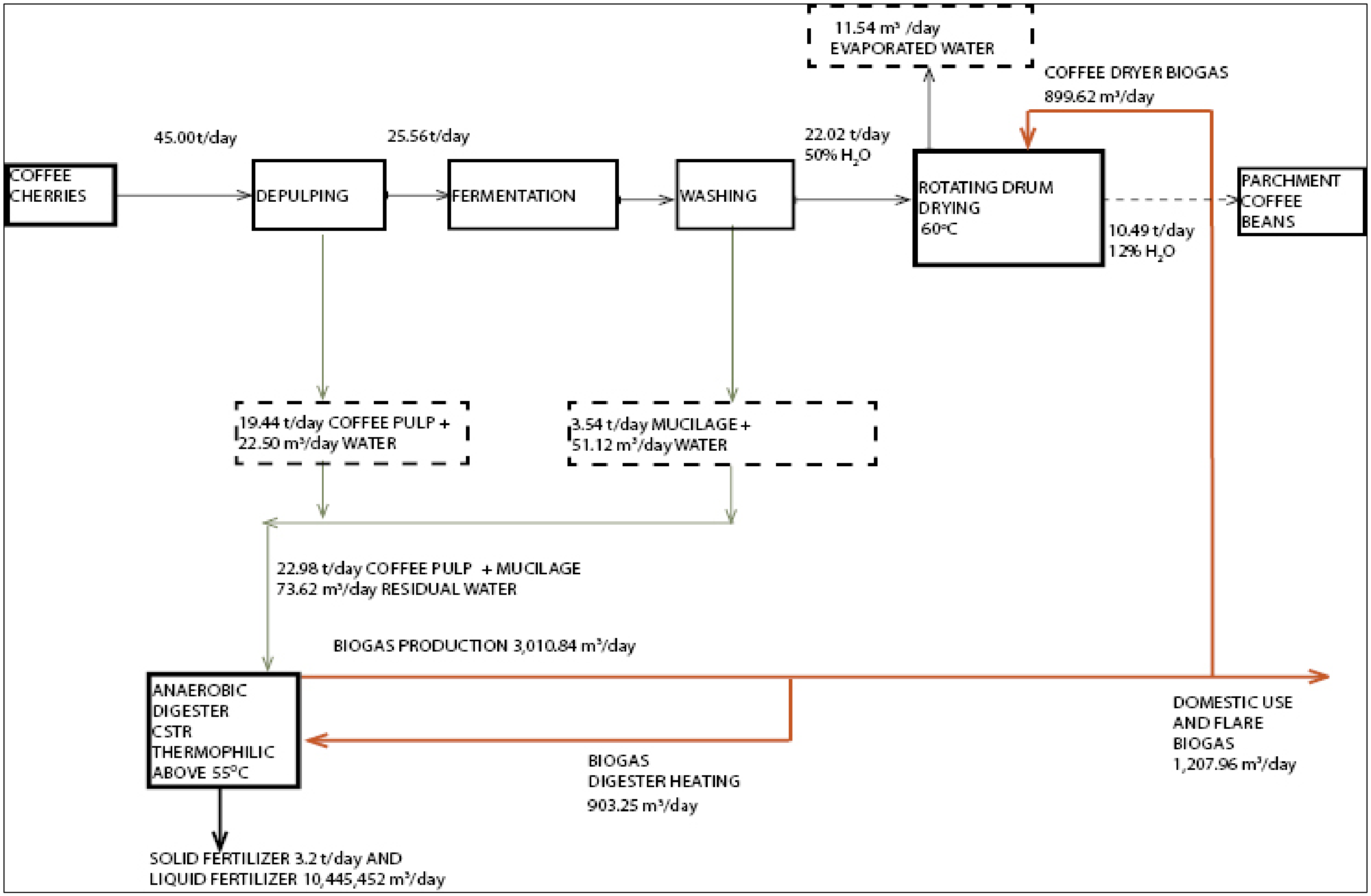

Figure 1.1 AD-CWS Block Flow Process Diagram

The wet processing method used in Huatusco produces a high quality coffee bean for the mild Arabica organic market[8]. In SC coffee cherries are transformed into parchment coffee beans by removing two layers that surround the bean: coffee pulp and mucilage. The coffee pulp is about 43.2% of the weight of the cherry and the pulp is 77% weight in water[9]. The mucilage is a viscous fine coating that surrounds the bean and constitutes about 11% of the weight of the coffee cherry and 84.2% humidity[9].

During the wet processing method, coffee cherries flow though a series of steps helped by water, which acts as a conveyor, and gravity as illustrated in the process block diagram (Figure 1.1). After the coffee cherries are collected, they are transferred to the depulping machines, where the pulp from the coffee bean is removed. The next step is fermentation. Maximum fermentation time is approximately 24 hours, depending on the outside temperature[10]. During fermentation the 0.5-2.0 mm in depth mucilage layer is removed. Then the coffee beans are washed and rinsed to finally be dried. In the drying process the coffee beans moisture drops from 50% to 12% in a carefully monitored process to avoid any burning that will affect the quality of the coffee[10]. Finally, the parchment coffee beans are safe to store.

The AD-WCS will use the waste generated by depulping and washing – containing coffee pulp, mucilage, and water (refer to Figure 1.1). This waste will be collected in mix tanks; after the waste is mixed, it will go inside the digester tank. After which biogas generated in the digester will be burned to produce heat that will be used to dry coffee beans.

The AD-CWS is based on a medium size coffee processing plant that processes 45 tons of coffee cherries a day. The anaerobic digestion will run during the harvest period, about 100 days from September to March. AD-CWS uses a Continuous Stirred Tank Reactor (CSTR) at thermophilic condition. The CSTR is used when the residue slurry is 2- – 10% solids like coffee waste[11]. Thermophilic means that the reactor would run above 55^{o}C. It is thought that at this condition, high biogas yield would be ensured. Theoretically, it is estimated that a plant this size will generate 22.98 tons of coffee pulp, 3.54 ton of mucilage and 73.62 m^3 of wastewater, see Figure 1.1.

Statement of Objectives

The aim of this study is to design the AD-CWS to use in Huatusco and to build an economic model that works as a guideline to construct an AD to treat coffee waste in Huatusco, which will be ultimately a model for Mexico and other coffee producing countries. In order to achieve this, it is necessary to base the framework on the proposed system, AD-CWS, shown in Figure 1.1. The proposed system uses coffee waste to produce biogas through AD technology. The biogas will be used to dry coffee. The effluents of the digester may be used as fertilizer. AD-CWS will enable the location to reduce the negative impact of coffee waste disposal on the environment while creating assets for the community: fertilizer and biogas.

The first objective of the study is to theoretically determine the design feasibility. The second objective is to find out the cost of the building an AD-CWS in Huatusco, including the installation and operating cost. The economic model will consider AD’s effluents as a marketable, high value fertilizer. In SC the solid waste, mucilage and coffee pulp, is separated and sold to the surrounding community as fresh and composted fertilizer, while most of the liquid waste is treated.

Significance of Research

The significance of the project is to design an economic reference for anaerobic digestion technology in rural areas of the developing world. In the literature there are examples of introducing anaerobic digestion to utilize organic waste to supply energy while reducing pollution. Examples of such efforts can be found in numerous coffee producing countries. In Mexico, seven anaerobic digesters exist that use coffee waste[12]. Unfortunately, of the seven digesters, at least two are not in operation[8]. Moreover, these digesters are not taking advantage of the biogas produced. Most importantly, coffee-growing communities using anaerobic digestion will produce energy and fertilizer, while decreasing pollution to their soil and water. Energy and fertilizer will be an asset for the community.

However, before offering AD as a solution, an economic framework needs to be built and evaluated. The lack of similar anaerobic digesters operating in Mexico makes it imperative to build a model, so coffee producers are able to make decisions about the future of this technology within the coffee industry. The coffee industry is in a severe price crisis, which impacts the capital available to build solutions to the pollution crises, like Anaerobic Digestion. Even more, Mexico is facing a deeper coffee crisis due to its loss in coffee market shares to other countries like Vietnam. So it is even more crucial to be aware of the economic limitations of the industry and find out precisely the cost of the technology and its potential economic benefits.

Huatusco is a rural area of Mexico with large amounts of organic waste derived from the coffee plantations and animal production. Putting a digester on site will help the region take advantage of this waste to produce biogas in order to operate processes like a coffee dryer which would increase their economic situation and reduce pollution derived from organic waste. Most anaerobic digestion projects are designed to use biogas to produce electricity through internal combustion engine cogeneration systems; however, we are proposing a simple model that does not include electric generation. Instead, the biogas will be used in the coffee drying process. This way the generated biogas will be more cost effective and valuable for our location, especially considering the high capital cost and inefficiency of cogeneration. In addition, selling the AD's effluent, a high value fertilizer, will make the fertilizer business side of the coffee plant more efficient. The value of AD's effluent fertilizer will be higher compare to fresh and composted solid coffee waste.

Chapter 2 Literature Review

In order to develop a study of the potential of coffee waste as an energy source it is necessary to understand anaerobic digestion technology as well as to review research that has used coffee waste to generate biogas and reduce pollution.

Anaerobic Digestion Technology

Anaerobic Digestion (AD) technology has been used for decades as a way to treat wastewaters, mostly sewage. However, anaerobic digestion technology has been further refined and developed, pushed by worldwide interest in waste reduction and alternative energy generation. AD has been specialized to treat agricultural waste, which has become a pollution problem due to the intensification of animal and crop production. This technology principally consists of using organic waste to produce biogas and effluents. Organic waste is collected in a reactor where complex biological processes occur anaerobically (in the absence of oxygen). Anaerobic microbes, of which anaerobic bacteria are the main agents, are inserted in the digester reactor at startup. These microbes will use the waste material as a food source, reproducing and colonizing in the reactor. The reactor is fed organic waste, coffee pulp in this case, and anaerobic bacteria convert complex organic compounds in the waste into simpler organic compounds, through biological reactions. The end result of the digestion is the conversion of organic waste to biogas and an effluent rich in ammonium that can be used as fertilizer[13]. The efficiency of the digester lies on its ability to convert most of the carbon molecules in the feed into biogas (methane and carbon dioxide) with little nitrogen loss.

Biogas is composed of methane, carbon dioxide, water vapor, and a small percentage of nitrogen, hydrogen sulfide, and other products[14]. Biogas composition is closely linked to the substrate used in AD. Biogas can be burned to produce heat. When biogas is 65% methane it yields 5,857 kcal/cubic meters[15], which is lower than pure methane and natural gas[14]. However, the significance of anaerobic digestion lies beyond generating methane. Its main facility is to create an alternative to control pollution generated by agricultural intensification by providing a valuable fertilizer source. High ammonium and neutral pH fertilizer is very desirable for agricultural activities and especially in subtropical areas like the region of Huatusco.

Anaerobic Digestion and Coffee Waste

In relation to AD in treating waste from coffee processing, efforts to adapt AD to treat coffee waste have been documented by many authors over the last 30 years. Recent research has focused on treating coffee processing wastewater rather than the solid waste, aimed at reducing water pollution and avoiding discharge fines[3, 4]. However, solid waste, specifically coffee pulp, is able to generate more biogas than wastewater[16, 17]. Also, coffee pulp carbon degradability is high compared to other agricultural wastes, with an anaerobic degradability of about 70%, making it a prime material for anaerobic digestion[18].

Biogas yield from coffee waste tends to vary in the literature. In Guatemala, AD experiments with fresh coffee pulp at 6% solids and with a carbon nitrogen ratio of 71.8 at 35^{o}C yielded a maximum daily volumetric production of biogas of 1.30 m^3/m^3 reactor volume with 60% methane and a pH of 7.5, while the retention time was 60 days[19]. Fresh coffee pulp generated the highest biogas production in comparison to cow manure and precomposted pulp[19], which underscores the potential of fresh coffee pulp for generating high yields of biogas.

Also reported was biogas yield of 380 m^3 per ton of dry coffee pulp in lab experiments done by Hofmann and Baier in a report submitted to the Swiss Federal Office of Energy. The lab experiments were carried out in 400 ml semi-continuous digester, batch fed at 36^oC and 16 days HRT (Hydraulic Retention Time). This is equivalent to 61.67 m^3 of biogas per ton of fresh coffee pulp, with a reported humidity of 83.77%[18]. The report also found that coffee pulp has great degradation potential and it is possible to use mixed tank digesters for biogas generation.

Kivaisi and Rubindamayugi[17] in Tanzania reported that one ton volatile solids from coffee waste have the potential of generating 730 m^3 of methane, and it is assumed that biogas is composed of 60% methane. Therefore, the biogas yield is estimated to be 252 m^3 per ton of fresh coffee waste, making this the higher range of biogas yield reported.

On the other hand, lab experiments in Kenya using a Single-Phase (SP) digester yielded different results. The SP digester was set up to work at 37^o C (mesophilic temperature range). The inoculum was effluent from a cow dung digester. Coffee pulp was fed at 0.01 grams per gram of the cow dung effluent. The experiment yielded maximum biogas production of 0.0018 cubic meters the 18th day at 0.19 grams of coffee pulp per gram of inoculum feeding rate. Based on the experiment results it is possible to generate 131 m^3 of biogas from one ton of fresh coffee pulp[16]. The reported values in this study fall into the mid-range of the previously reported biogas yields and the article was published in a peer-reviewed journal (Water Science and Technology). Also the AD-CWS uses a SP digester-coffee waste system, similar to the reactors used by Gautho, et al[16]. Therefore, the proposed model AD-CWS will be based on generating 131 m^3 of biogas per ton of fresh coffee pulp. The estimated methane percentage of the biogas will be 65%. This value is at or near the methane percentage reported on several different publications for biogas generated from anaerobic digestion coffee pulp.

Temperature of AD operation

Biogas yield is influenced by temperature. Digesters working at the thermophilic range, between 50 to 60^oC, are expected to produce more biogas, have a faster reaction time, and improve separation of liquid and solid, and superior destruction of pathogens compared to mesophilic (30 - 40^oC) reactors[20, 21]. Also, due to the faster reaction time, AD reactors working in the thermophilic temperature range have a shorter retention time (the time that material is stored in the digester reactor from loading to discharge) than those operated at mesophilic temperatures[21]. Since the days needed to retain a certain amount of feed will decrease the retention time is decreased. Typical retention times for mesophilic reactors are 20 days, while thermophilic reactors treating the same waste have a retention time of 10 days, thus reducing the capital cost of the reactor.

By having an anaerobic digester run at thermophilic temperatures, organic solid conversion rate to biogas is higher than mesophilic, which means that more solids will convert to biogas rather than to digester effluent, reducing the amount of effluent to dispose of and increasing biogas and methane production[21].

In relation to coffee pulp, based on Boopathy's experiment, digestibility increased with temperature. Boopathy reported that in experiments carried out in a 2.5 liter digester working at 40^oC with a mixture of 50% cow dung and 50% coffee pulp at 25% solids, gas yields peaked at 0.0022 m^3 the 4^{th} week, decreasing the retention time from 10 weeks to 4 weeks. Also at 40^{o}C the experiment reported a solids reduction of about 60%[22].

Coffee Waste Inhibition

AD digestion performance could be inhibited by the coffee waste pH, though Hofmann and Baier[18] only found moderate inhibition. This implies that to improve biogas production, pH and digester operating temperature should be considered when planning anaerobic digestion of coffee waste. Coffee pulp pH has been reported to be 5.4 by Hofmann and Baier[18]. The pH can be increased by adding an inexpensive base, such as calcium carbonate (limestone), to the digester if pH falls below optimal levels.

CSTR AD Reactor

To allow greater solids to methane conversion and capital cost reduction, the best option is to operate a Continuously Stirred Tank Reactor (CSTR) at a thermophilic range. This type of reactor ensures the lowest retention operation times and maximum biogas production for feed concentrations above 2% total solids. CSTR digesters are the recommended digester types for 2-10% solids waste[11], which is in the range of coffee waste; 6.8% (wastewater, pulp, and mucilage).

CSTR or high-rate digesters consist of agitation of the digester to produce a well mixed substrate. Temperature is maintained in the mesophilic or thermophilic ranges; in this case thermophilic. Most of AD plants with a thermophilic CSTR are designed to have a HRT of 10 days[23].

Economic Analysis

The amount of coffee processing waste necessary to produce sufficient biogas to dry coffee and the amount of effluent produced from anaerobic digestion will be calculated based on a coffee processing plant in Huatusco, Mexico. The economic analysis will include the cost of building and operating the AD-CWS. Also, it will include the cost of the potential income from fertilizer and methane sales.

The economic estimation model will base on real cost from Huatusco, and cost engineering estimation will be used to estimate cost for the unavailable information, but always adjusting the estimation to the circumstances of Huatusco, Mexico. The level of cost estimation for AD-CWS is of class 4; this means that the estimation of the fixed and variable costs are based on cost information of similar anaerobic digestion plants. A class 4 cost estimation study means that the estimated cost would be 40% higher than the real cost or 25% lower than the true cost[24]. At this level of cost estimation the economic feasibility can be determined, afterwards more accurate cost estimation can be performed that involve more specific information and include the contractor's cost estimation. However, to determine the economic feasibility of a project a Class 4 estimation is sufficient.

The fixed capital investment cost will be calculated based on the preliminary information of capital costs of similar anaerobic digestion plants. The model to use to calculate the fixed capital investment cost would be based on Hashimoto and Chen[25], their work is based on an anaerobic digestion plant similar to AD-CWS.

Furthermore, the cost estimation for capital and variable cost will be based on cost index factors used in cost engineering based on Turton, et al.[24] and Timmerhouse et al.[26].

Chapter 3 Analysis and Results

Solidaridad Cafetelera Coffee Processing Plant

The Anaerobic Digestion (AD) – Coffee Waste System (AD-CWS) - analysis is based on the *Solidaridad Cafetelera* coffee processing plant, located in Huatusco, Mexico. *Solidaridad Cafetelera* is a medium sized processing plant, using the wet processing method to produce high quality, organic coffee beans. A block diagram of the process flow showing the mass balance is given in Figure 1.1. It is assumed that this plant will process 45 tons of coffee cherries a day. The operational shift lasts 10 hours per day, with the plant in operation for 100 days. From the initial 45 tons of coffee cherries received, after depulping only 25.56 tons of beans remain. Depulping consists of removing the coffee pulp from the coffee bean. During depulping 19.44 tons of pulp are separated, requiring 22.50 m^3 of water. Only 0.5 L of water per kg of coffee cherry is used per day[8]. Depulping water is re-circulated for reuse, reducing the total cubic meters of water required for the process compared to the traditional wet processing method with no recirculation. The coffee beans are sent to the fermentation tank via a fresh water assisted auger system, where they remain for a period of 24-48 hours. After fermentation, the beans are washed, removing 3.54 tons of mucilage, which is the adhesive coat that covers the coffee beans. The two liters of water per kg coffee bean remaining after depulping are used to wash the mucilage from the beans, resulting in 51.12 m^3 of wastewater which is discharged each day[8]. After washing, 22.02 tons of coffee beans at 50% humidity remain. These beans enter the rotary dryer where they drop from 50%

humidity to 12% humidity, reducing weight of the coffee beans to 10.49 tons. These are called dry parchment beans, and are ready to store in bags for shipping.

The waste produced from depulping (19.44 tons of coffee pulp and 22.50 m^3 of water), as well as the waste derived from washing (3.54 tons of mucilage and 51.12 m^3 of water) are collected, and a total of 22.98 tons of solid waste (coffee pulp and mucilage) and 73.64 m^3 of residual water enter the AD system daily.

The AD process temperature will be 55°C (thermophilic). A CSTR (Continuously Stirred Tank Reactor) will be the AD vessel. This system will theoretically produce a total biogas volume of 3,010.84 m^3 a day at 65% methane based on experimental data by Gautho, et al[16] and 3.2 tons of solid fertilizer (at 50% water) and 104.45 m^3 of liquid fertilizer per day.

From the total biogas produced, one third (903.25 m^3) will be used to maintain the digester operating temperature of 55°C and using a water to sludge heat exchanger, based on the AD design of Stafford, et al[23]. A total of 899.62 m^3 of biogas will be used to dry the coffee beans in the rotating drum dryer. The remainder of the biogas, 1,207.96 m^3, will be used by the processing plant, sold for domestic use, or flared, if necessary, for safety.

The material balance for the coffee processing plant was calculated theoretically (Table 3.1 and 3.2.) based on experimental results from Bressani[9]. In order to calculate the amount of waste generated after every step of the process, the coffee cherry composition study from Bressani was taken as a reference.

Table 3.1 Coffee Processing Material Balance

Initial product	45,000.00	kg of coffee cherries					
Coffee Processing				**Coffee Waste**			
process/ product	**product in (kg)**	**product in db (kg)**	**product out (kg)**	**product**	**solid waste (kg)**	**solid waste db (kg)**	***waste water m^3**
depulping *coffee cherries -> beans*	45,000	15,525	25,560	*coffee pulp*	19,440	4,502	23
washing and fermenta-tion *beans -> wet parchment beans*	25,560.	11,209	22,016	*mucilage*	3,544	549	51
Drying *dry parchment beans*	22,016	9,357	10,480	Total waste	22,984	5,051	74
Final product	10,480	kg of dry parchment beans		Waste % compare to initial product	51%	33%	n/a
*Data from Díaz Cárdenas[8]							

Bressani found that the coffee cherry is composed of 43.2 % coffee pulp (Table 3.2); therefore, coffee pulp in Table 3.1 is 43.2% of the initial coffee cherry on a fresh weight basis. Also, based on this material balance, it was found that coffee waste is 51.07% of the total input of the process on a fresh weight basis and 32.54% of the dry weight of the coffee cherry (Table 3.1).

Referring to Table 3.2, column 1 indicates the weight distribution of the different components in the coffee cherry; coffee pulp is 43.2% of the weight of the coffee cherry, while the bean, mucilage, and hulls are 56.8%. Column 2 shows the dry weight content of the different components of the coffee cherry found experimentally by Bressani[9]; 34.5% of the coffee cherry is dry matter, and coffee pulp is 29% of dry matter of the coffee cherry. Likewise, the bean, mucilage, and hulls represent 72.2% of the dry weight of the coffee cherry. The mucilage was found to be 4.9% of the dry weight of the coffee cherry. Columns 2 and 3 explain the moisture and dry base content of each product; the coffee cherry is 65% water, and 34.5% dry base, coffee pulp is 77% water and 23% dry base.

Table 3.2 Coffee Bean Composition*

Product	**(1) Weight % relating to the coffee cherry**	**(2) Dry weight % relating to the coffee cherry**	**(3) Moisture % in the individual product**	**(4) Dry weight % in the individual product**
Coffee cherry	100	34.5	65.5	34.5
Coffee pulp	43.2	29	77	23
Beans: mucilage + hulls	56.8	72.2	56	44
Mucilage	NA	4.9	84.5	15.5
Wet bean + hulls	NA	NA	57.5	42.5
Dry beans + hulls	NA	NA	12	88

*Data from Bressani[9]

Coffee Dryer

The coffee dryer calculation was based on a dehydration model by Saravacos and Maroulis[27]. The model used is shown as in Figure 3.1.

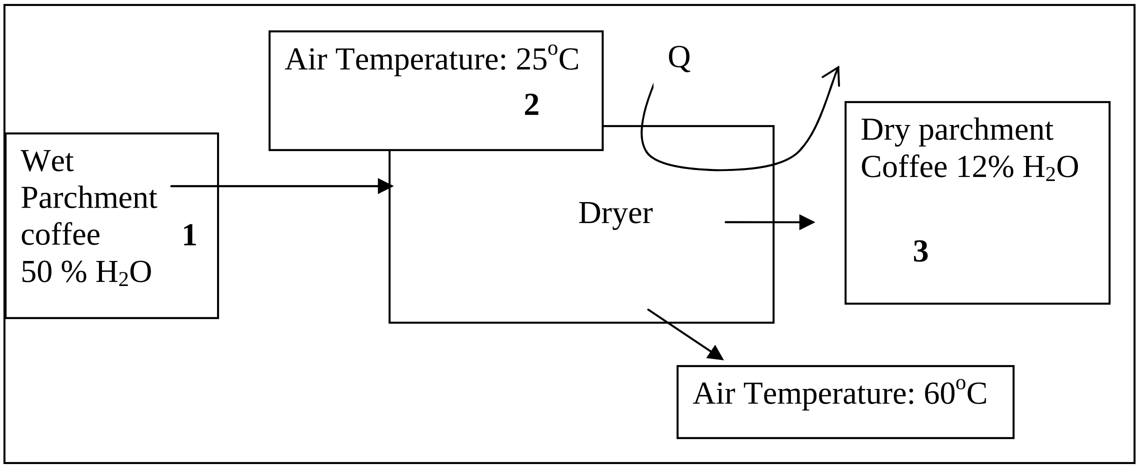

Figure 3.1 Coffee Dryer Block Diagram

After the coffee beans are fermented and the mucilage removed, they are dried, lowering the humidity from 50% to 12%, referenced by Sivetz, et al[28]. The general process has been summed up in Figure 3.1. The wet parchment coffee (step 1) enters the drying process where it is dehydrated by hot forced air (step 2). After a period of time, the coffee bean humidity drops to 12% (step 3). The beans are never to be burned, as this will alter the taste of the coffee beverage. The air temperature in the dryer should not be higher than 60°C. A burner fed with biogas is used to heat the air from 25°C to 60°C. Based on this temperature increase, the heat required will be 255.33 kW, equivalent to 899.62 m^3 of biogas at 65% methane. The calculations done to generate these results are described in Appendix A.

Biogas Production

Table 3.3 shows the amount of water derived from depulping and from fermentation. These volumes are based on 0.5 L per kg of coffee cherry processed for depulping and an additional 2 L per kg coffee bean remaining after depulping for fermentation and washing. Water from the moisture in pulp is calculated to be 14.97 m^3 and from mucilage 2.99 m^3. These calculations are based on Bressani's results, shown in Table 3.2. Therefore a total of 91.58 m^3 of water will be fed into the digester daily.

Table 3.3 Waste Water from Coffee Processing

Product	***m^3/day***
Waste Water from Pulp	22.50
Waste Water from Mucilage	51.12
Water from moisture in pulp + mucilage	17.96
Total	91.58

Table 3.4 is the amount of Total Solid (TS) fed to the digester daily, which represents the dry weight of pulp and mucilage derived from the depulping and washing processes. The dry weight for pulp and mucilage can be calculated from moisture percentage in Table 3.2, with pulp 23% dry weight and mucilage 15.5% dry weight.

Based on the amount of wastewater and solids, shown in Table 3.3 and 3.4, the digester must be designed to process 5.051 tons of total solids (pulp and mucilage) and 91.58 m^3 of water daily. It can be calculated that the slurry derived from mixing the solid components with the waste water will contain 6.86% TS. Knowing this, and assuming that 1 ton of fresh coffee pulp generates 131 m^3 of biogas[16], the AD-CWS will generate 3,011 m^3 of biogas daily, containing 65% methane, which means that the projected energy generated from 100 days of operation is 7.38 GJ/year from biogas, 7.25 GJ/year from methane alone. The results are summed up in Table 3.5.

Table 3.4 Total Solids from Coffee Processing

Product	TS kg/day
Pulp	4,502.25
Mucilage	549.24
Total	5,051.49

Table 3.6 shows the biogas distribution, one third of the biogas (903.25 m^3) will be used to heat the digester - based on heating requirements for thermophilic digesters similar to AD-CWS[23]- and 899.62 m^3 will be needed to meet the coffee dryer requirement. The remainder of biogas (1,207.96 m^3) will be used for coffee plant internal requirements or sold for domestic use.

Table 3.5 Projected Biogas Production

	m^3/day	kJ/day	kJ/year	GJ/year
Projected production for biogas @ 65% methane	3,011.00	73,832,065.14	7,383,206,513.53	7.38
Projected production from methane component of biogas	1,957.00	72,474,687.50	7,247,468,750.07	7.25

Table 3.6 Biogas Distribution

	Biogas distribution m^3/day	kJ/day	GJ/year
Heat digester	903.25	22,149,619.54	2,214.96
Dryer requirement	899.62	22,060,633.88	2,206.06
Domestic use	1,207.96	29,621,811.71	2,962.18
Total	3,010.84	73,832,065.14	7,383.21

In order to calculate the size of the digester tank, it was necessary to calculate the total volume of the digester feed. The coffee pulp and mucilage based on the humidity calculation of Bressani contain 77% and 84.5% water respectively (refer to Tables 3.2 and 3.3). Therefore, it was necessary to also calculate the water present in the solid waste to have a better estimation of the total volume of the waste. In order to calculate the total volume in the waste, the moisture content in the pulp and mucilage was found. It is assumed that the density of dry coffee waste is 0.275 kg/L; assuming this, the volume that the dry coffee waste occupies can be calculated.

The volume of the entire amount of coffee waste generated per day is shown in Table 3.7. The total is 109,952.13 L, or 109.95 m^3/day. Assuming a 10 hour per day loading period, 11 m^3/hour must be fed into the digester. With this information, the size of the digester can be calculated. A thermophilic CSTR digester with a 12 day HRT (hydraulic retention time) will need a total volume of 1,319,425.56 L, based on the design by Stafford, et al.[23]. With the recommended 10% additional volume for biogas headspace, the digester tank will have a volume of 1,466,028.40 L or approximately 1,466 m^3.

Table 3.7 Projected Volume from Coffee Waste

	Volume (L/day)
Coffee waste liquid	91,583.06
Dry coffee waste solid	18,369.1
Total	109,952.13

Based on the digester specifications and coffee waste characteristics, it can be inferred that daily discharge will be 95% of daily input, based on results of Espinosa-Solares[29]. Assuming that the biogas is 65% methane, with an input of around 5 t/day of

TS (pulp and mucilage) the AD-CWS system will discharge 1,583.01 kg TS/day (calculation based on Input TS - 1.152 kg per m^3 biogas produced) and 104,454.52 L/day of digested liquid.

Table 3.8 shows the solid and liquid discharge volumes and nitrogen concentration. Basically 5 tons of dry solids enter the AD-CWS and 1.5 tons of solid comes out with a nitrogen content of 0.9%. The liquid discharge contains most of the input nitrogen, in the form of ammonium, based on the experimental results from Liedl, et al[30]. This indicates the liquid can be marketed as a nitrogen fertilizer for agronomic crops. Below, Table 3.9, shows the value of a liter of liquid effluent at 0.069% total nitrogen content, which is US $0.00041 per liter of effluent. The price for nitrogen is derived from US $0.59/kg, based on the price of Anhydrous Ammonia[31].

Table 3.8 AD-CWS Input vs. Outputs

Nutrient Content	***Kg/day***	***Dry TKN* %***	***Total kg N†***
IN Dry Pulp and Mucilage	5,051.49	1.7	85.9‡
OUT Dry Digested Solid	1,583.01	0.9	14.2§
	L/day	***mg/L N†***	***Total kg N†***
OUT Digested Liquid liters	104,454.52	686	71.6

*TKN indicates Total Kjehldahl Nitrogen
†N indicates Nitrogen
‡Based on Gebru, et al[32]
§Based on Liedl, et al[30]

Table 3.9 Liquid Fertilizer Cost (US $)

	L/day	Nitrogen kg/day	Nitrogen concentration	*Nitrogen price ($/kg)	Effluent price ($/L)
Liquid Fertilizer	104,454.5	71.62833	0.069%	0.599	0.00041

*Based on reported data by Wisconsin USDA[31]

Table 3.10 is a summary of the design characteristics of the AD-CWS, including inputs and outputs.

Equipment

Equipment will include water pumps, H_2S screen, liquid effluent pump, heat exchanger, recirculation pump, gas blower, effluent solids separator, valves, piping, and gas flare. A complete process flow diagram with equipment is included in Appendix D. The AD-CWS will be loaded from the mixing tank by gravity, thus eliminating the need for a feed loading pump.

Table 3.10 AD-CWS Design Specifications

AD Characteristics	
Inputs	
Daily waste water m^3	91.58
Daily kg TS	5,051.49
Working volume m^3	109.95
Tank volume m^3 (including 10% gas space)	1,466.03
Biogas output	
Gross energy production Gj/year*	7,383.21
Net heating requirement † Gj/year	2,214.96
Domestic supply * Gj/year	2,962.18
Coffee Dryer supply * Gj/year	2,206.06
Fertilizer output	
Solid Fertilizer dry kg /year	158,300
Liquid Fertilizer m^3 / year	104,445
* Assume 1 year is 115 days of operation † Assumes that the digester uses 1/3 of the heat produced	

Costs Estimation Model for AD-CWS

The cost estimation for AD-CWS performed in this study is class 4; this means that the cost estimation is based on preliminary information of similar anaerobic digestion plants. It is expected that the cost estimation would be 40% higher than the real cost or 25% lower than the true cost. In order to estimate the system's true cost, more detailed information will be needed. However, since this study's main purpose is to develop a cost framework to evaluate its feasibility, class 4 estimation is acceptable. Thus the fixed capital investment cost was calculated based on the preliminary information of capital costs of similar anaerobic digestion plants. Therefore, the fixed capital investment cost was calculated using the following formula by Hashimoto and Chen[25] for AD digestion plants.

Fixed Capital Investment Cost (FCIC) =2970 X (Reactor Volume) $^{0.7}$

In addition, it is assumed through this study that the exchange rate for Mexican pesos and US dollars is 10 pesos per US dollar. All values are given in US dollars unless otherwise indicated and all costs figures at based on the year 2006. In order to adjust the total capital cost to the conditions of Huatusco Mexico, the equipment cost was calculated. Based on this, the total capital cost was determined. The complete calculation steps are shown in the Appendix C.

To adjust the total capital cost formula from 1979, when it was published, to 2006, the Chemical Engineering Plant Cost Index (CEPCI) was used; in Table 3.11 the calculation adjustment is shown. In order to estimate the total capital cost in 2006, the CEPCI reported for 2005 was used. This index adjusts the cost of building a chemical plant in the US in 1979 to 2006.

Table 3.11 Fixed Capital Investment Cost Adjustment

	Fixed Capital Investment Cost	CEPCI
FICC 1979	329,975.57	238.7 *
FICC 2006	647,227.31	468.2†

*Reported on Institute of Chemical Engineers in 1988[33]
†Reported on Institute of Chemical Engineers in 2006[34]

The AD-CWS plant will be in operation for a total of 145 days a year. Of the 145 days, a 30 day startup period will be necessary to reactivate the microbes. During this period, little biogas will be produced and discharge will be minimal. The AD-CWS will run for 100 days during the coffee plant operation. Immediately following this, the system will shut down, feed input will cease and the digester will no longer be heated to 55°C; however, it will continue to generate large quantities biogas for approximately 15 days longer. In the off season, maintenance will be performed. No additional land will be purchased, since the digester plant will be built within the existing coffee processing plant.

The life cycle of the plant will be 15 years. It is expected that the capital cost spent to build and set up the plant will be used in the first two years, year 1 and 2. The capital cost distribution the first two years will be 60% year 1 and 40% year 2. During year 2 the working capital, which is the capital necessary to start production and equivalent to a month of operating cost, will be spent. The plant will start producing revenue the 3rd year of operation.

Variable Costs

AD-CWS will start producing biogas and fertilizer during the third year of operation, and the calculated total annual variable cost is $191,616.76. All cost figures were calculated at 2006 base price. No raw material or waste treatment is necessary. The working capital is $39,644.85, it is estimated to be equivalent to one month of variable cost. In the case of AD-CWS, annual operation is only 145 days. By adjusting the variable cost to 30 days, the working capital is calculated.

Variable cost includes direct and indirect costs. They are explained in the following sections.

Direct Costs

Direct cost includes all costs that are related to produce the product, in this case processing the coffee waste. Therefore, direct costs included in the AD-CWS are utility, labor, maintenance, supplies, and laboratory work. The estimated total direct cost is $51,744.96, and the direct costs calculation is included in the Appendix C.

Utility costs were calculated based on the average utility cost for a plant this size in Mexico. Electrical cost in Mexico was estimated to be $2,000 a year – in the case of AD-CWS (130 days operation) – cost would be $722.22. In the remaining days, the plant will be shutdown. The electric equipment needed to operate the proposed system include, motors and submersible pumps.

The labor cost is based on 3 operators working a 10 hour shift; the base salary is $11/day, which is the base salary for the area[8] and above the minimum Mexican salary. The total labor cost was estimated to be $4,785.00 for 3 operators, and 145 days of labor. Supervisory and clerical work cost was assumed to be 18% of labor cost[24, 26].

Fixed Costs

The costs not directly linked to the operation are the fixed cost, and they include maintenance, supplies, and laboratory work. The total fixed cost is $139,871.80, they were calculated based on the average values of the indexes in chemical engineering[24, 25]. A detailed description of the calculations is shown in Appendix C.

Projected Revenues

The project will generate revenues from treatment fees, biogas at 65% methane, and fertilizer. The coffee waste processing fee was calculated to be 9% of the coffee production cost. This cost includes waste disposal and fine avoidance. Projected revenues were estimated on 2006 base price.

The average coffee production cost for the coffee plant, over the last 5 years, was estimated to be $1,528,624.03 for *Solidaridad Cafetelera*[6]. This cost was based on the AD-CWS model specifications; meaning that the coffee plant (SC) generates 11 tons of coffee beans. The AD-CWS model is set up to charge a total of $289,810.52 annually, to treat 96,603.51 kg/day of coffee waste. At these conditions, AD-CWS will charge about $0.03 per kg of coffee waste treated, representing 19% of the average production cost. The product revenue break down is shown in 3.12.

Table 3.12 AD-CWS Revenue Break Down

(All numbers in US dollars at 2006 base price year)				
	$/kg	**kg/day**	**$/day**	**$/year**
coffee waste processing fee	0.003	96,603.51	2,898	289,810.52
solid fertilizer (50% Moisture)	0.050	3,166.01	158	15,830
liquid fertilizer (nitrogen)	0.599	71.63	43	4,287
	$/MM BTU	**MM BTU/day**	**$/day**	**Year**
Biogas Methane* (natural gas)	8.5	47.11	400	46,047
			Total Revenue	**355,974.83**
*Calculated based on 115 days of production				

The biogas was valued based on 65% methane content, at $8.5 per MM BTU, which is the projected average price of natural gas (90% methane) in the area of Huatusco[35, 36]. The AD will be operating during the northern hemisphere's winter months, which is the time when natural gas prices tend to rise.

Currently in Huatusco, one ton of coffee pulp compost (50% moisture) is sold for $50, so it can be assumed that the solids from the digester will be sold at the same rate. Also, the liquid fertilizer is valued based on nitrogen content. The price of nitrogen in the international market is $0.599 per kg of nitrogen[31].

The projected revenue, based in Table 3.12, is $355,974.83 a year. The expected yearly profit, revenues less operating cost, will be $164,358.07.

Based on the estimated capital cost, operating cost and revenue, a cash flow analysis is built. The discounted cash flow was based on two interest rate scenarios. A yearly interest rate of 10% represents the worse case scenario. And an interest rate of 5% represents the best scenario.

The cash flow analysis is based on the estimated fixed capital investment cost (FCIC) of $647,227.31. During year 1, 60% of FCIC, $388,336.38, is used. Likewise, during year 2, 40% of FCIC, $295,535.77, is spent as well as the working capital, which is $39,644.45. This comes to a total of $298,535.77, which will be spent in year 2. During year 3, the project will start operation with expected revenue of $355,974.83 and with a variable cost of $191,616.76. Therefore, the cash flow for year 2 thru year 15 is expected to be $164,358.07. The investment cash flow analysis for AD-CWS at 10% interest rate, worse scenario, is illustrated in Table 3.13. and Figure 3.2.

Table 3.13 Cash Flow analysis for AD-CWS discounting at 10% interest rate

(All numbers in US dollars at 2006 base price year)

year	ND* cash flow discrete	ND* cumulative cash flow	DC† cash flow	DC† cumulative cash flow
0	(388,336.38)	(388,336.38)	(388,336.38)	(388,336.38)
1	(298,535.77)	(686,872.15)	(271,396.15)	(659,732.54)
2	164,358.07	(522,514.08)	135,833.12	(523,899.42)
3	164,358.07	(358,156.01)	123,484.65	(400,414.77)
4	164,358.07	(193,797.94)	112,258.77	(288,156.00)
5	164,358.07	(29,439.87)	102,053.43	(186,102.57)
6	164,358.07	134,918.19	92,775.85	(93,326.72)
7	164,358.07	299,276.26	84,341.68	(8,985.05)
8	164,358.07	463,634.33	76,674.25	67,689.21
9	164,358.07	627,992.40	69,703.87	137,393.07
10	164,358.07	792,350.47	63,367.15	200,760.22
11	164,358.07	956,708.54	57,606.50	258,366.72
12	164,358.07	1,121,066.61	52,369.55	310,736.27
13	164,358.07	1,285,424.68	47,608.68	358,344.95
14	164,358.07	1,449,782.75	43,280.62	401,625.56
15	164,358.07	1,614,140.82	39,346.02	440,971.58

*ND indicates Non Discounted
†DC indicates Discounted

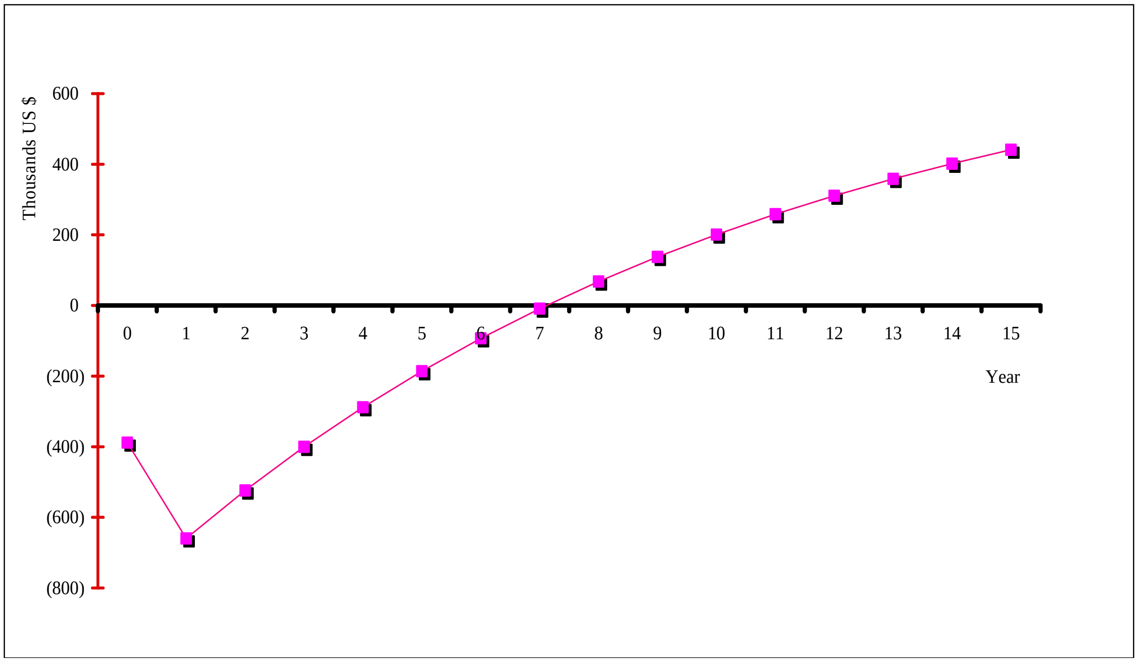

Figure 3.2 Cash Flow Analysis Chart for AD-CWS discounted at 10% interest rate.

Profitability

In order to evaluate the project profitability two scenarios were evaluated based on the cash flow analysis. The worse scenario is at 10% interest rate. The best case scenario at 5% interest rate.

At 10% interest rate, the cash flow analysis the results are the following. The discounted payback period is 6.64 years, meaning that it will take 6.64 years to recover the working capital, which is $39,644.85 and the discounted break-even point is at 7.12 years. Likewise, the project net present value is $440,971.58 and the present value ratio is 1.67; which gives a relation between positive cash flow and negative cash flow. Present value ratios higher than 1 mean that the project is profitable.

The cash flow analysis at 5% yield a discounted payback period of 5.64 years, therefore it will take 5.64 years to payback the working capital, and the discounted break-even point is 5.96 years. Furthermore, the project net present value is $876,792.90 with a net present value ration of 2.30.

The project Discounted Rate of Return (DCROR) on investment is 19.80%, independently of the interest rate chosen for the cash flow analysis. This is the rate that will generate a net present value of zero on year 15. And it can be interpreted as the project's maximum interest rate allowed to borrow from a financial institution to break even.

By evaluating the different scenarios at 5% and 10% interest rate, it is concluded that the project is profitable in both conditions.

Sensitivity Analysis

The sensitivity analysis is performed to evaluate how different scenarios on revenues and costs affect the model. The estimated cost and revenues model for AD-CWS is called the base case scenario. A number of variables were changed to perform the sensitivity analysis; these variables are Coffee Waste Processing Fee (CWPF), solid and liquid fertilizer price, methane price, variable cost, and fixed capital investment cost. All figures are base on 2006 base year and US dollars.

Coffee Waste Processing Fee

The Coffee Waste Processing Fee (CWPF) was varied 15% from the base case. The fee was also compared with the coffee average production cost in order to analyze how the coffee processing plant is influenced by the fee. Therefore, a fee of 45% over the base case means that the fee will be 32% of the average coffee operating costs. The average coffee operating cost was estimated for *Solidaridad Cafetelera* to be $1,528,624.03[6]. All cases were set to treat 96,603.51 kg/day. The sensitivity analysis is shown in Table 3.14 and Figure 3.3.

Table 3.14 Sensitivity Analysis Variable: Coffee Waste Processing Fee (CWPF) and comparison with Average Coffee Processing Operating Cost (ACOC)

Δ%	**CWPF $/kg**	**CWPF $/year**	**AD-CWS $/year**	**DCROR***	**CWPF/ ACOC**
-45%	0.0165	159,395.79	225,560.09	-4.28%	10.43%
-30%	0.0210	202,867.36	269,031.67	6.20%	13.27%
-15%	0.0255	246,338.94	312,503.25	13.60%	16.12%
Base case	**0.0300**	**289,810.52**	**355,974.83**	**19.80%**	**18.96%**
15%	0.0345	333,282.10	399,446.40	25.35%	21.80%
30%	0.0390	376,753.67	442,917.98	30.46%	24.65%
45%	0.0435	420,225.25	486,389.56	35.26%	27.49%

*Indicates Discounted Rate of Return

Reviewing the sensitivity analysis it is concluded that AD-CWS should be conscious of the fee to charge the coffee processing plant for the treatment of waste, preventing the fee from becoming an excess burden to the coffee processing plant, *Solidaridad Cafetelera*. Coffee waste treatment should be affordable to the coffee industry in Huatusco. However, AD-CWS is based on charging a fee to cover operating costs and capital invested. Therefore, the minimum fee to charge should be closely evaluated as should the maximum fee to charge. The fee level to choose should consider the rate of return of AD-CWS, and thus ensure the plant's profitability.

For example, for a fee of 45% lower than the base case, $0.0165 per kg of coffee waste, AD-CWS rate of return is -4.28%. But the coffee waste treatment represents 10.43% of the average coffee processing cost. On the other hand, at this fee level, AD-CWS is not profitable. And at a fee level 45% higher than the base case, $0.0435 per kg of coffee waste, AD-CWS yields a rate of return of 35.26%, a very profitable investment, but the cost of coffee waste treatment is 27.49% of the average coffee processing cost. Therefore an agreement between the AD-CWS and the coffee processing plant should arise, in which the profitability of both operations is not compromised.

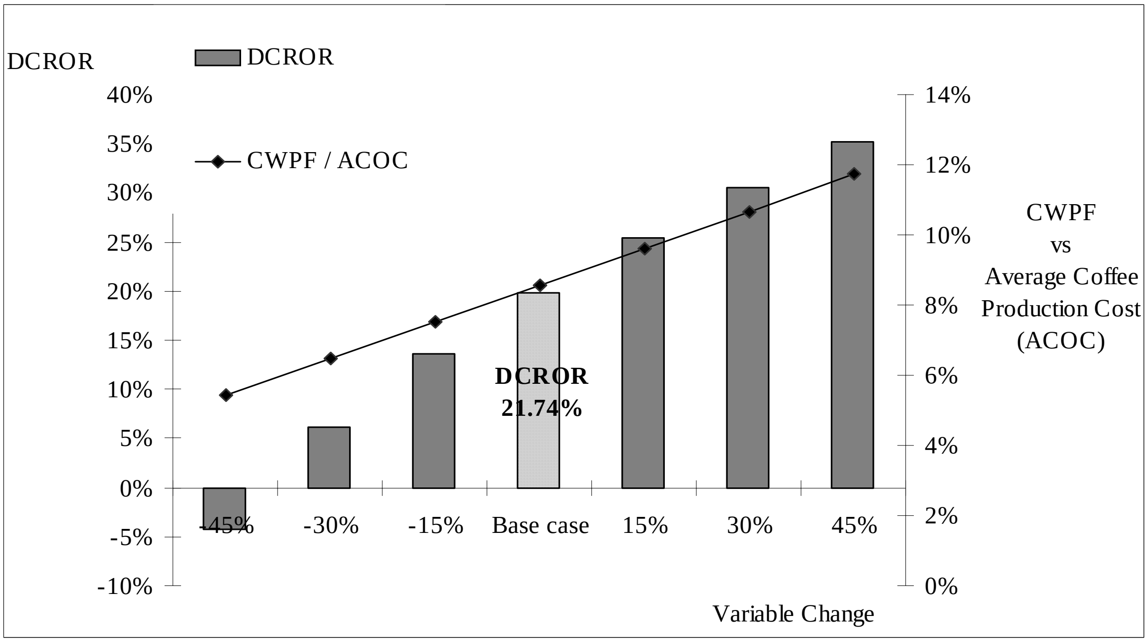

Figure 3.3 Sensitivity Analysis Variable: Coffee Waste Processing Fee (CWPF)

Solid Fertilizer Price

This second scenario shows how the solid fertilizer price can affect the AD-CWS profitability. For this case the price of fertilizer was varied 15% from the base case. In the US market, the price of nitrogen based fertilizer has varied about 17% in the last 3 years[31]. The solid fertilizer in this model is about 0.9% Nitrogen (d.b.) and 50% moisture. In Huatusco, exists a well developed market for coffee derived fertilizer. The price in 2006 was set up to be $50 per ton of solid coffee derived fertilizer[8]. For all cases, solid fertilizer production was set to 3,166.01 kg/day. If the solid fertilizer is sold for 45% over the base case price, the result is an AD-CWS discounted rate of return of 22.22%. On the other hand, if the price of fertilizer is set to be 45% lower than the base case price, the discounted rate of return for AD-CWS is 18.84%. The different scenarios are illustrated in Table 3.15 and Figure 3.4.

Table 3.15 Sensitivity Analysis Variable: Solid Fertilizer Price

Δ%	**Solid Fert. $/kg**	**Solid Fert $/year**	**AD-CWS $/year**	**DCROR***
-45%	0.0275	8,706.54	348,851.30	18.84%
-30%	0.0350	11,081.05	351,225.81	19.16%
-15%	0.0425	13,455.56	353,600.32	19.49%
Base case	**0.0500**	**15,830.07**	**355,974.83**	**19.80%**
15%	0.0575	18,204.58	358,349.34	20.12%
30%	0.0748	23,665.95	363,810.71	20.84%
45%	0.1084	34,315.62	374,460.39	22.22%

*Indicate Discounted Rate of Return

In order to ensure the AD-CWS profitability and long term operation, the solid fertilizer price should respond to the market behaviors. It is very important for AD-CWS profitability that all assets produced are sold. Therefore, the price of assets cannot be such that the fertilizer customers are unable to afford it. Most of the fertilizer customers are small coffee and crop farmers. However, it should also be considered that the fertilizer generated by AD-CWS would be of higher quality than the currently available organic fertilizer in Huatusco.

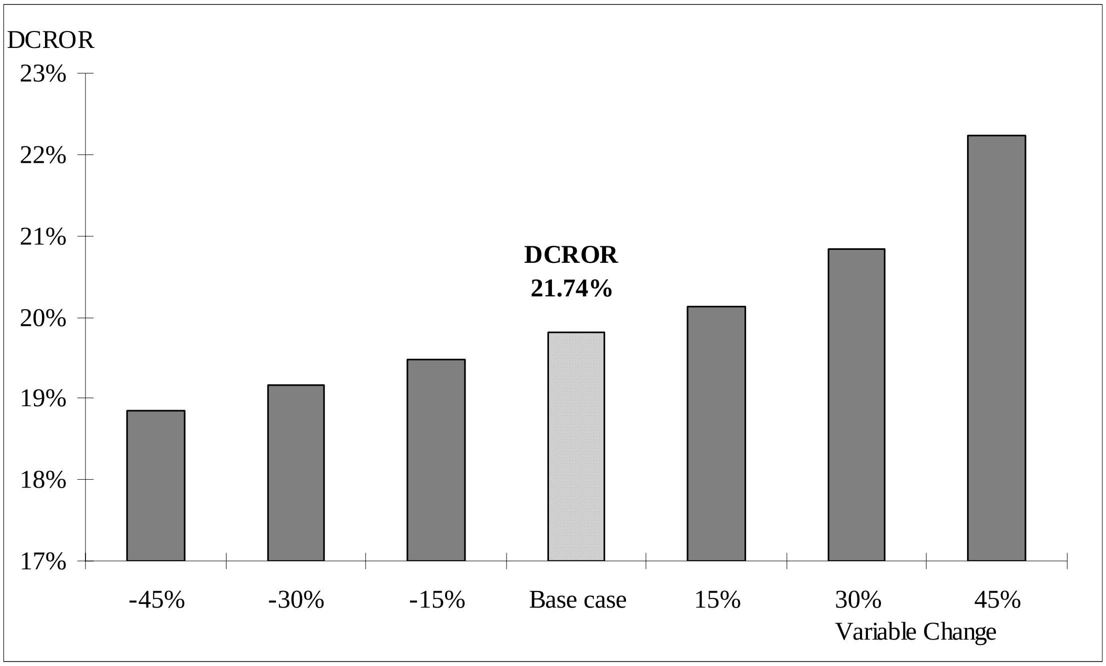

Figure 3.4 Sensitivity Analysis Variable: Solid Fertilizer Price

Liquid Fertilizer Price

The third scenario deals with liquid fertilizer prices and how they affect the AD-CWS profitability. Like the solid fertilizer, for this case the price of fertilizer was also varied, this time 15% from the base case. The fertilizer in this model is about 0.069% Nitrogen. As explained before, Huatusco has a well developed market for coffee derived fertilizer; however it lacks a market for liquid fertilizer. A better possibility is selling the fertilizer to sugar cane plantations that surround the town. For all cases analyzed, liquid fertilizer production was based on the nitrogen content, which is 71.63 kg of Nitrogen a day, contained in 104.45 m^3 of liquid. If the liquid fertilizer is sold for 45% over the base case price, it means the AD-CWS discounted rate of return is 20.47%. On other hand, if the price of fertilizer is set to be 45% lower than the base case price, the discounted rate of return for AD-CWS is 19.55%. The different scenarios are illustrated in Table 3.16 and Figure 3.5.

Table 3.16 Sensitivity Analysis Variable: Liquid Fertilizer Price

Δ%	**Solid Fert. $/kg**	**Solid Fert $/year**	**AD-CWS $/year**	**DCROR***
-45%	0.3292	354,045.51	354,045.51	19.55%
-30%	0.4190	354,688.62	354,688.62	19.63%
-15%	0.5088	355,331.72	355,331.72	19.72%
Base case	**0.5986**	**355,974.83**	**355,974.83**	**19.80%**
15%	0.6883	356,617.93	356,617.93	19.89%
30%	0.8948	354,045.51	358,097.08	20.09%
45%	1.2975	354,688.62	360,981.41	20.47%

*Indicate Discounted Rate of Return

Reviewing the previous cases, the variability on the price of fertilizer does not affect the model profitability as much as the coffee waste processing fee. Even though the price of solid and liquid fertilizer varied substantially, the discounted rate of return remains between approximately 18% and 20% for both previous variables.

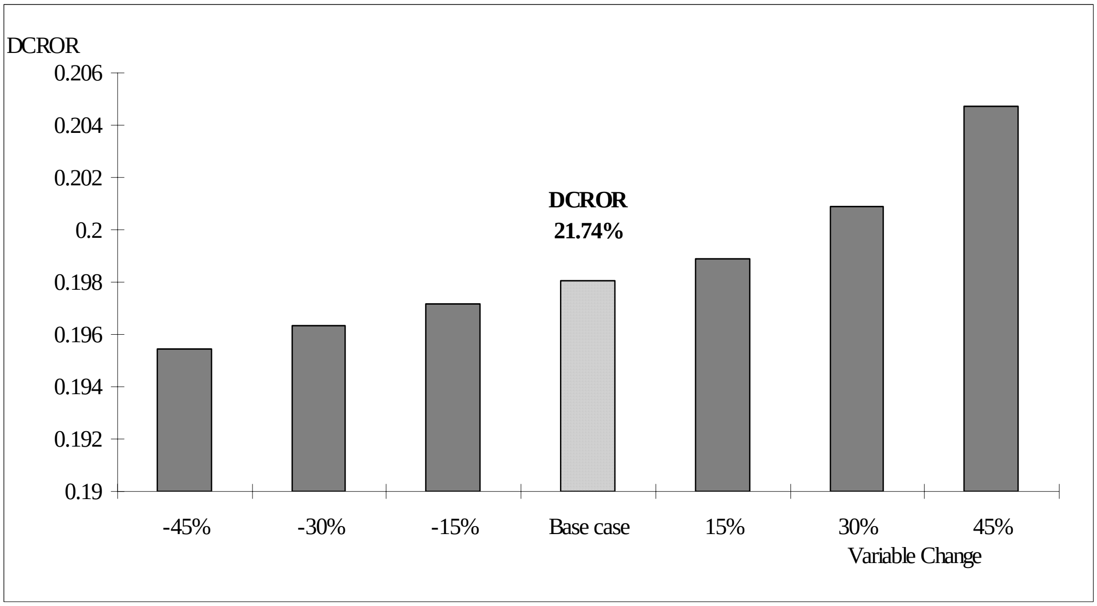

Figure 3.5 Sensitivity Analysis Variable: Liquid Fertilizer Price

Methane Price

The fourth scenario shows the relation between methane price and AD-CWS profitability. It is assumed that AD-CWS generates biogas at 65% methane. The price of methane references the price of natural gas (90% methane) in the area of Huatusco. In the last 3 years the price of natural gas in the area has changed 14%[35, 36]. Therefore, the methane price was also varied 15%. For all cases, it was assumed 47.7 MMBTU or 1,369.93 m^3 will be sold per day.

If the methane price is 45% over the base case of $8.5 per MMBTU, the project discounted rate of return is 26.59%. On the other hand, if the price of methane is 45% under the base case, the project yields a discounted rate of return of 16.95%. The different cases analyzed are described in Table 3.17 and Figure 3.6.

Table 3.17 Sensitivity Analysis Variable: Methane Price

Δ%	**$/MM BTU**	**Methane $/year**	**AD-CWS $/year**	**DCROR***
-45%	4.6750	25,325.78	335,253.74	16.95%
-30%	5.9500	32,232.81	342,160.77	17.92%
-15%	7.2250	39,139.84	349,067.80	18.87%
Base case	**8.5000**	**46,046.87**	**355,974.83**	**19.80%**
15%	9.7750	52,953.90	362,881.86	20.72%
30%	12.7075	68,840.07	378,768.03	22.77%
45%	18.4259	99,818.10	409,746.06	26.59%

*Indicate Discounted Rate of Return

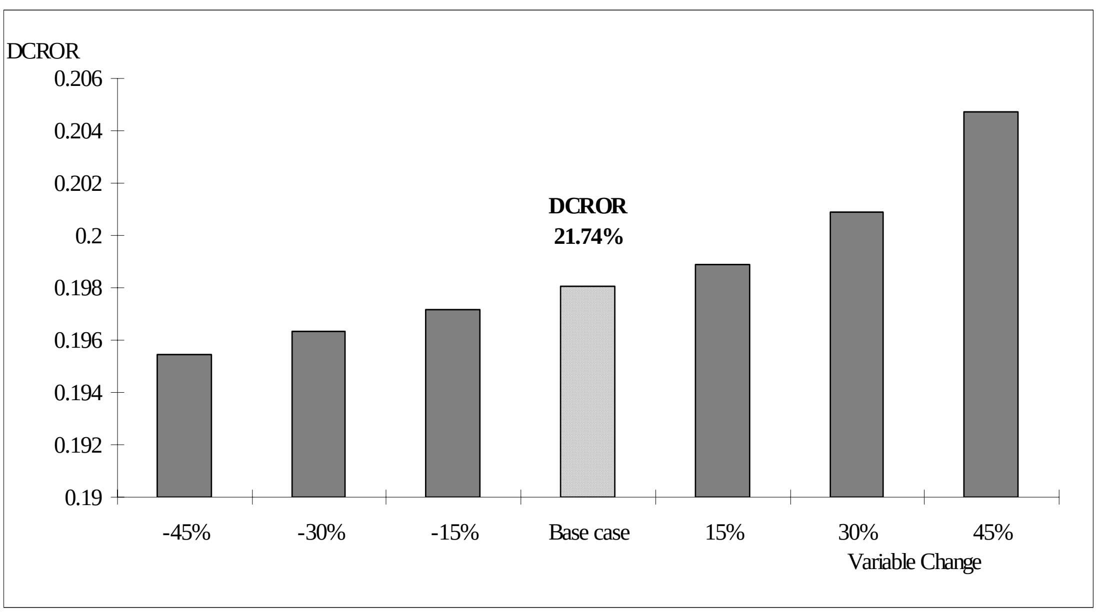

Figure 3.6 Sensitivity Analysis Variable: Methane Price

As the in the case of fertilizer, the change in the price of methane, contained in the biogas generated by AD-CWS, does not affect the project profitability as much as the coffee processing fee. Therefore, in order for the project to be feasible it is necessary to charge a fee to treat the waste.

Variable Cost

The fifth scenario shows how variable costs affect the AD-CWS profitability. Variable cost was varied 5% from the base case. This variability was based on the estimated annual inflation for Mexico, around 3% to 7%[38]. Referring to the analysis in Table 3.3, the working capital was assumed to be one month of variable costs and all other variables remained constant. The base case, corresponds to the estimated variable cost for 2006.

The different case scenarios illustrated in Table 3.18 and Figure 3.7, show that if the variable cost rises 15% over the base case, the AD-CWS discounted rate of return is 10.20% and if the variable cost drops 15% the discounted rate of return for AD-CWS is 27.71%.

Table 3.18 Sensitivity Analysis Variable: Variable Cost

Δ%	**Variable Cost $/year**	**Working Capital $/year**	**DCROR***
-15%	162,874.24	33,698.12	23.71%
-10%	172,455.08	35,680.36	22.43%
-5%	182,035.92	37,662.60	21.13%
Base case	**191,616.76**	**39,644.85**	**19.80%**
5%	201,197.60	41,627.09	18.45%
10%	221,317.36	45,789.80	15.50%
15%	254,514.96	52,658.27	10.20%

*Indicate Discounted Rate of Return

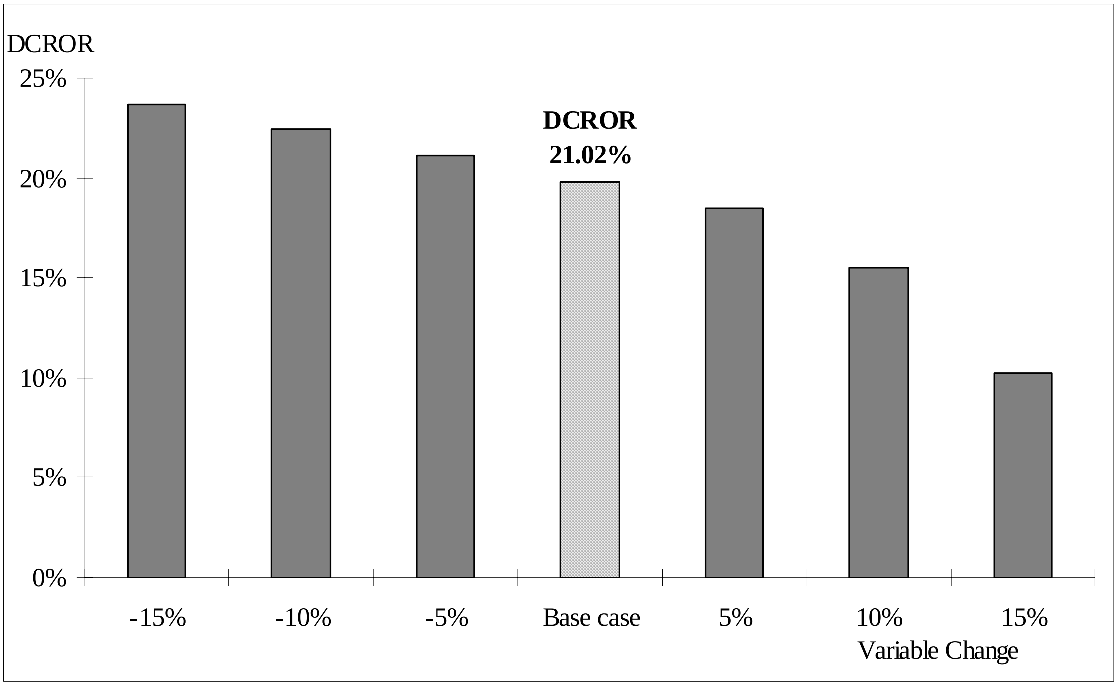

Figure 3.7 Sensibility Analysis Variable: Variable Cost

Fixed Capital Investment Cost

The sixth scenario shows how fixed capital investment cost affects AD-CWS profitability. Fixed capital investment cost was varied 10% in order to find the point at which the discounted rate of return is negative. All remaining variables are the same. When the fixed capital investment cost is 30% higher than the base case, the project is unfeasible, since the DCROR is -9.09%. However, if the fixed capital investment cost drops 30% less than the base case, the project discounted rate of return is 36.99%. The analysis is described in Table 3.19 and Figure 3.8.

Table 3.19 Sensitivity Analysis Variable: Fixed Capital Investment Cost

Δ%	**Fixed Capital Investment Cost $/year**	**Variable Cost $/year**	**Working Capital $/year**	**DCROR***
-30%	453,059.11	137,947.80	28,540.92	36.99%
-20%	517,781.84	155,837.45	32,242.23	30.31%
-10%	582,504.57	173,727.10	35,943.54	24.68%
Base case	**647,227.31**	**191,616.76**	**39,644.85**	**19.80%**
10%	711,950.04	209,506.41	43,346.15	15.45%
20%	854,340.04	248,863.65	51,489.03	6.92%
30%	1,110,642.06	319,706.68	66,146.21	-9.09%

*Indicates Discounted Rate of Return

The sensitivity study was performed in order to find out how the proposed project, AD-CWS, will be affected by changes in the market. It is concluded that the coffee processing cost as well as the fixed capital investment cost are the most important variables to review as to procure the feasibility and profitability for the project. In the case of the coffee processing fee, if it is 45% lower than the base case the project is unprofitable. If the fixed capital investment cost rises 30% higher than the base case, the project is also not feasible.

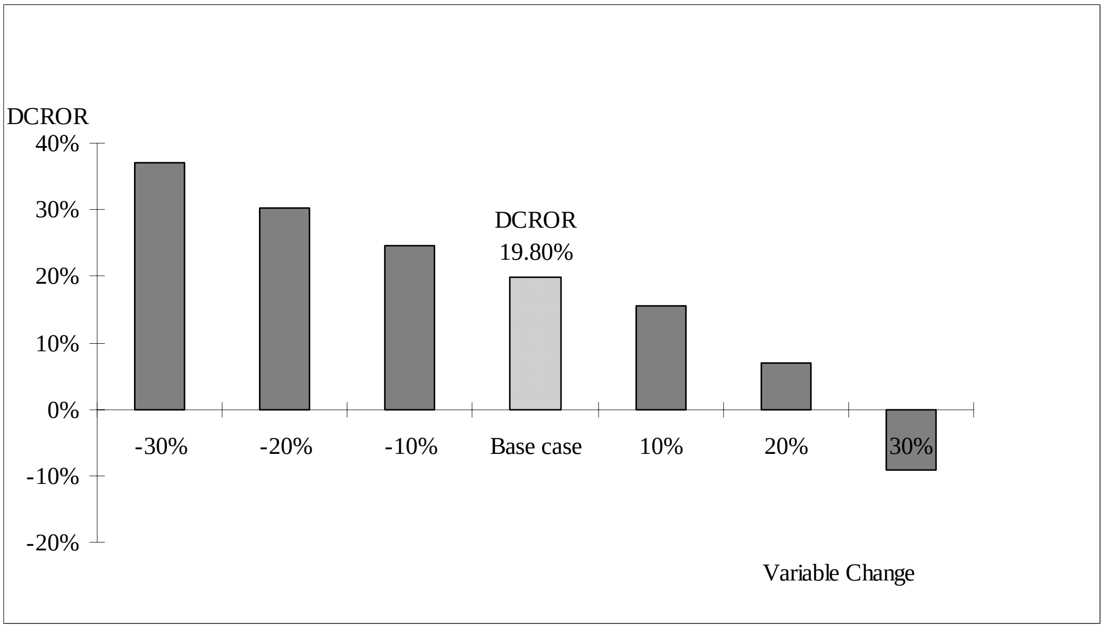

Figure 3.8 Sensibility Analysis Variable: Fixed Investment Cost

Chapter 4. Conclusions

At the design specification, it is concluded that AD-CWS is a feasible, as well as a profitable project. This conclusion is derived from the theoretical results presented in Chapter 3 that shows that AD-CWS will treat all the waste produced by *Solidaridad Cafetelera* and transform the treated waste into biogas and fertilizer. The biogas generated by AD-CWS will have the potential to heat to the digester reactor, dry coffee beans, and provide fuel to the coffee plant.

The economic model for AD-CWS was built based on a working life of 15 years, with two years required for construction and set-up. The 3rd year the plant will start operating, and generating assets: biogas and fertilizer. It is assumed that AD-CWS will charge a fee of 18.96% of the average coffee processing operating cost; the fee was set to be \$0.03 per kg of coffee waste (Chapter 3). The solid fertilizer will be sold at \$50 per ton and the liquid fertilizer will be sold at \$0.599 per kg of nitrogen. The biogas, assumed to be 65% methane, is expected to generate \$46,047. The reference price used for methane is \$8.5 per MM BTU, the expected price for the region of Veracruz[35, 36]. The total expected revenue for the AD-CWS model is \$355,974.83 annually.

The cost estimation performed for the model is class 4, implying that the estimated cost have a deviation from the true cost of 40% over and 25% under. The cost framework was performed based on the cost engineering scheme used in chemical engineering[24, 26]. The fixed capital investment cost was based on the model given by

Hashimoto and Chen[25] for AD digestion plants. The exchange rate for Mexican pesos and US dollars was 10 pesos per US dollar and all costs have 2006 as the base year.

The fixed capital investment cost is estimated to be $647,227 yearly, variable or operating cost is $191,616. The working capital cost is $0.40 million, one month worth of variable cost. The plant will start operations on year 2, with expected profits of $164,358 a year. The AD-CWS cost model yields a Discounted Rate of Return (DCROR) of 19.8%. This means that 19.8% is the project's maximum interest rate that AD-CWS is allowed to borrow from a financial institution to break even.

Likewise, from the discounted cash flow analysis it was found that at 10% interest rate the estimated discounted payback period, the time necessary to recover the working capital ($39,644.85), is 6.64 years and the discounted break-even point is at 7.12 years. An interest rate of 10% is considered to be the maximum interest rate the project may encounter; therefore it is considered the worse case scenario. If the interest rate is 5%, the optimum interest rate to be found in the 2006 US financial market, the payback period will be 5.64 years and the discounted break-even point will be at 5.96 years. However, it is more realistic to evaluate the project profitability at 10% interest rate.

At 10% interest rate, the project net present value was found to be $440,971.58. The present value ratio yielded 1.67; which gives a relationship between positive cash flow and negative cash flow. A present value ratio higher than 1 yields a profitable project. Although the capital cost is high, AD-CWS has an expected internal return of investment of 19.8% which is attractive compared to a low risk alternative, like US treasury bonds which have a return of about 5.31% for a 15 year bond[39].

In order to place AD-CWS in context, it is of value to compare it to a project of similar magnitude and technology. Washington State received a proposal to build a thermophilic anaerobic digestion, similar to AD-CWS. This project was developed to treat waste from dairy cattle with an estimated capital cost of $7 million[40]. This proposed project will have a 9,474 m^3 digester reactor capacity and will sell fertilizer and electricity from biogas generation. The Washington State project proved to be of higher cost per m^3 of digester than AD-CWS, due mainly to reactor cost, transportations cost, electricity generator equipment, as well as installations and constructions costs. However, the anaerobic digestion project in Washington State has an estimated internal rate of return of 13.89%.

In many other regions in which AD has been proposed, AD cannot be developed due to high transportation costs to distribute fertilizer and very high capital costs. The comparative advantage of AD-CWS over the AD project in Washington State and others lies in the fact that Huatusco is located in an agricultural area with a well-developed fertilizer market, proximity to crops, and diminishing transportation costs. In addition installation, construction and labor costs are substantially lower in Huatusco compared to Washington State. Although the possibility to generate electricity from biogas exists as it is the case of the proposed AD in Washington State, the additional expense for electrical generator grid accessibility increases the capital cost of the project. Therefore, the use of biogas as a fuel to dry coffee beans represents a more attractive option. Also, Huatusco has the potential to use the biogas for domestic uses in the coffee plant or to sell to the community.

Although these two projects differ from each other, both are characterized by its high capital cost and less than 20% rate of return. Therefore, it is important to approach anaerobic digestion technology not as a business enterprise, but on the contrary, as a waste treatment alternative that provide enough assets in fertilizer and biogas to be economically feasible. Moreover, in the case of AD-CWS, it is capable of treating coffee waste without becoming an economic burden for the coffee industry. And in the long run, the high capital cost will be downplayed by AD-CWS capability to procure fine avoidance.

The AD-CWS economic model charges a fee of $0.03 per kg of coffee waste, base case, which represents 18.96% of the average coffee processing cost[6]. Consecutively, the sensitivity analysis performed found that the coffee waste processing fee and the fixed capital investment cost of AD-CWS were the most important variables affecting profitability. In the case of the coffee waste processing fee, it was found that a fee 45% lower than the base case, $0.0165l per kg of coffee waste, make the project fail because it yields a discounted rate of return of -4.23% (Table 3.14). Likewise, if the fixed capital investment cost, at base case $647,227.31, rises 30% to $1,110,642.06, the project will be unprofitable, yielding a discounted rate of return of -9.09% (Table 3.18).

The most significant finding about the evaluation of AD-CWS is that the system has the potential to provide revenue by producing methane and fertilizer, and eliminates the need to treat the wastewater and compost coffee pulp. The success of AD lies in its ability to sell solid and liquid discharge as fertilizer.

Moreover, AD-CWS has the potential to prevent the disposal of coffee wastewater, about 73.62 m^3 a day, in the Huatusco's rivers. More importantly, the

Mexican government, through environmental regulations, has been pressuring the industry to manage its coffee waste problem. It is foreseen that in the near future, the government will increase the standards of waterways environmental quality, which will put economic pressures in Huatusco's already strained coffee industry. Therefore, it is important to develop a viable proposal to treat waste, such as AD technology and the proposed AD-CWS model.

Through this study, the design and economical feasibility of AD-CWS has been proven. The proposed model, AD-CWS, will not only offer an option to the current practices of coffee processing waste treatment, but also will generate revenue through fertilizer and methane sales. At this time, further studies are needed to verify the biogas yield from coffee pulp at thermophilic temperatures (above 55°C) in order to properly forecast revenues. Enforcement of environmental laws in Mexico may result in fines to the coffee plants that fail to comply, thus increasing coffee processing operating costs. AD-CWS can help the coffee industry comply with environmental regulations and avoid fines.

More importantly, the major significance of the AD-WS model is to provide a viable solution the problem of coffee waste in Mexico and so preserve an industry that is key to the region. Ultimately, the main objective of the plant is also to provide the region with the capability to learn and absorb the anaerobic digestion technology and initiate a new industry that will help preserve the environment and provide jobs to the surrounding community. In the case there is an anaerobic digestion technology transfer a Mexican human capital will be trained and be able to obtain better jobs and pay in their communities without having to migrate to urban areas or to other countries. Also, a possibility exist that the coffee will be sold at a higher price under an environmentally friendly label, increasing the income of the industry.

Chapter 5. Recommendations

Further studies are needed to identify coffee waste exact biogas yield at thermophilic temperature in order to refine the project design. Also, there is a lack of serious and sophisticated research in this area, this is necessary in order to understand how to best manage coffee waste in anaerobic digestion.

With refined information about how coffee waste behaves in anaerobic digestion, and a better reference of biogas yield optimum design studies need to be performed. The optimum design study will provide information about how to best design an anaerobic digester plant that treat most of the coffee waste at the lowest cost possible. This way, a package design can be developed that can be deployed in any coffee processing area in the world.

In order to refine the cost of the model, it is recommendable that all costs are reviewed based on the country conditions. The AD-CWS model is based on the specific circumstances of Huatusco Mexico, but in order to simplify cost estimation, the fixed capital cost of the plant was based on US prices. Further costs estimation will need to included the tax structure of Mexico or the area where the plat will be built. For every country a cost should be adapted to the country’s circumstances.

Also, in further development, the plant design needs to be developed to include a pre-treatment lagoon that will work as an overflow storage when the reactor capacity is maximized or in the case that the digester is temporarily unavailable to prevent waste discharge.

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Appendix A Coffee Dryer Calculations

The calculations for the heat requirement of the coffee dryer are based on the model presented in *Food Process Design* by Maroulis and Saravacos[1]. As follow, Figure A.1 describes the dryer block diagram used to model the coffee dryer.

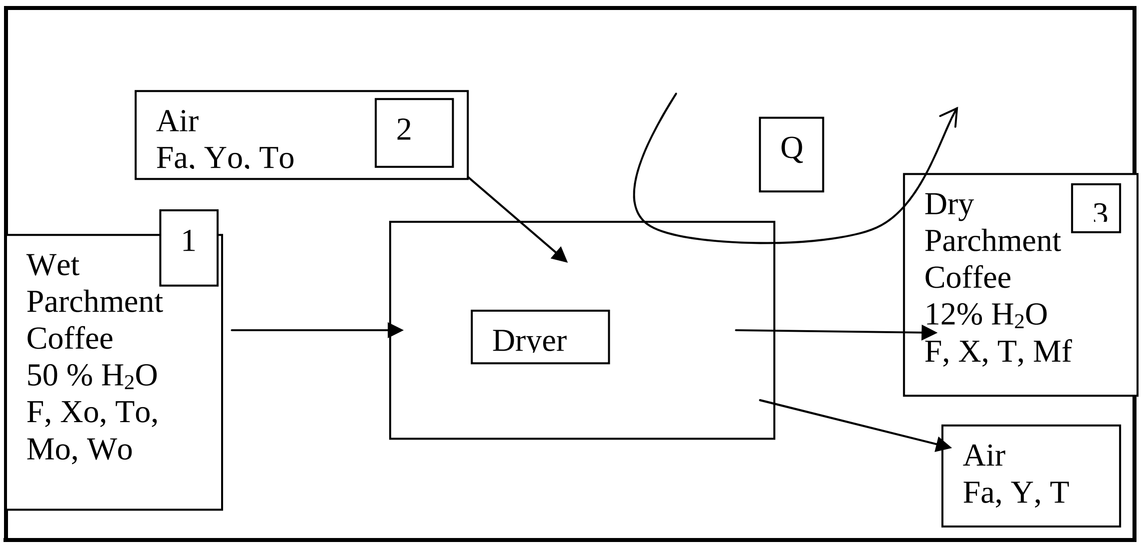

Figure A.1 Coffee Dryer Block Diagram

The process variables, Table A.1, shows the different variables used for the drying air, dryer, thermal load, material to dry and dryer performance. The material to dry is wet parchment coffee bean at 50% humidity as is shown in the step 1 of the block diagram (Figure A.1).

Table A.1, shows the process data, which is the data about coffee, air and methane needed to perform the different calculation in Table A.5.

The process data (Table A.2) contains the data necessary for each material, which are the specific heat of water, coffee beans and air and latent heat for water, the density of methane and the heat of combustion for the methane.

Table A.1 Coffee Dryer Process Variables

Drying air		Dryer	
Fa ton/h	fresh air flow rate	W t/h	Drying rate
T ^oC	Drying air Temperature		
Y kg/kg db	Drying air humidity	Thermal Load	
To ^oC	Ambient Temperature	Qwe kW	Water vaporization
Yo kg/kg db	Ambient humidity	Qsh kW	Solid heating
		Qah kW	Air heating
		QkW	Total thermal load
Material		Performance	
Mo kg/day	Material Mass Input	n	Thermal efficiency
M1 kg/day	Material Mass output		
F t/day db	Material Flow Rate		
Xo Kg/kg db	Initial Moisture Content		
X Kg/kg db	Final Moisture Content		

Table A.2 Coffee Dryer Process Data

Specific heat (kJ/kg K)		Latent heat (kJ/kg)	
		ΔHo	Steam condensation at 0^oC
		Methane (CH_4) density	kg/m^3
Cpl	Water	Methane Molecular weight (MW CH_4)	
Cpv	Water vapor	Heat of Combustion kJ/mol	ΔHc
Cpa	Air		
Cps	Dry material		

Table A.3 and A.4 explain the different process specification values set up for the model. The different nomenclature used is explained in Table A.1. The drying air humidity (Y) was calculated using a Psychrometric chart at relative air humidity of 90% and 25°C, Table A.3 and A.4. Table A.4 shows the conditions set up for the model, called design variables. Based on these design variables, the heat requirement for the dryer will be calculated.

Table A.3 Coffee Dryer Process Specification

Mo	22,016.49		kg/day Wet Parchment Coffee		
XWo		50	% fresh base		
W1		0.5	gr of H_2O per 100 gr of total basis		
Mf	10,479.85		kg/day Dry Parchment Coffee		
XWf		12	% fresh base		
W2		0.12	gr of H_2O per 100 gr of total basis		
Mo dry base	11,008.25		kg /day db		
1 day => sec		86400	sec		
F		0.127	kg/sec db		
Xo		1.000	kg/kg db		
Xf		0.136	kg/kg db		
To °C		25	°C	298.15	K
RH		90%			
Yo		0.018	kg/kg db		

Table A.4 Coffee Dryer Design Variables

Y	0.14	kg/kg db	RH	90%
T	60	°C	333.15	K

The Table that follows, A.5, indicates the process equations used in the coffee drying model. These are the equations set up by Maroulis and Saravacos and the material and heat balance for a food dryer system. The different variables are explained in Table A.1.

Table A.5 Coffee Dryer Process Equations

Material balance			
X=W1/(1-W2)	F=(XWo/100)*Mo	W=F(Xo-X)	W=F(Y-Yo)
Thermal energy requirements			
Q=Qwe+Qsh+Qah		Qwe=F(Xo-X)[ΔHo-(Cpl-Cpv)T]	
Qsh=F[Cps+XoCpl](T-To)		Qah=Fa[Cpa+YoCpv](T-To)	
Mass m= Q/ΔHc		Density ρ=m/v	Performance index n=Qwe/Q

Table A.6, indicates the calculation procedure and equations used to derive heat requirement (Q) and fuel volume for methane (CH_4) and biogas. The heat capacity for coffee (Cps) was calculated separately and it is explained in Appendix B.

This model, based on figure A.2, to dry 22,016.49 kg (Mo) of wet parchment coffee bean at 50% moisture to 12% needs 255.331 kW (Q). It also means that 595.71 m^3 of methane or 899.62 m^3 of biogas at 65% methane will be needed daily.

Table A.6 Coffee Drying Calculations

Process specification			Process Design results		
F	0.127	kg/kg db	Drying air		
Xo	1.000	kg/kg db	Fa	0.90193556	kg/sec
x	0.136	kg/kg db			
			Thermal load		
To	298.15	K			
Yo	0.018	kg/kg db	Qwe	190.8857412	kW
Design variables			Qsh	31.79830802	kW
Y	0.14	kg/kg db	Qah	32.64736147	kW
T	333.15	K	Q	255.3314107	kW
Process Data			Performance		
Cpa air T=25^{o}C or 298K	1	kJ/kg K	n	75%	
Cpl water T=25^{o}C	4.2	kJ/kg K	Energy requirements		
Cpv water vapor	1.9	kJ/kg K	Q	255.3314107	kW
Cps 50% $H_2$0	2.93	kJ/kg K	Q	255.3314107	kJ/sec
CH_4 density *	0.667151	(Kg/m^3)	Q	22,060,633.88	kJ/day
ΔHo*	2501	kJ/kg			
MW CH_4*	16.04		Methane Requirement		
ΔHc *	890.36	kJ/mol	Mass	397.43	kg/day
ΔHc *	55,508.73	kJ/kg	Volume	595.71	m^3/day
ΔHc Biogas †	24,522.09	kJ/m^3	Volume	21,037.19	ft^3/day
65% CH_4			Biogas Requirements		
ΔHc =Q/volume			Volume	899.62	m^3/day

* Based on Felder[2]
† Based on U.S. Department of Energy[3]

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Appendix B Specific Heat Calculations

In order to determine the specific heat for wet parchment coffee bean at 50% humidity the equations for the specific heat of major food components was used. This equation are shown in Saravacos and Maroulis[1](2003, 489). Equations B.1 and B.2 are used to calculate the specific heat of wet parchment coffee beans.

$Cp = (\sum Xi) \text{ X } (Cpi)$ (Equation B.1)

$Cpi = b_0 + b_1T + b_2T^2$ (Equation B.2)

Cp: specific heat of food

Cpi: Specific heat of component i

Xi: Weight fraction of component i

T: temperature (^oC)

Equations B.1 and B.2 are based on Maroulis[1], Zacharias B. 2003, 489).

The coefficients b_o, b_1 and b_2 in equation B.2, are coefficients set up for every component that is part of a specific food and they are reproduced from Maroulis and Saravacos in Table B.1.

In order to calculate specific heat, it was necessary to obtain the composition of the wet parchment coffee beans or green coffee beans. Green coffee beans are the coffee bean state before they are roasted, they can be approximated to wet parchment coffee, by adjusting its humidity to 50%. Green coffee bean dry weight composition and wet parchment coffee at 50% humidity composition is shown in Table B.2.

A continuation, equation B.2 was used to find Cpi for every component, at 25^oC. The results are displayed in Table B.1, column 7. Consequentially, the result from Table

B.2 and column 7, are multiplied by the weight fraction composition of the wet parchment bean at 50% humidity (*Xi*) X (Cpi), the procedure is shown in Table B.3.

Table B.1 Specific Heat of Foods

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Components	bo	b_1	T	b_2	T^2	Cpi (Eq. B.2)
Protein	2.01	1.21E-03	25	-1.31E-06	625	2.04E+00
Fat	1.98	1.47E-03	25	-4.80E-06	625	2.01E+00
Carbohydrate	1.55	1.96E-03	25	-5.94E-06	625	1.60E+00
Ash	1.09	1.89E-03	25	-3.68E-06	625	1.13E+00
Water	4.18	-9.09E-05	25	5.47E-06	625	4.18E+00

Table B.2 Composition of Wet Parchment Coffee Bean 50% Humidity

Components	*Xi* (weight fraction of component) gr / 100g green coffee dry base*	Weight (gr) in 100gr of dry coffee bean	*Xi* gr / 200g Wet parchment coffee at 50% humidity
protein	14.5	14.5	0.0725
fat	10.3	10.3	0.0515
carbohydrate	70.3	70.3	0.3515
ash	4.9	4.9	0.0245
total	100	100	0.5
*Based on Franca[2]			

In Table B.3 it is calculated Xi Cpi for every component. then all (*Xi*) X (Cpi) are added, and the specific heat for wet parchment coffee is determine. The specific heat of wet parchment coffee at 50% humidity (Cps) is 2.93 kJ/kg K, as indicated in Table B.3.

Table B.3 Specific Heat Final Calculations

Components	Cpi (Table B.1)	*Xi* (Table B.2)	Cpi (Eq. B.1)
protein	2.04E+00	0.0725	1.48E-01
fat	2.01E+00	0.0515	1.04E-01
carbohydrate	1.60E+00	0.3515	5.61E-01
ash	1.13E+00	0.0245	2.78E-02
water	4.18E+00	0.5	2.09E+00
	Cps To 50% humidity (kJ/kg K)		**2.93E+00**

References

1. Maroulis ZB, Saravacos GD. *Food Process Design.* New York: Marcel Dekker; 2003.

2. Franca A, Mendonca J, Oliveira S. Composition of green and roasted coffee of different cup quality. *Swiss Society of Food Science and Technology*. 2004.

Appendix C Fixed Capital Investment Cost

The fixed capital investment cost was calculated based on the preliminary information of capital cost of similar anaerobic digestion plants. Therefore, the fixed capital investment cost was calculated using the fixed capital investment cost formula by Hashimoto and Chen for Anaerobic Digestion (AD) plants[1].

It is assumed through this study that the exchange rate for Mexican pesos and US dollars is 10 pesos per US dollar. All values are given in US dollars unless otherwise indicated.

Tank liters with 10% gas headspace (m^3)	1,466.03
Tank Volume	1,500
*Fixed Capital Investment Cost	2,970 X $(\text{Tank Volume})^{0.7}$
Fixed Capital Investment Cost 1979 US $	496,615.57
* Based on Hashimoto and Chen[1]	

In order to adjust the capital cost to the conditions of Huatusco, Mexico, the equipment cost was extracted from the fixed capital investment cost estimated using Hashimoto and Chen. The procedure is shown in Table C.1.

Table C.1 Fixed Capital Investment Cost Break Down

Fixed Capital Investment Cost in 1979 is $496,615.57		
engineering and inspection fees	20%	of purchase equip cost (CC)
contingency	10%	of purchase equip cost (CC)
escalation and start up	12%	of purchase equip cost (CC)
installed	10%	of purchase equip cost (CC)
	52%	of purchase equip cost (CC)

Based on the information above, the equipment cost for the anaerobic digestion plant using Hashimoto and Chen equation, was found to be $109,870.00.

Table C.2 Estimation of Fixed Capital Investment Cost

Direct Costs		
A. Equipment + Installation + Instrumentation + piping + electrical l+ insulation + painting		Cost Index
This quantities all refer to the equipment cost		
Purchase Cost	$ 109,870.00	22%*
Installation (25%)	$ 27,467.50	25%*
Instrumentation (18%)	$ 19,776.60	18%†
Piping (10%)	$ 10,987.00	10%*
Electrical (10%)	$ 10,987.00	10%*
Total A:	**$ 179,088.10**	
B. Buildings, Process and auxiliary		
This quantities all refer to the equipment cost		
<u>Buildings</u>	$ 10,987.00	10%*
C. Service facilities		
<u>Service</u>	$ 43,948.00	40%*
D. Land ‡	$ 0.00	
Total B:	$ 54,935.00	
Total Direct Cost (A+B)	**$ 234,023.10**	
Indirect Costs		
This quantities all refer to the total direct costs		
<u>A. Engineering and supervision</u>		
Engineering	$ 70,206.93	30%§
<u>B. Construction</u>		
Construction	$ 14,041.39	6%*
<u>C. Contingency</u>		
Contingency	$ 11,701.16	5%*
Total Indirect Cost	**$ 95,949.47**	
Fixed Capital Investment Cost	**$ 329,972.57**	

* Based on the low index value[2]
† Based on the average index value[2]
‡ Assumption that the land is already available
§ Based on upper index value[2]

In Table C.2, the fixed capital investment cost components are adjusted to Huatusco, Mexico special circumstances of low construction and labor cost. In the tables below, it can be notice that the lowest cost index range given in Timmerhouse, et al[2] were taken into consideration when calculating the components of direct and indirect cost for the fixed capital investment cost. Table C.2 describes the procedure followed to calculate the fixed capital investment cost for AD-CWS.

To adjust the total capital cost formula from 1979, when the Hashimoto and Chen formula was published, to 2005, the Chemical Engineering Plant Cost Index (CEPCI) was used; in Table C.3 the calculation adjustment is shown.

Table C.3 Total Fixed Capital Investment Cost Adjustment

	Fixed Capital Investment Cost	CEPCI
FICC 1979	329,975.57	238.7 *
FICC 2005	647,227.31	468.2†

*Institute of Chemical Engineers 1988[3]
†Institute of Chemical Engineers 2006[4]

Variable Cost Model

Variable cost or operating cost was calculated using the cost index factor shown in the Table C.4. These cost indexes were based on the cost-variable model in Turton, et al[5]. The figures used for the cost index factors are average or middle range. The fixed capital investment cost was calculated using the equation by Hashimoto and Chen[1] described above. The base year is 146 days. Variable cost came up to be $191,616.76.

Table C.4 Cost Estimation for AD-CWS in Huatusco, Mexico			
(All numbers in US dollar at 2006 base year)			
		Yearly (145 days)	Cost Index Factor
	Fixed Capital Investment Cost	647,227.31	FCI
Variable Cost			
1	**Direct Costs**		
a	Raw Materials	0	
b	Waste treatment	0	
c	Utilities		
	electric power	0	
	boiler feed water	0	
	Total Utilities	722.22	C*ut*
d	Operating labor	4,785.00	C*ol*
e	Direct supervisory and clerical labor	861.30	0.18 X C*ol*
f	Maintenance and repairs	38,833.64	0.06 X FCI
g	Operating supplies	5,825.05	0.009 X FCI
h	Laboratories charges	717.75	0.15 X C*ol*
I	Patents and royalties	0	
	Total Direct costs	51,744.96	
2	Fixed Costs		
a	Depreciation	64,722.73	0.1 X FCI
b	Local taxes and insurances	20,711.27	0.032 X FCI
c	Plant overhead cost	26,687.96	0.708 X Col + 0.036 X FCI
3	**General expenses**		
a	Administration costs	6,671.99	0.177 X Col + 0.009 X FCI
b	Distribution and selling costs	21,077.84	0.11 X COM
c	Research and development	0	
	Total Fixed Costs	139,871.80	
	Total Variable costs	191,616.76	COM
	TOTAL COST Capital + Variable Cost	**838,844.06**	

Table C.5 Cost Estimation Summary for AD-CWS in Huatusco, Mexico

(All numbers in US dollar at 2006 base year)	
Fixed Capital Investment Cost (FCIC)	647,227.31
Variable Cost (COM)	191,616.76
Variable Cost per day (based on a 145 day-year)	1,321.49
Working capital (30 days worth of COM)	39,644.85
Total Capital Investment Cost (FCIC + WC)	686,872.15

References

1. Hashimoto AG, Chen YR. The overall economics of anaerobic digestion. In: *Anaerobic Digestion : [Proceedings of the First International Symposium on Anaerobic Digestion, Held at University College, Cardiff, Wales, September 1979]*. London: Applied Science Publishers; 1980:449.

2. Max S. P, Klaus D. T, Ronald E. W. *Plant Design and Economics for Chemical Engineers.* 4th ed. New York: McGraw-Hill; 1991.

3. Institution of Chemical Engineers. Economics indicators. *Chemical engineering research & design*. 1988;66:9.

4. Institution of Chemical Engineers. Economics indicators. *Chemical engineering research & design*. 2006;117:104.

5. Turton R, Bailie R, Whiting W, Shaeiwitz J. *Analysis, Synthesis, and Design of Chemical Processes.* 2nd ed. NJ: Prentice Hall/PTR; 2003.

Appendix D AD-CWS Process Flow Diagram

Equipment List

Displayed Text	Description	Displayed Text	Description	Displayed Text	Description	Displayed Text	Description	Displayed Text
Pul-1	Depulper	Pul-1	Depulper	E-5	Feed Tank	E-8	Solid Screen	E-11
E-1	Fermentation Tank	E-3	Dryer	E-6	Solid Screen	E-9	Gas Blower	E-12
E-2	Washer Tank	E-4	Burner	E-7	Anaerobic Digester	E-10	Heat Exchanger	E-13