Final Technical Report

Energy Economics of Farm Biogas in Cold Climates

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Table of Contents

Lists of Figures, Tables and Appendices

Executive Summary

Many manufacturing companies use large amounts of energy. Food manufactures produce organic wastes that could be converted to energy using anaerobic digestion. Similarly dairy farms produce large amounts of manure that can be used as feedstock for anaerobic digestion, generating biogas that can be used in combine heat and power (CHP) systems to generate heat and electricity. Anaerobic digestion is a capital intensive process. The overarching hypothesis of this research is that combining high energy waste products (e.g. cheese whey) with dairy waste will improve the economic viability of the farm digestion system. Biogas can be used CHP systems or combusted directly in boilers to generate heat. In addition to internal combustion engines, micro turbines or fuel cells could be used to convert the biogas energy in mechanical energy. The goal of this research was to develop a model that would determine the most economical biogas use for a particular manufacturing process and to simulate the co-digestion of dairy manure with high energy compounds. A mathematical model was developed to determine the optimum biogas utilizing technology for Breyers Yogurt Company, a yogurt and cheese manufacturing plant in North Lawrence, New York. The plant produced cottage cheese and yogurt. The major manufacturing energy costs were from electricity and heat. In order to reduce these costs, the plant built a biogas generation system to utilize biogas and offset energy demand from fuel oil. The objective of this study was to evaluate biogas utilizing alternatives economically and to develop a tool that can determine the optimum technology for Breyers Yogurt Company.

The model was developed given the manufacturing constraints of the plant. This study focused on the major unit operations for yogurt and cottage cheese manufacturing. Mass and energy balances over these unit operations were studied and a mathematic model was developed consisting three interconnected models. First, the energy consumption model can be used to estimate the heat and power demand and associated cost given the production of the plant. Second, the energy generation model for the whole plant can estimate the biogas generation and corresponding energy generated from each alternative by using biogas. Four biogas utilizing technologies considered in the model include direct combustion, internal combustion engines, fuel cells and microturbines. Third, the overall economic evaluation model shows predicted cash flows for each alternative. The calibrated model was used to evaluate various possible scenarios as production level, its scheduling and variation in energy prices. The study concludes that for the present situation it is beneficial to use the biogas in the boiler to generate only heat. Having a slight difference in net annual savings, direct combustion and microturbines turned out to be most profitable alternatives for Breyers Yogurt Company.

To simulate the co-digestion of dairy manure and cheese whey the Dynamic Anaerobic Reactor & Integrated Energy System (DARIES) model has been developed as a biogas and electricity production model of a dairy farm anaerobic digester. DARIES, which incorporates the Anaerobic Digester Model No. 1 (ADM1) and models developed to simulate combined heat and power (CHP) and digester heating systems, may be run in either completely mixed or plug flow reactor configuration. DARIES biogas predictions were shown to be statistically coincident with measured data from eighteen dairy facilities in the Northeastern United States. Comparison was also made to biogas predictions by the U.S. AgSTAR model FarmWare 3.4. DARIES electricity production predictions were verified by statistically comparing the predictions to data from the NYSERDA DG/CHP Integrated Data System. A model is valuable not only for its individual predictions but also for its ability to address research questions. Once verified as a working model, DARIES was used to

investigate the effect of operational and design parameters on model output. Sensitivity analysis was performed on DARIES using Morris's Elementary Effects method. DARIES output was shown to be most sensitive to influent flow rate, chemical oxygen demand (COD), and biodegradability, and somewhat sensitive to hydraulic retention time (HRT) and digester control temperature. The DARIES model was subsequently used to investigate energy how through the model. It was determined that the heat exchanger effectiveness parameters are very important to the digester heat balance. DARIES was also used to investigate the effect of hydraulic retention time (HRT) and codigestion on the ratio of methane production to digester surface (a proxy for benefit to cost ratio) and on the methane yield (L methane/L influent)(a proxy for degree of treatment). Tradeoffs between these two metrics were found when HRT was adjusted, and codigestion was found to improve both measures as long as the organic loading rate (g COD per L reactor per day) did not exceed the digester's capacity.

Both models accurately predicted plant energy consumption and digester performance respectively. The models represent a useful to evaluate the economic viability of this renewable energy process. Given economic inputs the model quickly can predict the economic viability of installing fuel-cells, microturbines, CHP or direct combustion systems at the dairy processing plant. The modular structure of the model allows for easy adaptation of the model for different processing facilities.

Introduction

The dependence of manufacturing facilities in northern New York on fossil fuels results in significant costs during times when oil and gas prices have increased significantly. Even before the recent fuel price increases, several cheese manufacturing plants and dairy farms have experienced economic difficulties, related in part to energy costs. At the same time, priorities intended to reduce dependence on foreign oil have been established by the State of New York and the Federal Government by promoting the use and development of biofuels. The development of energy supplies from local biomass resources not only increases our energy security, it also provides economic relief to the struggling dairy industry, especially when synergies among industry components or value-added processes are integrated into the bioenergy project. There is such a synergy between cheese manufacturing plants and dairy farms - waste cheese whey can provide a valuable feedstock into farm digesters. The wastewater treatment costs of the cheese manufacturing plant are reduced and the whey waste improves the performance and energy output of the farm digester. Indeed, it is believed that in northern climates and for smaller farms, digesters may only be economical if cheese whey waste or other similar food waste is added to increase the percentage of readily digested organic materials. Yet, policy instruments are not always correlated to the technically optimal operation of biogas systems. For example, the amount of food waste in a NY State farm digester is currently limited to 25% by volume in order to qualify for net metering benefits. It is unclear how this legislative limit affects the overall economics of the manure digester and dairy processing plant. It is further unclear how transportation distances, temperatures and composition of the high organic content waste will affect farm and plant economics.

Analysis of the value of biogas generation at a farm or cheese manufacturing plant is complicated by the daily to seasonal variability in heat and power generation and needs. In fact, it is often tariffs associated the short-term power needs that result in excessive electricity bills. Optimizing heat and power from an on-site biogas system could contribute substantially to minimizing these costs. Without a detailed analysis and understanding of the dairy operations and energy recovery systems, along with tax incentives and tariff expenses, it is difficult to quantify the benefits and justify capital investments for digestion systems. Thus, the goal of the research completed here is to define critical variables and optimum combinations of waste streams to maximize the economic value of biogas generation and reduce consumption of fossil and imported fuel supplies.

This paper focuses on the gas and electricity usage at a Cheese manufacturing plant (Breyers Yogurt Company, St. Lawrence County, NY) and a farm (North Harbor Dairy, Sackets Harbor, NY). Niagara Mohawk, now known as National Grid, provides both the plant and the farm with their required electricity. The goal of this research was to investigate the heat and energy consumption at each facility and to determine the most economic use of biogas generated via anaerobic digestion at the Breyers Yogurt Company facility. A numerical model was developed to determine the impact of production changes, capital cost changes or economic incentives on optimum biogas utilization.

Background

Breyers Yogurt Company currently called St. Lawrence Yogurt company, is located in North Lawrence, New York. The facility produces varieties of yogurt and cheese. It processes 300 million pounds of milk per year and produces approximately 33,750 kg/day of cottage cheese and 151,000 kg/day of yogurt.

The entire milk processing facility can be divided into three compartments: (1) milk pasteurization and fat removal (i.e. pretreatment of raw milk), (2) cottage cheese process and (3) yogurt process.

Cottage cheese manufacturing

Process Overview

Cottage cheese is a soft granular un-ripened cheese in which the curd granules are lightly coated with a salted cream dressing. It is made from skimmed, pasteurized milk by inoculating it with a lactic acid-producing starter. The starter normally consists of lactic acid-producing bacteria. There are two types of cheese depending on the set time. Long-set cottage cheese is incubated at 21-23˚C for 14-15 hours, whereas short-set Cottage cheese is incubated at 30-32^{O}C for 4-5 hours (Fox and others, 2000).

The major steps for cottage cheese manufacturing can be described as follows (Figure 1).

Homogenization is the process in which desired characteristics of milk are achieved through treatment. Filtration, addition or removal of fat, addition or removal of cream may be carried out during homogenization as required (Fox and others, 2000).

Pasteurization is the process of killing all potential pathogens that may be present in the feed stream. It is achieved by either batch pasteurization (low temperature holding) or high temperature short time pasteurization. Batch pasteurization is carried out at 63^{O}C for 30 min while high temperature short time pasteurization occurs at 72^{o}C for 15 seconds (Pasteurization milk ordinance, 1989).

Pasteurization of cheese milk may damage its cheese making properties if the heat treatment is too severe or exposure is too long. The extent of this damage is negligible under high temperature short time pasteurization conditions, however (Fox et al., 2000).

Curd formation: After the milk has been standardized, pasteurized, or otherwise treated, it is transferred to vats. These vats are of various shapes (hemispherical, rectangular, vertical cylindrical or horizontal cylindrical), may be open or closed, and may range in size from a few hundred liters to 30,000 liters. Here, it is converted to cheese curd, a process that involves three basic operations: acidification, coagulation, and dehydration (Fox et al., 2000).

Acidification is usually achieved through the in situ production of lactic acid through the fermentation of the milk sugar (lactose) by lactic acid bacteria. Coagulation involves coagulation of the casein component of the milk protein system to form a gel. And coagulation may be achieved by limited proteolysis by selected proteinases (rennets), acidification at a pH of 4.6 or acidification to a pH value greater than 4.6 and with additional heating to 90^{O}C (Fox et al., 2000).

Other processes for special operations as cheddaring, stretching, salting, molding and pressing may be carried out. Thus formed cheese curds are packed and stored in refrigerator. Various dressings may be added while packing if required.

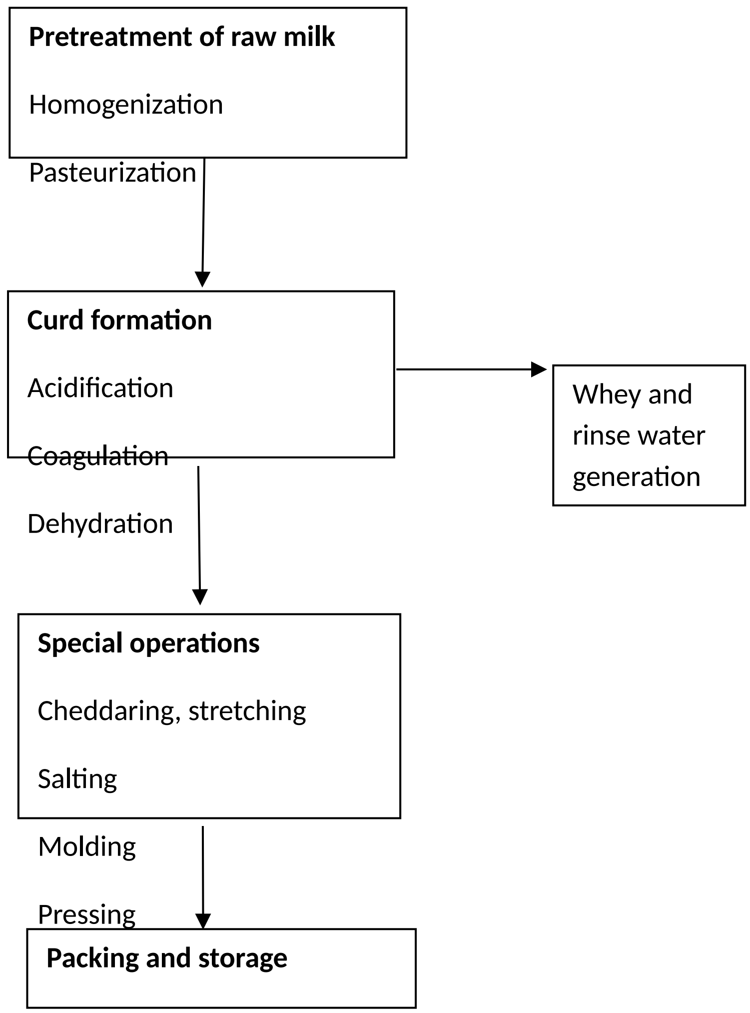

Figure 1: Important steps of cheese manufacturing

Typical waste generation during cottage cheese manufacturing

Waste generated from the milk processing cheese manufacturing has high organic content (Nemerow and Dasgupta, 1991). Typical waste characteristics are summarized in Table 1.

	Cheese Whey	Rinse water	Separated whey
Biochemical oxygen demand (mg/l)	32,000	1,890	30,100
Solids (mg/l)	72,000	41,516	54,772
Organic solids (mg/l)	64,000	2,698	49,618

Table 1: Characteristics of wastewater (Nemerow and Dasgupta, 1991)

Cheese whey is the liquid separated during curd formation. The rinse water is generated while cleaning the cheese curd after the whey has been drained. Thus whey and rinse water mainly contribute in waste generation from a cottage cheese processing plant. Approximately 9 liters of whey is generated to produce 1 kg of cottage cheese. Generally whey retains 50-55% of milk nutrients at a water content of 93% (Calli and Yukselen, 2002).

Yogurt manufacturing process

Yogurt is a milk product resulting from fermentation caused by thermophilic lactic bacteria, usually *streptococcus thermophilus* and *lactobacillus delbrueckli ssp. Bulgaricus* (Motttar 1989; Ginovart 2002). There are three major types of yogurts practically manufacturing in the world: set-type, stirred and drinking yogurt (Benezech, 1994). According to U.S. Food and Drug Administration (FDA), lowfat yogurt, with a similar composition to yogurt, has a milk fat content of 1 - 3%. Nonfat yogurt contains less than 0.5% milk fat. A typical yogurt manufacturing process includes pre-treatment, homogenization, fermentation, and cooling (Tamime, 1999) (Figure 2).

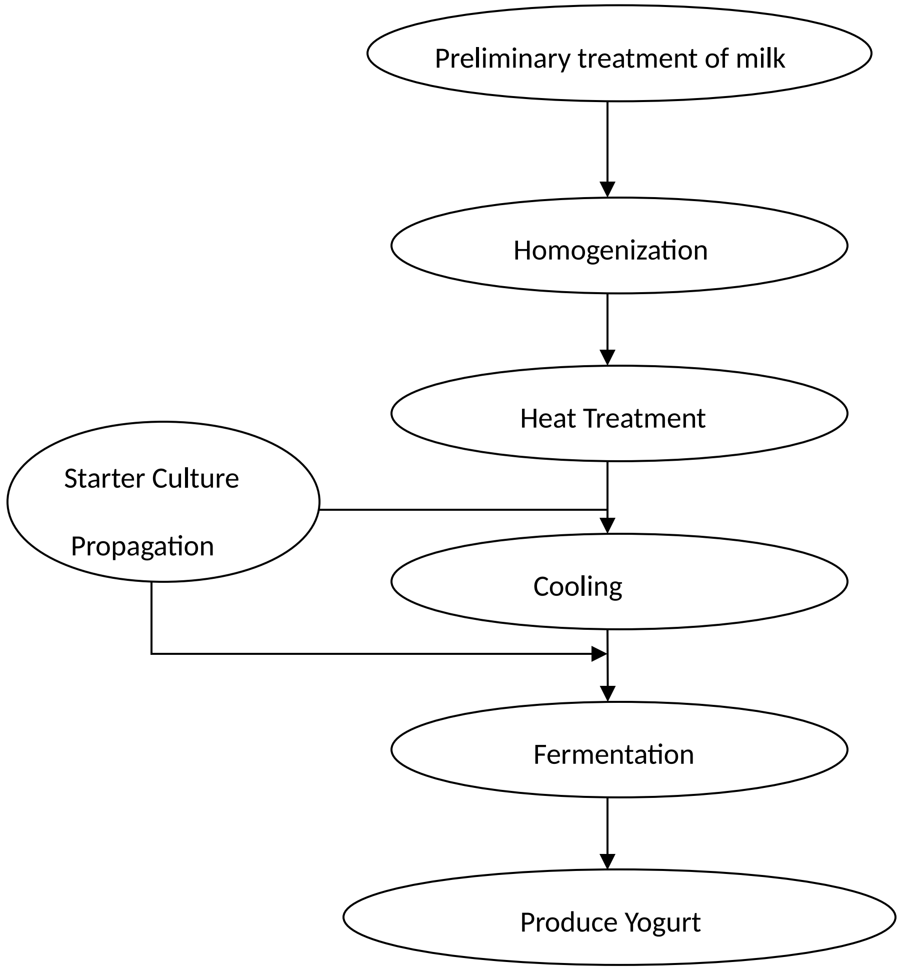

Figure 2: Process Schematic of Yogurt Manufacturing

Pre-treatment: Cellular matters and other contaminants (epithelial cells and leucocytes) present in milk are separated from raw milk. Then milk is standardized to achieve the desired fat content through removal part of the fat content from milk or mixing cream with skim milk, addition of cream to regular milk or skim milk followed by the use of standardizing centrifuges (Tamime, 1999).

Homogenization: The milk is homogenized to achieve enhanced stability, storage and body. Yogurt milk is an oil-in-water emulsion which may separate upon standing. In order to prevent this, the milk base is forced under a high pressure through a small orifice or annulus to achieve high speed mixing or homogenization (Tamime, 1999).

Heat treatment: The objective of heat treatment is to reduce pathogen and microorganisms concentrations without affecting milk base properties. Several heat treatment processes used in yogurt manufacturing are summarized in Table 1 (Tamime, 1999). The higher the temperature and the contact time, the higher the level of destruction of organisms. Thermisation is a low temperature process and at short contact time which can only result in destruction of psychotropic bacteria. Batch pasteurization and pasteurization is the mostly used processed in dairy industry with the destruction of pathogenic organisms and unchanged flavor. The other processes using higher temperatures may result in changed whey proteins and destructed micro-organisms.

Table 2 Typical Methods of Heat Treatment of Yogurt Milk Base

Time	Temperature °C	Process	Comment
Few seconds	≤65	Thermisation	Destruction of psychotropic bacteria with no other irreversible changes
30 min 15 sec	65 72	Batch pasteurization Pasteurization	Destruction of almost all pathogenic organisms, but not all vegetative cells; flavor and whey proteins stay unchanged.
4-20 sec 30 min 5 min	85 85 90-95	High pasteurization	Destruction of all vegetative cells but not bacterial spores; denaturation of whey proteins.
40-20 min 20-2 sec	110-120 130-150	In-Container sterilization and autoclaving Ultra high temperature	Destruction of all micro-organisms and spores.

Fermentation process: The heat-treated milk is cooled to the temperature of starter culture and then pumped to the fermentation tank. The starter culture is normally added directly to the milk. In general, the milk is fermented at 40-45 °C. The fermentation can either takes place in the retail container for set yogurt or in bulk for stirred yogurt. Set yogurt is left undisturbed during the fermentation and the resultant coagulum is in the form of continuous semi-solid mass. Stirred yogurt, by contrast, the coagulum structure is broken down at the end of fermentation and prior to cooling it is further processed to add flavorings or fruits or vegetables (Tamime, 1999).

Objectives

This proposed research aims to bridge and leverage existing research related to dairy waste-to-energy systems. Clarkson has been working both with a 500-head dairy farm (North Harbor Dairy) and a cheese manufacturing plant (Breyers Yogurt Company, Inc. in North Lawrence, NY) on related research. The goal of the overall ongoing project with North Harbor Dairy (NHD) is to determine the environmental and economic impact of a manure digester for NHD. Research included the optimization of the digester/combined heat and power system and a life-cycle assessment to determine the net environmental impact of manure digestion. In addition, a farmer survey has been conducted to determine their understanding and perception of digester technology. Feedback was used to focus the research effort on farmer identified obstacles of the digester technology. Research conducted at both the Breyers Yogurt Company and NHD sites will provide case studies for the research described here, but the analysis will not be limited to these facilities.

The specific objectives of this research included:

- Document the average and maximum monthly heat and electricity requirements and costs of a cheese manufacturing industry. (Tasks 1)
- Document the average and maximum monthly heat and electric energy and daily peak power requirements and costs of an example dairy farm. (Tasks 2)
- Identify best technologies for combined heat and power from the digester biogas (fuel cells, microturbines, gas engines) based on reliability, cost and ability to provide required heat and power needs. (Task 3)
- Determine optimal systems to minimize the net energy consumption and costs associated with various dairy waste mixtures (Task 3 and 4)
- Disseminate results in a manner useful to both technical and industrial/agricultural audiences (Task 5)

Project Tasks

Task 1: Cheese Manufacturing Plant Energy usage and waste analysis

Breyers Yogurt Company

Breyers Yogurt Company currently called St. Lawrence Yogurt company, is located in North Lawrence, New York. The facility produces varieties of yogurt and cheese. It processes 300 million pounds of milk per year and produces approximately 33,750 kg/day of cottage cheese and 151,000 kg/day of yogurt.

The entire milk processing facility can be divided into three compartments: (1) milk pasteurization and fat removal (i.e. pretreatment of raw milk), (2) yogurt process and (3) cottage cheese process.

Pre-treatment of raw milk: raw milk is separated in a separator into cream and skim milk. Then the cream and skim milk are pasteurized at 60 °C for 30 seconds and stored in different silos. The standardization method used at this plant is to mix cream and skim milk together to achieve desired fat content. Thus the mixture is processed to make yogurt.

Yogurt producing: Cream and skim milk are mixed in yogurt batch tanks and then pasteurized at 60 °C for 30 seconds. Then the mixed milk and yogurt starter are mixed in the yogurt set tanks. The fermentation takes about 3 hours in the yogurt set tanks. The yogurt base is formed in this process. This yogurt base is cooled in the cooling press. Flavoring and various fruits are prepared separately in tanks and added to yogurt if required.

Cottage cheese production. Cheese starters and processed milk are mixed in cheese vats. The whole mixture stays in cheese vats for approximately 3 hours. Curd and whey are formed in this process. The curd is sent to a curd drainer and then to a blender. Thus processed curd is packaged in packing machines and stored at 4 ^{O}C. Various fruit dressings are prepared separately in tanks and are added to cheese if required.

Pre-treatment of raw milk

First raw milk is processed in a milk separator to extract the cream from the raw milk. The skim milk is then pasteurized (55 °C for 30 seconds) and stored in various silos before use in the yogurt and cottage cheese process. The cream is pasteurized and stored in silos before use to control fat content in cottage cheese and yogurt. Access cream is transported off the plant. The schematic process flow diagram for pre-processing is shown in Figure 3.

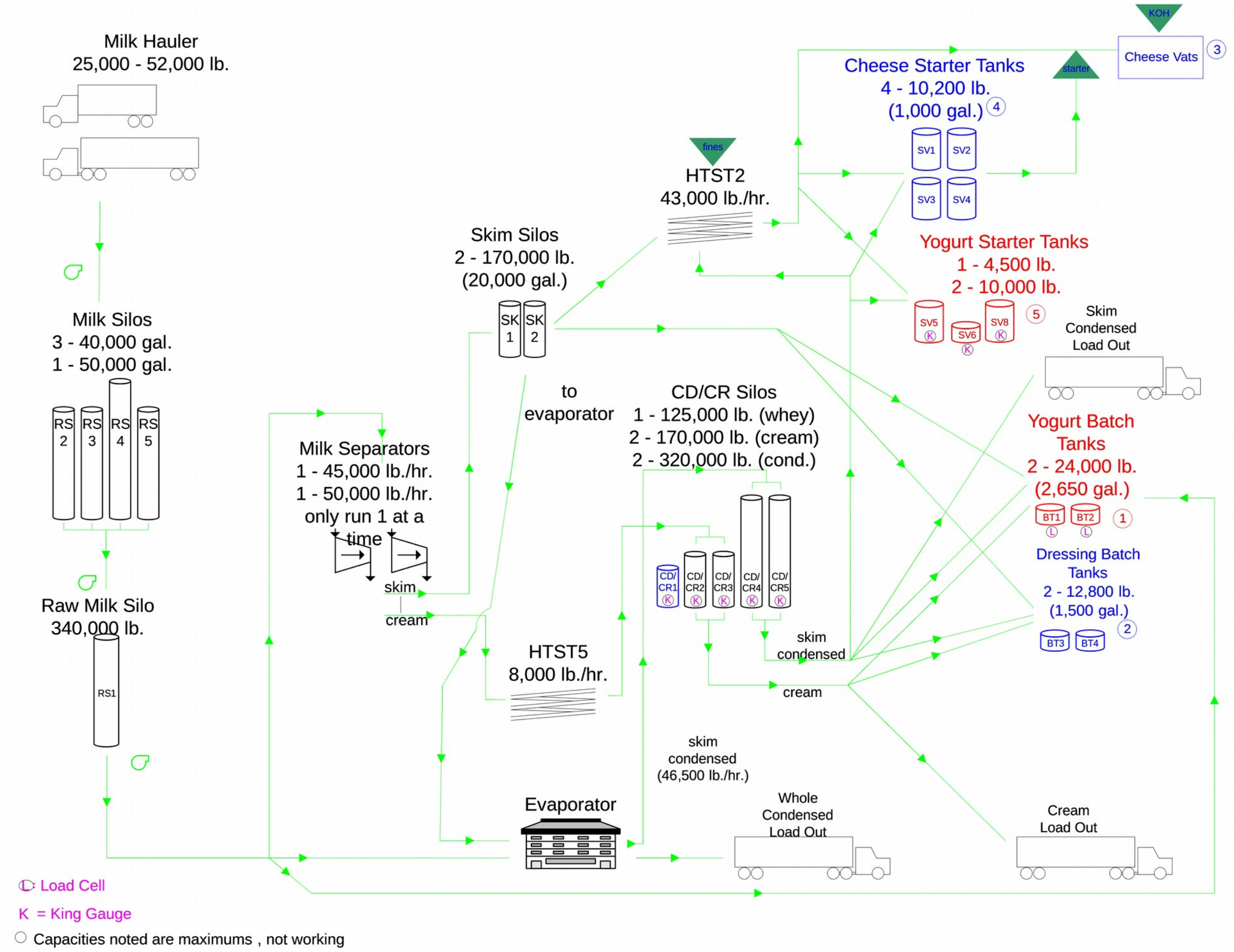

Figure 3: Flow Schematic of Milk Pre-Processing (Breyers Yogurt Company)

Breyers cottage cheese manufacturing process

Cheese starter is produced via fermentation of cultures in produced skim milk (Figure 3). Cheese starters and processed milk are mixed in cheese vats (Figure 4). The whole mixture stays in cheese vats for approximately 3 hours to produce curd and whey. The curd is sent to curd drainer, where it is washed, and then to blender adding dressing, cream to adjust fat content and various other constituents required for cottage cheese. Fruit dressings are prepared separately in tanks and are added to the cottage cheese either during blending (for premixed products) of during packaging (for fruit being packaged as a separate phase). Final product is packed in packing machines and stored inside the storage room at 4 ^{O}C. The whey generated in cheese vats is mixed with rinse water in whey tanks, treated in clarifier and then sent to the anaerobic digester. Before the installation of the anaerobic digester the water within this waste was reduced within the evaporator before disposal on area agricultural fields. This portion of wastewater represents the high strength wastewater stream as discussed below. The fines recovered from the clarifier are reused in curd preparation. The detailed process flow diagram for cheese manufacturing is as shown in Figure 4.

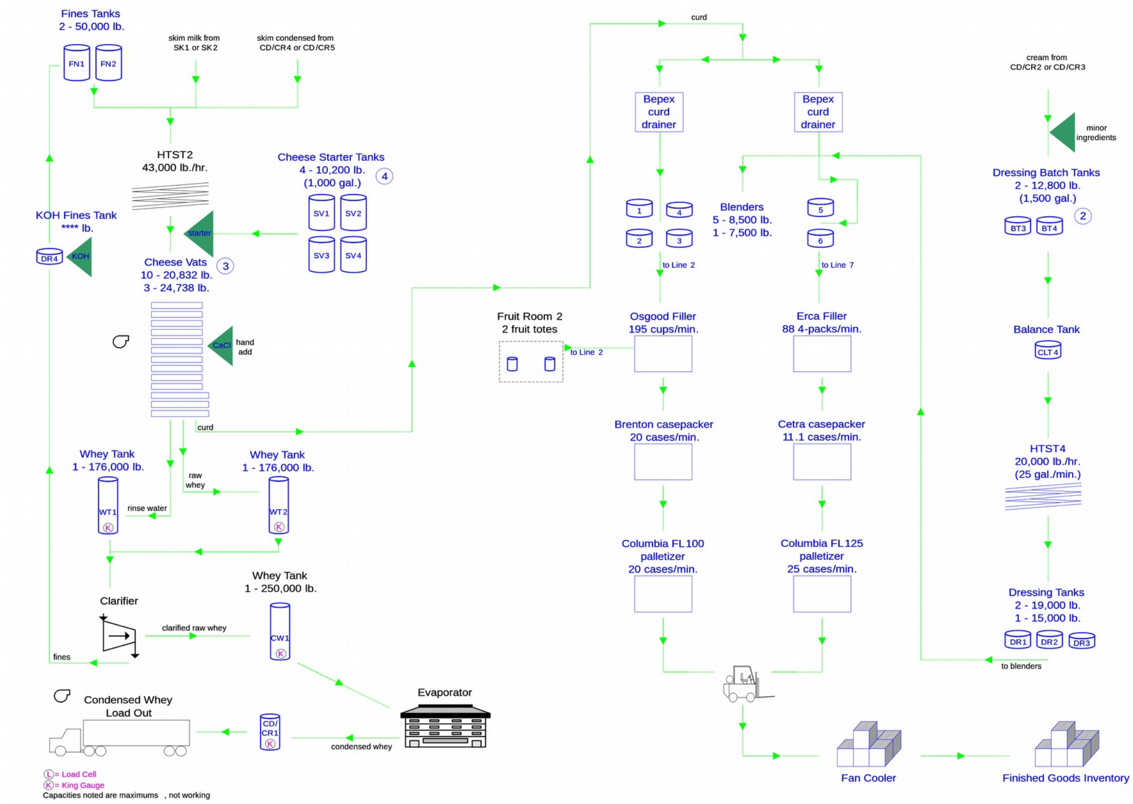

Figure 4: Breyers Yogurt Company Cottage Cheese process flow schematic

Yogurt Process.

The whole yogurt process mainly consists of four steps including milk separation, standardization, fermentation, and chilling. Figure 5 and Figure 6 greatly simplify the actual process representing every unit operation. Milk separation is the first step of making yogurt. Milk is transported to Breyers Yogurt Company by milk haulers every week and then pumped to milk silos with capacities of 40,000 gallons (151 m^3) and 50,000 gallons (189m^3). Milk is pumped to a large raw milk silos with capacity of 340,000 lb. The temperature is maintained at 40°F in all milk silos. Skim milk and cream are separated by milk separators, which have a capacity of 50,000 pounds of milk per hour.

Separated skim milk is stored in two skim silos with the capacity of 170,000 lbs each, while the cream is stored in two CD/CR silos (Figure 5) of the same capacity. Most of the skim milk is used within yogurt batch tanks without pasteurization.

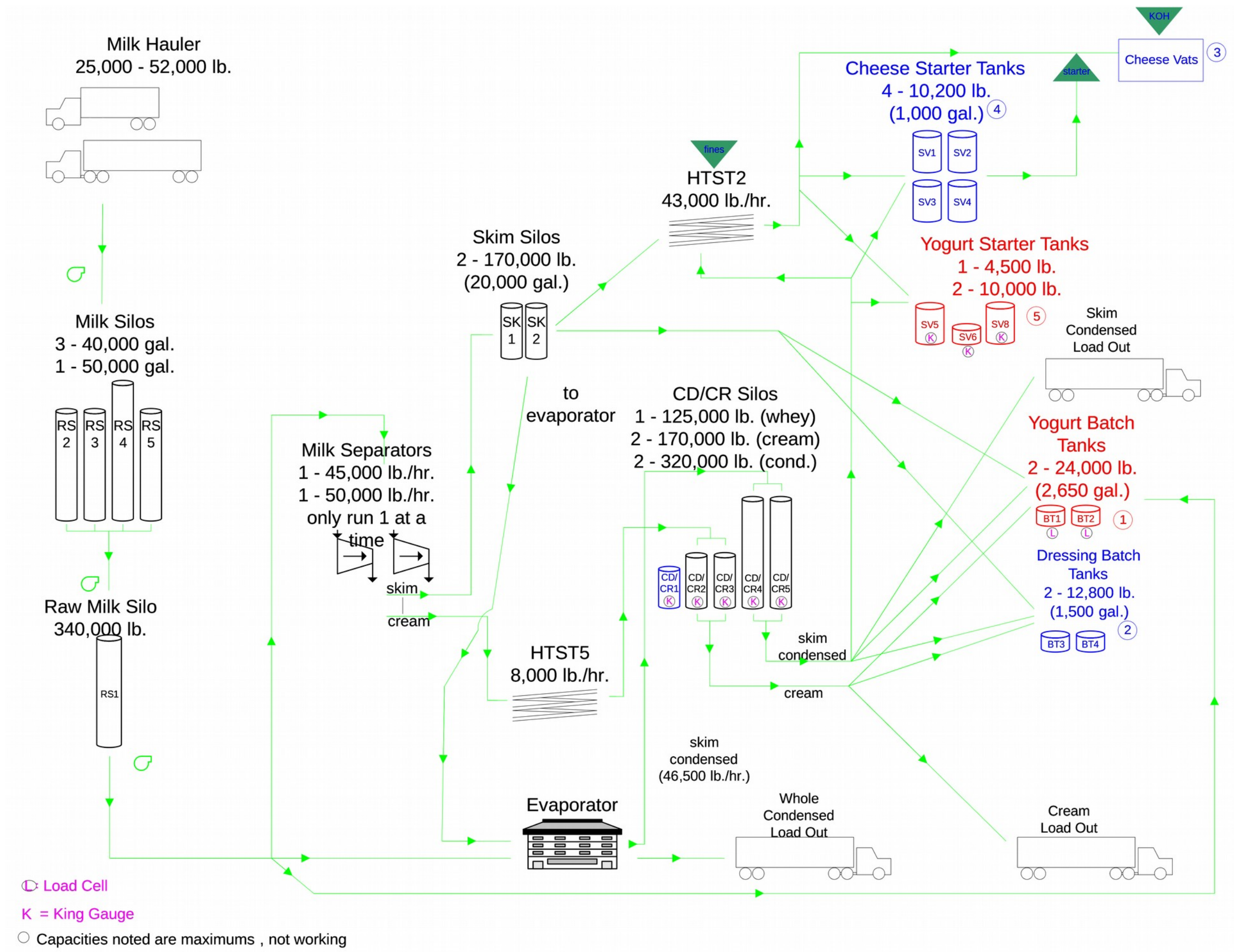

Figure 5: Yogurt Manufacturing Process- Beginning Part (Breyers Yogurt Company)

Three yogurt starter tanks are used to generate inoculum that is injected while the set tanks are being filled. Pasteurized skim milk and condensed skim milk are mixed in starter tanks followed by ten to twelve hours of heating from about 60℃ to 82℃ and thirty-six to thirty-eight hours of cooling from 82℃ to 4.5℃. The yogurt batch tanks are operated at 4.5℃. After twenty minutes of mixing skim milk, condensed skim milk and cream, the mixture in the batch tanks is pasteurized by HTST method and then pumped to the yogurt set tanks. Yogurt starter is injected to the set tanks when they are being filled up by mixture from the batch tanks.

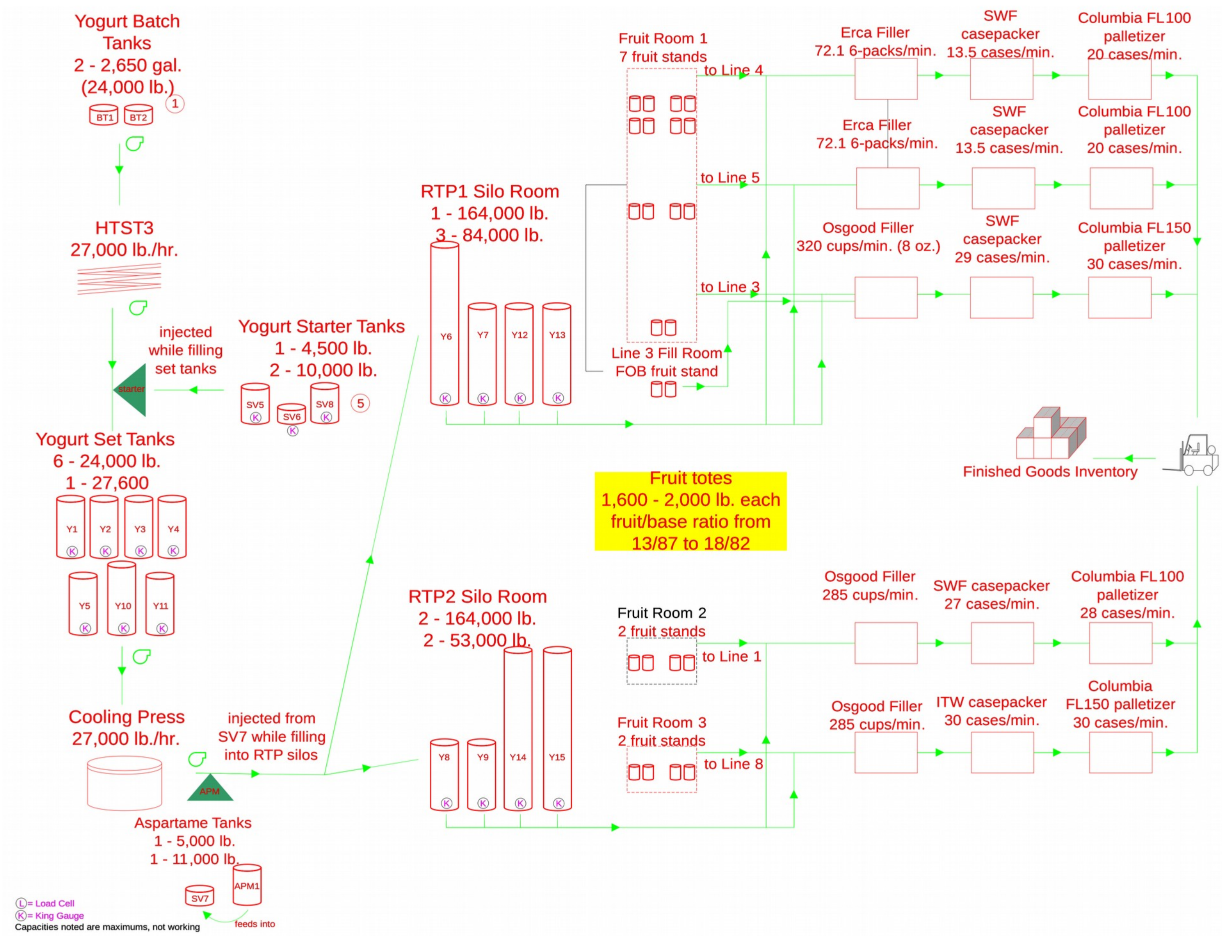

Figure 6: Yogurt Manufacturing Process- Later Part (Breyers Yogurt Company)

There are six 24,000 lbs set tanks and one 27,600 lbs set tank available. It takes 1.5 hrs to fill each set tank, which is operated at a 3.5 hrs at a temperature of 60°C. The mixture is then pumped to the cooling press equipment at a rate of 24,000 lbs/hr and maintained at a temperature of 4.5°C. Aspartame, an artificial sweetener is added to the cooled mixture before being stored temporarily in RTP silos (Figure 6). The base yogurt (plain yogurt) is stored in silos located in the RTP1 and RTP2 rooms (Figure 6) at 4.5°C. In PTP1 silo room there are one 164,000 lbs silo and three 84,000 lbs silos connecting to yogurt packing line3, line4 and line5. In PTP2 silo room there are two 164,000 lbs silos and two 53,000 lbs silos connecting to yogurt packing line1 and line8.

Yogurt is stored in the PTP silo till the packing lines start to work. Fruit is added at a fruit/base ratio from 13/87 to 18/82 depending on the type of yogurt produced. Two types of fillers are used in five yogurt lines at filling rate from 285 cups/min to 320 cups/min. After packaging the finished yogurt are case-packed at a packing rate 30 cases/min before being stored at 4°C.

Wastewater generation

The production activity generates high strength wastewater approximately 56,000 gallons per day. Breyers Yogurt Company in partnership with Ecovation Inc. has set up an anaerobic digester at their dairy processing plant. The digester receives an influent flow of (approximately) 50,000 gallons per day of high strength wastewater and produces (approximately) 4980 m^3 of biogas per day.

Cottage cheese and yogurt manufacturing involves various unit operations. Each operation is carried out with specific equipment and consists of different operations. The wastewater generated at manufacturing facility of Breyers Yogurt Company can be classified into two categories, high strength waste stream and low strength waste stream.

High strength wastewater: Whey and rinse water from the cottage cheese process are the prime sources of high strength waste. Processed milk is heated in cheese vats. Cheese curd is generated in this process and some part of water is separated from the milk. This separated liquid, termed whey, contains high concentrations of organic matter and it is responsible for majority of the high strength wastewater. Rinse water is the other source of waste. The curd is washed with water which gives out rinse water. Whey and rinse water comprise 91% of the total high strength wastewater generated from the plant. Characteristics of this waste stream are summarized in Table 3.

Table 3: Characteristics of high strength waste stream

	Whey	**Rinse water**	**Animal feed**	**Total**
Flow (GPD)	17500	24000	3800	45300
pH	4	*	7	*
Temperature(^{O}F)	135	135	70	124
TCOD (mg/l)	63500	29000	119778	49945
TSS (mg/l)	103	Low	44267	3751
TKN (mg/l)	627	*	4633	*

* Data not available
GPD (Gallons per day)
TCOD (Total Chemical Oxygen Demand)
TSS (Total Suspended Solids)
TKN (Total Kjeldahl Nitrogen)

Low strength wastewater: Rinsing of utensils, equipment and Cleaning-In-Place (CIP) operations are responsible for generating low strength wastewater. CIP is a method of cleaning the interior surfaces of pipes, vessels, process equipment, and associated fittings, without disassembly. The cheese vats and utensils used in curd formation are washed and cleaned with water. These washing operations generate process wastewater.

Wastewater treatment at Breyers Yogurt Company

Low strength and high strength waste streams are treated separately in the wastewater treatment plant (Figure 7). High strength waste is sent to an anaerobic digester to producing biogas. Digester effluent and low strength wastewater are treated in an aerobic waste treatment system before discharge to the river. The aerobic system consists of a series of aeration basins followed by aerated lagoons (Figure 8). Approximate dimensions of each treatment basin are provided in Table 4.

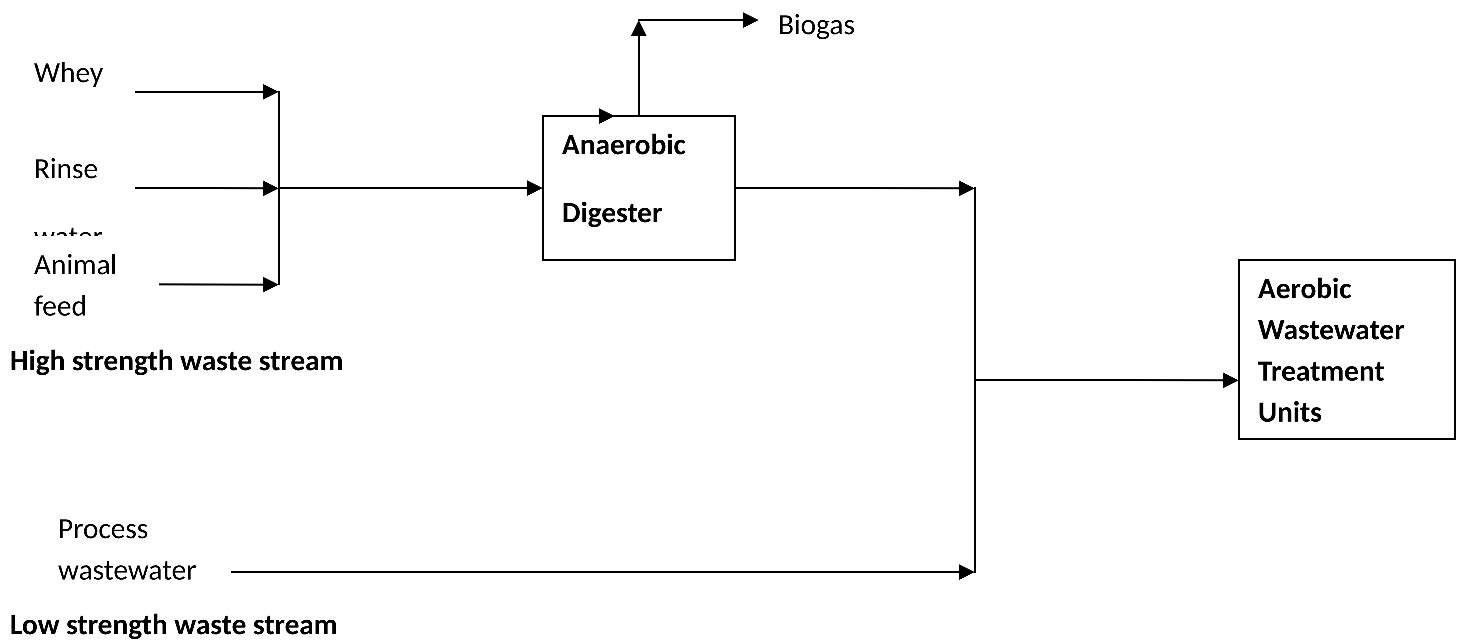

Figure 7: Wastewater treatment system at Breyers Yogurt Company

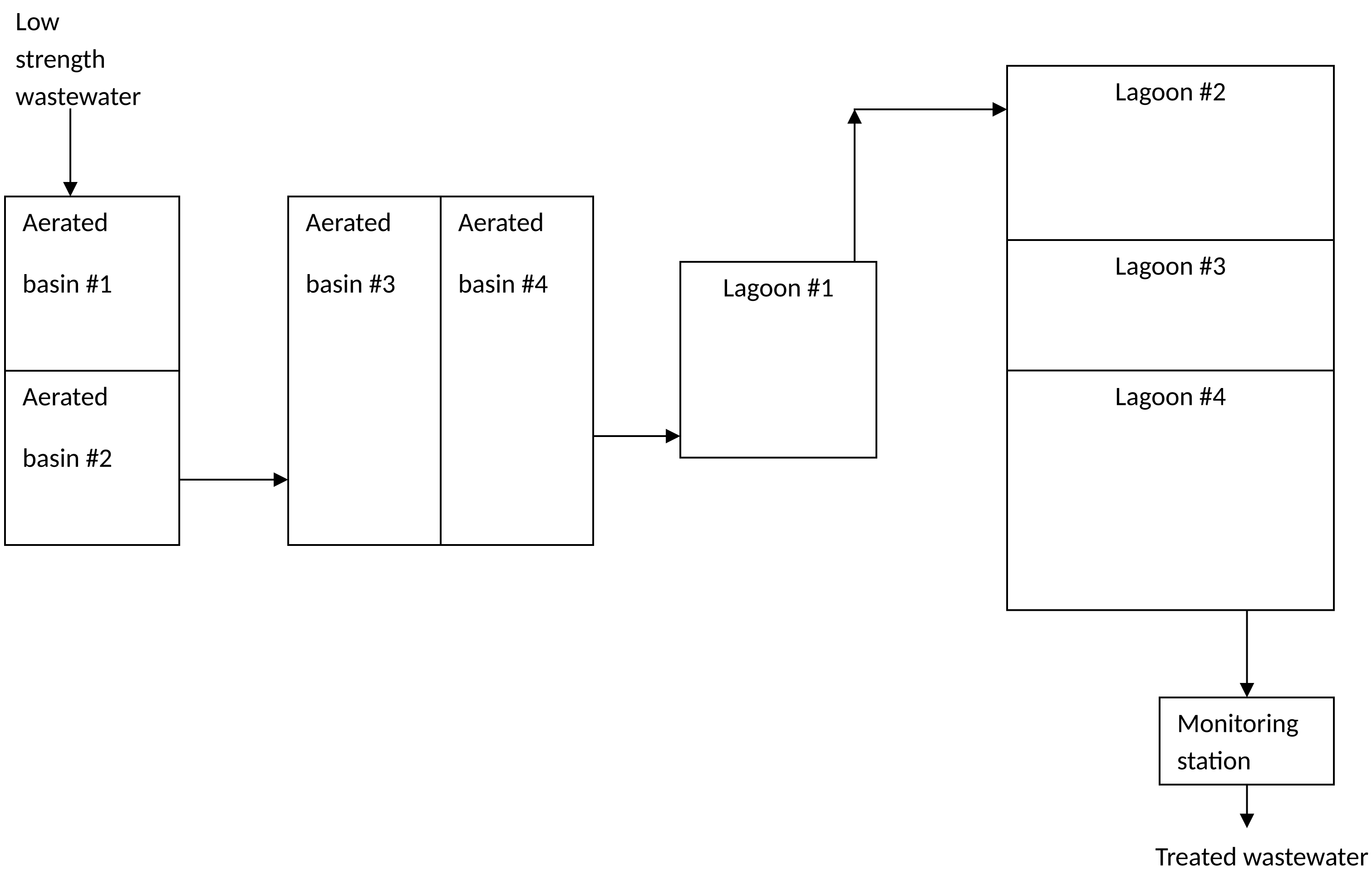

Figure 8: Aerobic wastewater treatment system at Breyers Yogurt Company

Table 4: Dimensions/characteristics of aerobic wastewater treatment unit operations.

Description	**No.**	**Dimentions or Capacity**
Aeration basins (#1, 2)	2	Each 4,725 m^3 capacity 3.9 m deep
Aeration basins (#3, 4, 5)	3	Each 17,766 m^3 capacity 3.9 m deep
Lagoon # 1	1	7,560 m^3 capacity 0.9 m deep
Lagoon # 2	1	43,092 m^3 capacity 0.9 m deep
Lagoon # 3	1	16,254 m^3 capacity 0.9 m deep
Lagoon # 4	1	51,786 m^3 capacity 0.9 m deep
Blowers	4	2 @ 1,800 m^3/hr (23 HP) & 2 @ 11,760 m^3/hr (150 HP)

Breyers Yogurt Company Electricity and Heating Costs

The heat demand of Breyers Yogurt Company are satisfied by burning fuel oil # 6 in a boiler whereas power is supplied by National Grid. Fuel oil is purchased from private companies by signing yearly contracts.

Electricity tariff

Breyers Yogurt Company receives electricity from National Grid under the class Large General (SC-3A). National grid charges are divided into the PFJ rider billing and Additional base tariff billing.

PFJ rider billing: Breyers Yogurt Company receives fixed supply of 1000 kW under the scheme called as Power for jobs (PFJ). Under PFJ head, they are charged for 1000 kW (or for maximum demand if the maximum demand is less than 1000 kW) of power demand per month with a fixed rate. Distribution delivery charge is also applicable for PFJ on those 1000 kW. Electrical energy usage corresponding to 1000 kW is calculated and fixed rate ($/kWh) is used for billing. Any additional usage from this is accounted with separate rates under additional base tariff billing.

Additional base tariff billing: The PFJ allocation of 1000 kW is subtracted from maximum demand and the remaining power demand is charged for distribution delivery charge and competitive transition charge. Reactive power demand is calculated and billed with reactive demand charge. Electrical energy usage above PFJ allocation is used to calculate amount corresponding to system benefit charge, revenue portfolio surcharge and transmission revenue adjustment charge. This additional energy usage is divided as off peak and on peak usage. This is considered under electricity supply on peak and off peak charges. These supply charges vary for each one hour. National Grid fixes these charges based on demand in that region, at a given time. The on peak and off peak energy usage is categorized based on the day and timings. On peak timings are 8:00 am to 10:00 pm from all weekdays except national holidays. Any usage on weekends or on national holidays is considered as off peak.

The same additional electrical energy usage above PFJ energy usage is used to calculate competitive transmission charge (CTC) block 1 on peak and off peak heads. Usage of first 250 hours of a month is considered and the corresponding amount is billed to the customer. Any usage after the first 250 hours will not be considered while calculating CTC block 1 on peak and off peak amount. In addition to this there applies a fixed monthly charge known as customer charge for this SC-3A category. The total electricity bill comprises of all the above mentioned heads. Table 5 describes the applicable charge for the above mentioned heads for SC-3A category (National Grid).

Table 5: Charges associated with customer SC-3A (National Grid).

SC-3A customer	
	Load zone E
Customer Charges	
Distribution Delivery	$1400.00
Demand Charges	
Distribution Delivery(per kW)	$3.74
Distribution Delivery(per kWh)	$0.00
Competitive Transition Charge (per kW)	$3.37
Energy Charges	
Electricity Supply Service Charge	Charge varies hourly
Fixed Price Competitive transition Charge	
1st 250 hours of use :on peak kWh	$0.0089
1st 250 hours of use :off peak kWh	$0.0067
RkVA Charge (per kW)	$1.02
System Benefits Charge (per kWh)	$0.00162
Renewable Portfolio Surcharges(per kWh)	$0.00028
Transmission Revenue Adjustment (per kWh)	Charge varies monthly

Task 2 Farm energy usage and waste analysis at North Harbor Dairy (NHD)

NHD is a farm located in Jefferson County New York, with 500 cows (dry, springers, heifers & bulls) where they use sand for bedding. Currently manure and waste water produced is stored in a pit where it is spread daily on the 3000 acres land controlled by the farmer. Due to the environmental concerns around the farm concerns and the odor problem the possibility of conversion of farm waste to biogas for heat and power purposes arose. Hence a manure management system was explored resulting in the use of Anaerobic Digester (AD). AD is a system that harnesses natural processes to treat waste by converting organic materials to carbon dioxide and methane i.e. produce biogas that can be used in a cogeneration system to provide heat. It consists of a heat exchanger, biogas recovery system and effluent storage structure.

Over 50% of AD's built between 1970 -1990 failed to operate properly. In 2003, about 30 new installations were under construction in US. Design and engineering deficiencies and insufficient training of the operators were common causes of failures. A thorough understanding of processes occurring inside and affecting its performance is necessary for selection of the most appropriate technologies for a given application to economically generate biogas from manure.

Sources of waste

Farm operations significantly affect the quality and quantity of manure to be delivered to the digester. Significant properties are the type of bedding material, dilution of wastes and manure transport. The current bedding material is sand; 88 tons/week (12 tons/day) at a cost of $18,000 per year. In the future, the dairy plans to continue with sand bedding. There is no interest in bedding with recovered digested manure fiber; however, there is a strong interest to develop a process that would allow for the recycling of the sand. NHD yields about 16000-18000 gallons of manure as a mixture of manure, bedding sand, wastewater from the milking parlor and other waste such as silage and cheese whey from the future plans of digesting 1 ton silage per day and 1000 gallons of cheese whey. Waste water is added during flushing to drive solid waste down a pit. Figure 9 below shows the flow of waste and recovered products

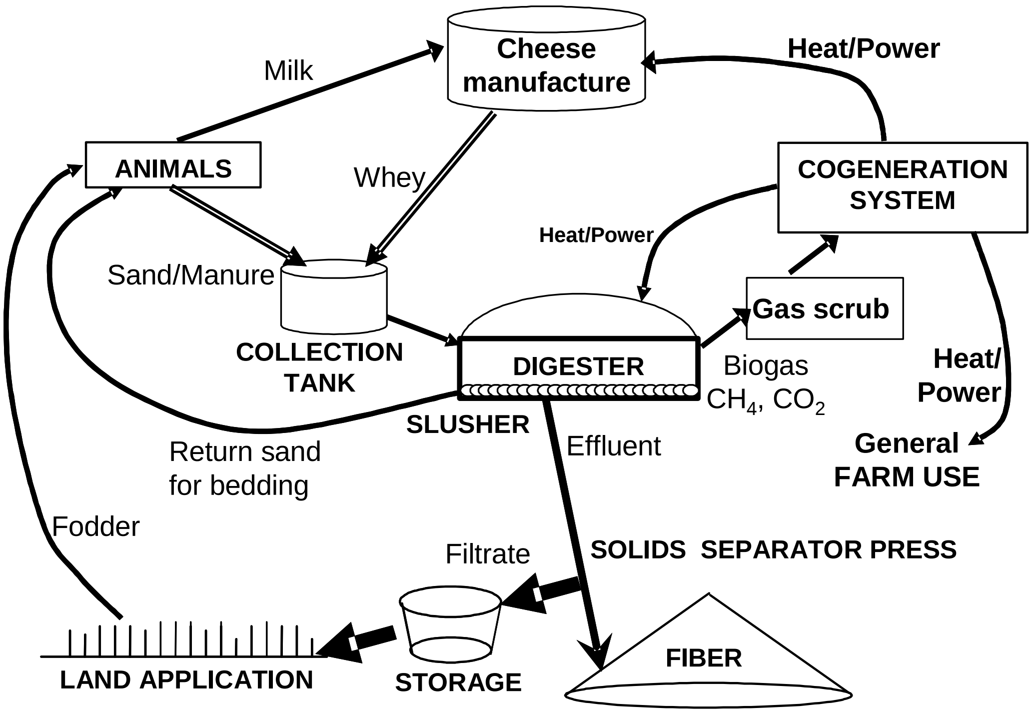

Figure 9: Daily waste collection incorporated in the AD system

Waste characterization and analysis

A mesophilic plug-flow AD will be installed which operates by displacing older material through the tank by new material within the retention time. This system digests thicker and viscous manure (manure with low water dilution). During the anaerobic digestion, organic material such as proteins, fats and carbohydrates are converted into organic acids such as sugars, fatty acids and amino acids and organic acids are converted into biogas.

Influent streams to the digester are summarized in , where that total flow is 125,420 lbs/d which includes 20% of sand bedding, 71% of wastewater and 8% of manure solids.

Table 6: Estimated daily digestion systems inputs

Total flow rate (lbs/d)					**Volatile Solids (lbs/d)**	
Source		Total solids	Water	Total	Total	Degradable
Cows	Lactating	6,665	46,655	53,320	5,465	2,077
	Dry	1,398	9,783	11,180	1,146	401
Whey		546	7,854	8,400	491	393
Silage		700	1,300	2,000	595	238
Sand		25,500	0	25,500	0	0
Water		0	25,020	25,020	0	0
Total		34,809	90,612	125,420	7,698	3,109

There are different indicators used to characterize wastes. Total Organic Carbon (TOC) and Chemical Oxygen Demand (COD) are widely used indicators amongst them. TOC is the measure of organic carbon present in the waste sample. Oxygen is required for the degradation of organic materials. Thus the higher the organic content, the higher the oxygen demand will be. COD measures the oxygen requirements of wastewater samples in order to chemically oxidize organic materials present in it. These indicators (TOC/COD) can be used to understand the degree of pollution. Water content, VS content and TOC are the important characteristics of manure.

Table 7: Manure characteristic collected January 2006

Sample Location	Water Content (%)	Volatiles (% of dry mass)	Total Organic Carbon (mg/100mg dry sample)	Avg. TOC
Fresh Manure	77.1	47.4	23.0	23.2
Fresh Manure	74.5	46.1	23.5	
Freestall Barn	48.5	11.0	4.5	8.1
Freestall Barn	48.5	12.2	6.7	
Freestall Barn	49.0	11.2	5.7	
Freestall Barn	62.9	23.7	8.2	
Freestall Barn	63.6	24.1	12.6	
Freestall Barn	63.4	23.6	11.0	
Lagoon	91.1	73.5	N/A	28.0
Lagoon	97.6	72.8	N/A	
Lagoon	75.2	29.4	23.0	
Lagoon	84	50	25.8	
Lagoon	93	69	41.7	
Lagoon	83	45	23.9	
Lagoon	92	60	22.0	
Lagoon	91	58	35.8	
Lagoon	84	39	24.0	
Sand (bottom of lagoon)	40	8.7	5.0	5.7
Sand (bottom of lagoon)	60	12.5	6.0	
Sand (bottom of lagoon)	60	12.1	6.0	

Table 7 shows the results when manure samples were taken at different points as shown in Figure 10 where manure was treated separately(fresh manure) and as a mixture(lagoon). Alley scrapers are used to move the manure within the freestall barn to the alley gutter. Water is the used to flush that into the manure lagoon. Since sand bedding is used at NHD the waste present in the lagoon consists of a mixture of manure, sand and wastewater.

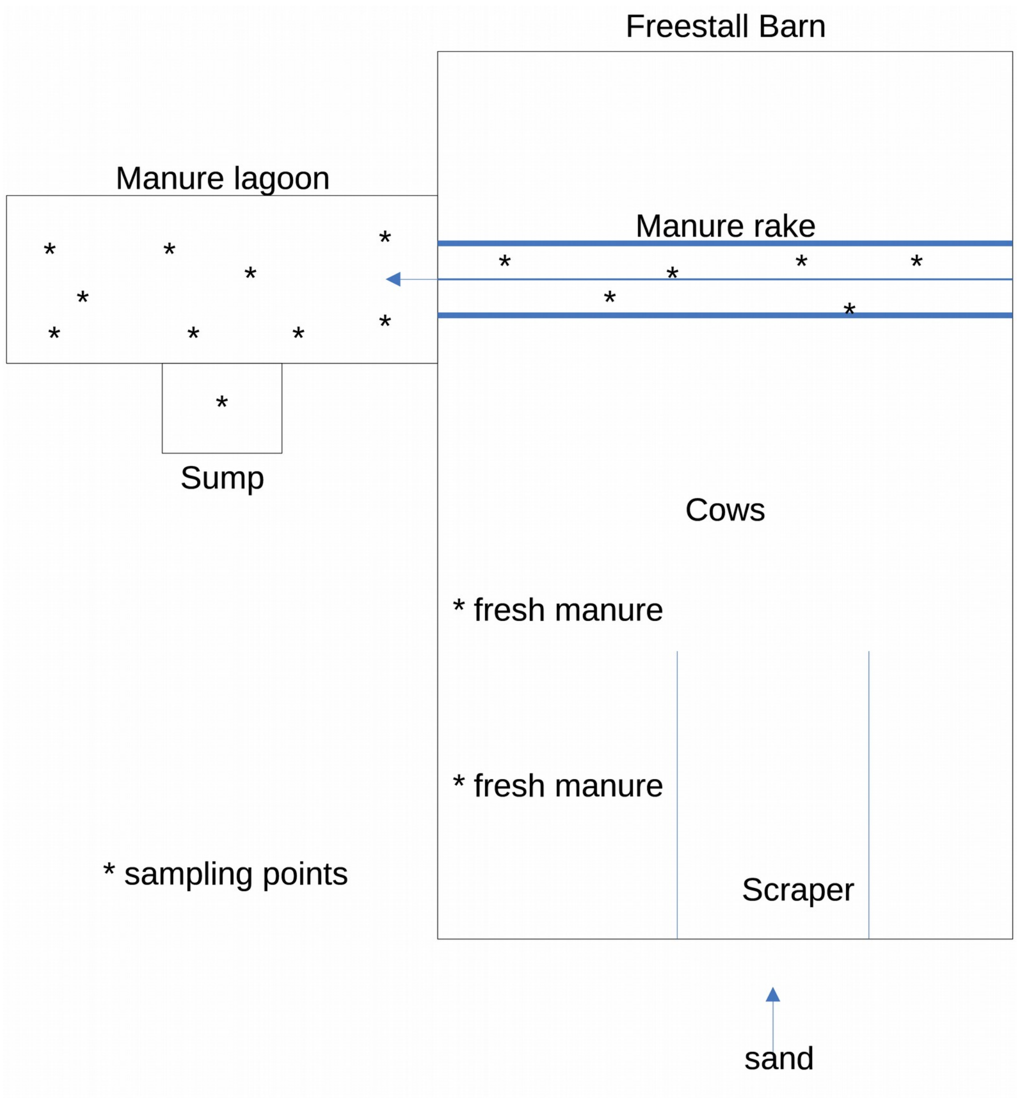

Figure 10: Sampling points at North Harbor Dairy within the freestall barn

Power supply and Electricity Usage of North Harbor Dairy

The energy provider to North Harbor Dairy is National Grid, New York. National grid classifies their customers according to the maximum peak demand recorded by the meter used during a period of 12 months. The farm pays for energy purchased through three existing meters at different locations on the farm- one each at the new barn, old barn and the workshop. Although NHD is classified as a residential customer, the existing meters are different: New Barn (SC1 non-heat), Old barn (SC-1C non-heat) and shop (SC-1C heat).The usage was assessed through the monthly recorded data from 06/2003-05/2004.

NHD currently consumes 20,500 kWh per month where the highest electric demand is during the summer period due to the ventilation fans (Figure 14). Historically the farm purchased over $40,000 for energy, electricity for power ($30,000) and propane for heat ($10,000) per year. This then results in $0.104/kWh for all the electric energy used in the farm billed monthly. From the analysis, 93% of the energy used is during off-peak periods. This is different from Breyers Yogurt Company because National grid has different times for residential and commercial customers. This time is determined by the class maximum load.

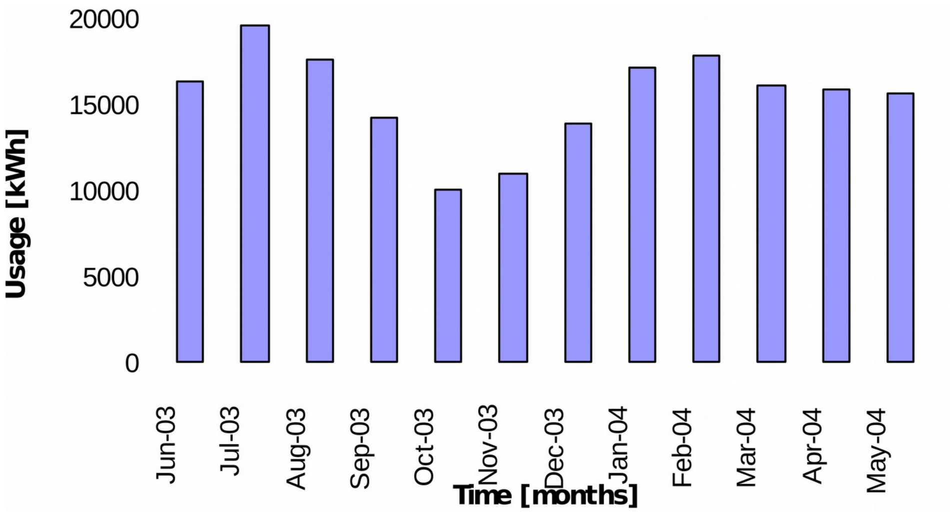

Figure 11: Yearly new barn usage

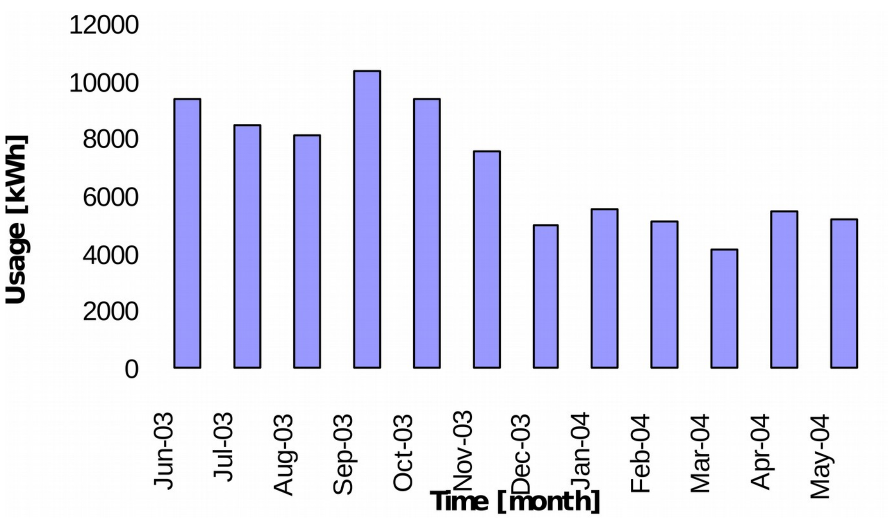

Figure 12: Yearly old barn usage

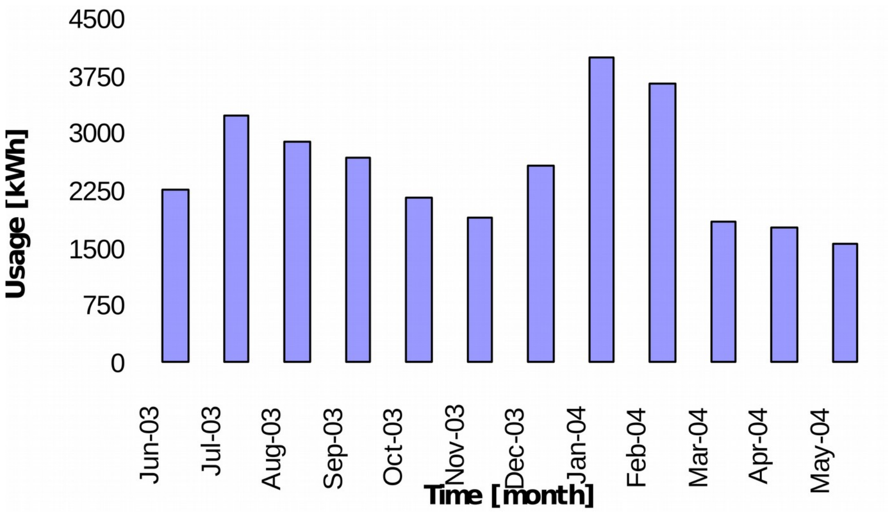

Figure 13: Yearly shop usage

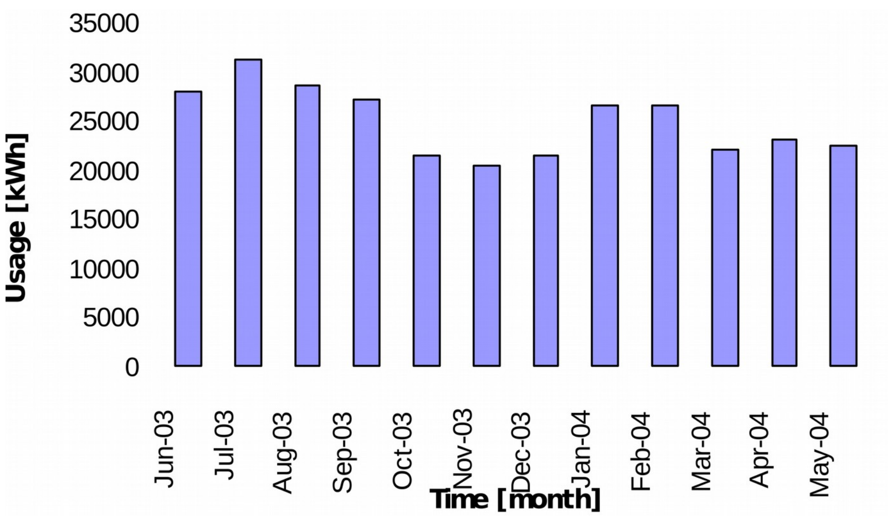

Figure 14: Yearly Total usage

The yearly electrical usage is given in Figure 11 through Figure 13, at each meter. It is unlikely that all three meters will be combined so the higher variations at individual meters will complicate the optimization

Power distribution and the value of electricity replacement

Net metering is a NY state mandate for customers who own qualifying facilities or renewable energy sources. In the event of on-site generation being more than required for the use on the farm, net metering allows the customers to receive a retail credit for the excess electricity generated as it can be exported back to the power grid for use at a later date. System economic viability depends in large part on the ability to use power produced. In net metering, the generator owner has an option of selecting a single meter with bi-directional capability or two meters measuring consumption and the generator's output. The owner will be responsible for the second meter installed. Considering the existing three meters at the farm, and all the barns receiving power from the generator, the meters will be reduced to either one or two. The new barn (parlor) meter is relatively close to the digestion system compared to the meter at the Old Farm to the west of the cogeneration and the Old MacDonald's meter, across NHD Rd. As a result the new barn meter can be replaced by the net metering meter and this will not offset the energy recorded by the other meters. To offset the farm's total usage all meters should be combined.

Electricity tariffs

Electricity tariffs are associated with the delivery cost and supply cost which varies according to the market price. The graphs above show the energy usage which the customers are billed for where the monthly billing invoice total is comprised of various charges:

Table 8: Charges associated with SC-1C customers

SC-1C customer	**Load Zone E**
Basic Service Charge	$30.00
Delivery Charge (per kWh)	$0.03
System Benefits Charge (per kWh)	$0.0016
Delivery Charge Adjustment	Charge varies by hours
Renewable Portfolio Surcharge (per kWh)	$0.00028
Transmission Revenue Adjustment	Charge varies monthly
Electric Supply Charge	Charges varies by hours
Customer Service Credit (per kWh)	$0.0004

Table 8 summarizes the distribution of cost between supply and delivery. Delivery charges include a fixed basic charge and variable charges that depends on the time of use. With the on-site generation there are charges that National grid charge regardless of the amount of energy used. NHD is hoping to offset $0.067/kWh instead of being charged $0.104/kWh. These charge that can be offset is supply charges as delivery charges do not vary because the same infrastructure is required to meet the site's full demand during outages.

Heating needs of North Harbor Dairy

Propane for heating use is supplied by Griffith Energy Watertown, NY. NHD has eleven propane consumption points and only three are close to the future digester-cogeneration system: the milkhouse, new barn and the calf barn. The annual average of propane consumption at these three locations was 21 gallons per day. Propane consumption varied from month to month (10-32 gal/d) with relatively high usage in the fall (Figure 15).

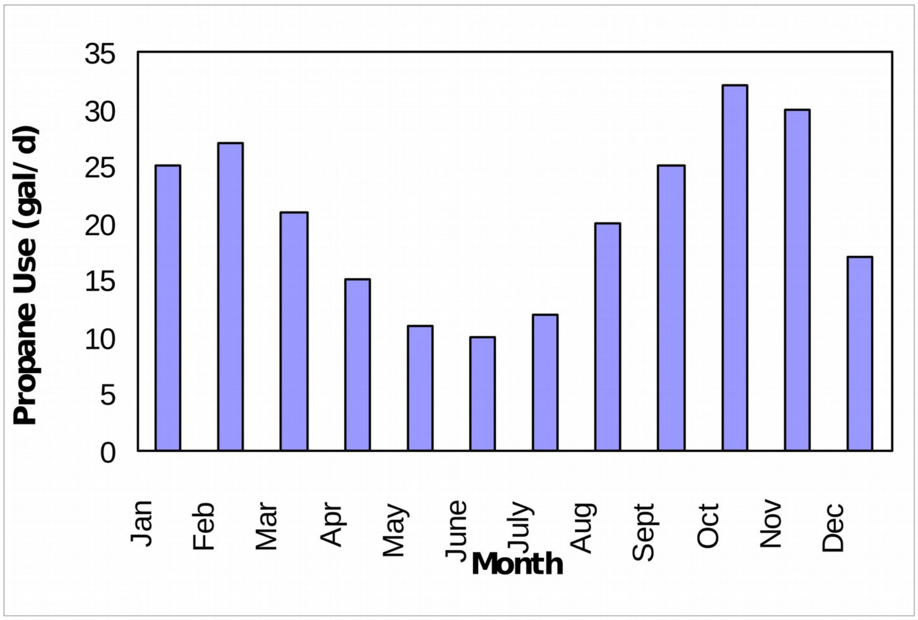

Figure 15: Yearly propane usage at North Harbor Dairy

Task 3 Develop mathematical model to optimize net energy consumption and cost

Process Model for Breyers' Yogurt Company

The mathematical process model was developed in order to optimize the use of renewable energy at the Breyers Yogurt Company, located at North Lawrence, NY. The model was calibrated using actual power consumption data for a two week period in the winter and summer of 2006. Calculated power costs based on actual production of cottage cheese and yogurt for a given time period were compared with actual energy expenditures. The model has several important uses for Breyers Yorgurt Company and other users. (1) energy consumption can be calculated for estimated production levels and production schedules, (2) energy requirement per mass of product (yogurt or cottage cheese) can be estimated for a given energy cost and (3) the model can be used to evaluate three different combined heat and power (CHP) systems given user entered economic data. Next to direct combustion of biogas CHP systems incorporated in the model include microturbines, fuel cells and internal combustion engines. The model was used to evaluate the impact of variations in energy cost and changes in production levels economics of the respective CHP systems. Primary results are summarized below.

Two versions of the model were developed; the first within Microsoft Excel while later within Matlab. The model consists of four interconnected modules, each focusing on a particular aspect of the system as depicted in Figure 16. For example cottage cheese and yogurt production information is used in total energy module to calculate total energy requirements and also to calculate biogas generated in anaerobic digester. Each module is described below in detail.

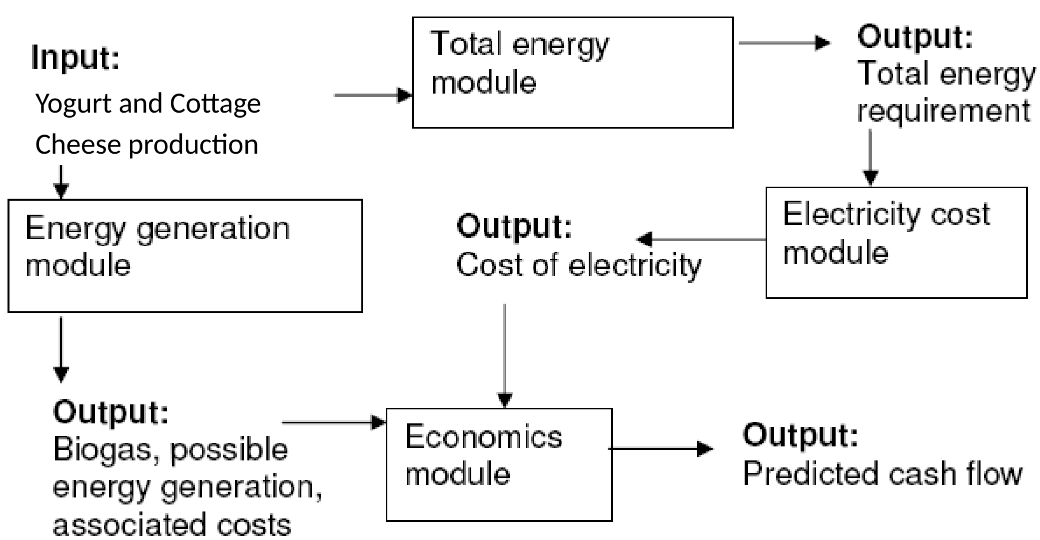

Figure 16: Model Schematic of Principle Components.

Total Energy Module

This model calculated power and heat requirements of the cottage cheese and yogurt manufacturing processes based on mass and energy balances over major unit operations. Current and historic energy requirement of the Breyers Yogurt Company plant were quantified using billing information for in 2005 and 2006. Heating bills, fuel oil purchases as well as electric energy bills were surveyed to determine plant-wide monthly energy demand for the past two years of operation. Energy use was related to production of dairy products over the same period in order to estimate future energy demands considering plant growth. In addition to surveying invoices, an inventory of major unit operations that consumes the majority of the plants energy (heat or electric power) was developed. This study focused on the yogurt process which has five parallel production lines operating at different time of day.

Calculation of mass flows within each process: The plant produces varieties of cottage cheese and yogurt. Various unit operations were involved in cottage cheese manufacturing. Major unit operations used at Breyers Yogurt Company were studied in detail using the process flow diagram supplied by Breyers Yogurt Company. Mass balances were developed for major unit operations listed in Figure 17 and Figure 18 for the cottage cheese and yogurt processes respectively. These operations were selected on the basis of heat and electrical power demands. Thus relation was established between processed product and the raw feed. Mass balances for each unit operations depended on mass flows and detention times while temperature, specific heat and electrical power demands were responsible for total energy needs.

In order to calculate heat and power demand for a given product at any given time, t, the residence time of the material in each unit operation has to be considered. For example the entire process to produce cottage cheese from the raw milk takes approximately 3 hrs. Thus to produce 1 lbs of cottage cheese at time, t, raw milk would have to be processed at (t-3) hrs. Similarly the same batch of raw milk from milk silos has to appear in milk separator, pasteurizer, cheese vats, packing machines and other unit operations at specific time. The corresponding time can be calculated on the basis of detention time and time required to pump the material between unit operations which was calculated assuming a fluid flow velocity of 1 m/s and distances estimated from the plant layout of Breyers Yogurt Company.

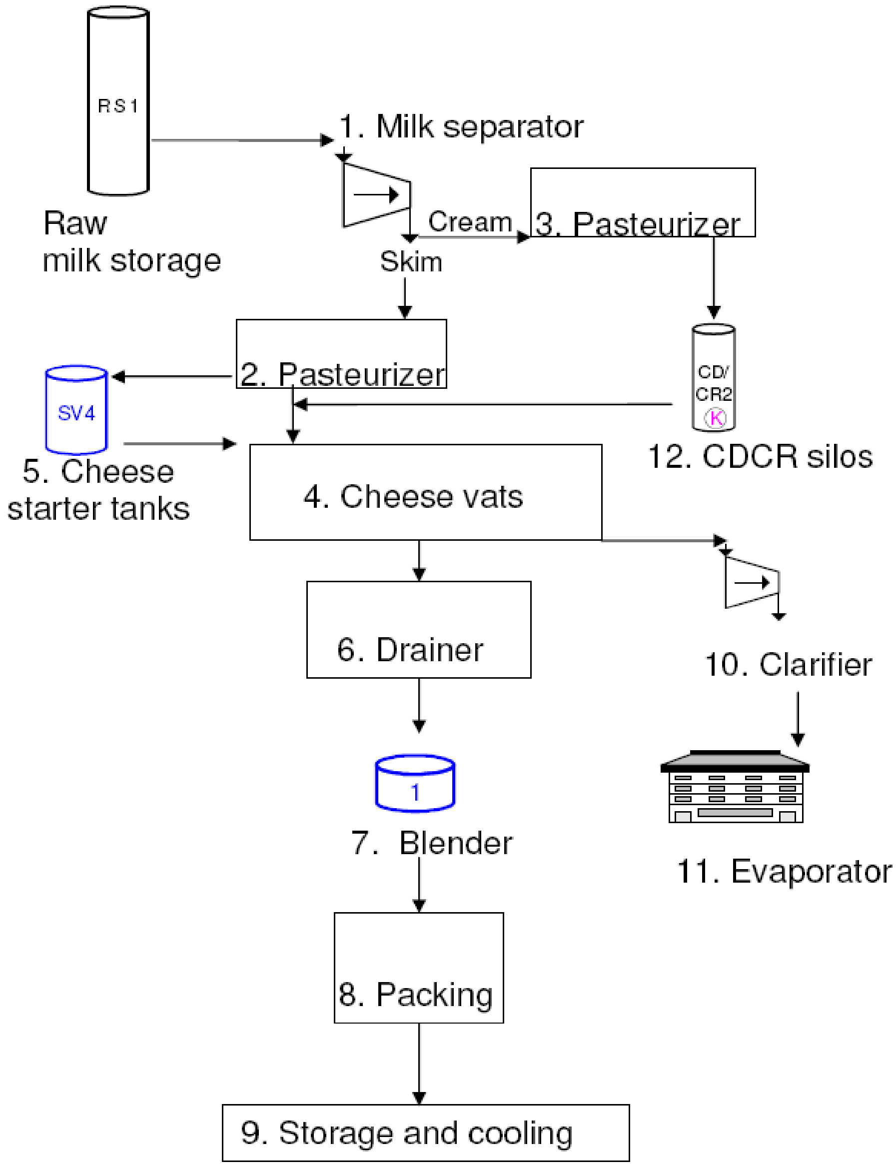

Figure 17: Major unit operations considered in the cottage cheese process model.

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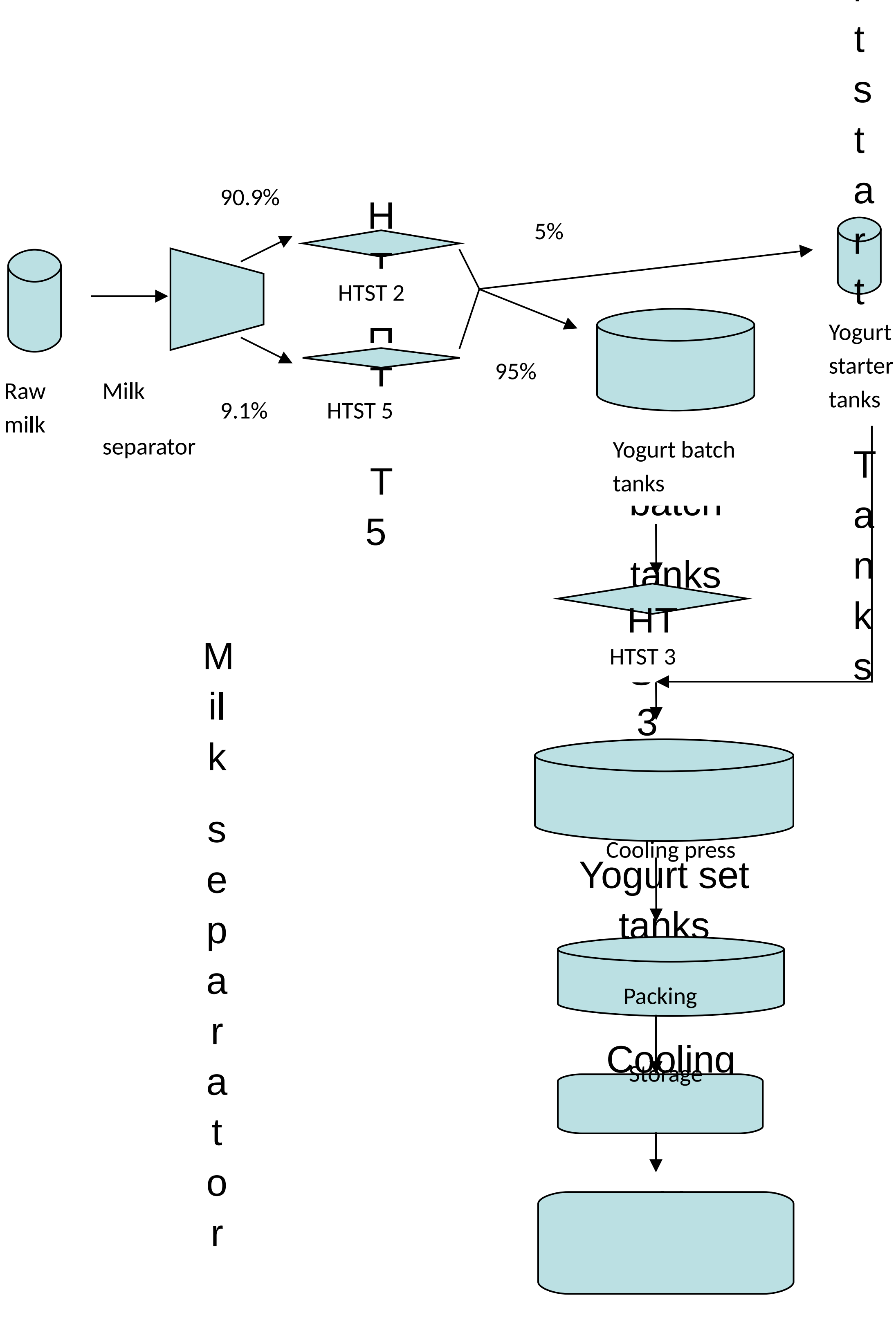


Figure 18: Major Unit Operations considered in the Yogurt process model

All the developed mass balances were on the basis of average values of production and waste generation. Unit operations were assumed to be continuous except curd formation in cheese vats. Operating conditions and power ratings of major unit operations are summarized in Table 10 to Table 12

Milk separation: Milk separator separates raw milk into skim and cream. Raw milk has fat content of 3.5-4% and the separated cream has fat content of 35-40%. Skim has no fat in it. The mass balance for milk separator was calculated using these values (Figure 8). Based on the information provided by Breyers Yogurt Company, cottage cheese to milk ratio was assumed to be 2.1 and corresponding requirement of milk in separator was calculated. The milk separator has power consumption of 25 kW when it runs at full capacity. Power demand was calculated by considering mass being processed in milk separator at a given time.

Pasteurization: The skim milk passes through pasteurizer HTST2 and cream passes through HTST5 which operate at 54^{O}C. The residence time in pasteurizers is 0.5 min. Cream is stored in CDCR silos at 4^{O}C and used wherever required. Skim goes to cheese vats after addition of cheese starter in it (Figure 17).

Cheese starter tanks and curd formation: Cheese starter tanks are used to prepare cheese starters. Starter dosing of 0.046 kg per kg of milk was adopted (Breyers Yogurt Company). Milk and cheese starters were mixed at 82^{O}C and curd formation occurs in cheese vats. This unit operation has detention time of 3 hours. Whey and rinse water were generated in the cheese vats. The fines from rinse water were separated in the clarifier and recirculated. Then the separated flow of fines goes to evaporator. The evaporator is used to reduce water content of the rinse water. It helps to reduce the volume of waste.

Curd to milk ratio, whey to milk ratio and waste to milk ratio were 0.45, 0.87 and 2.04 respectively (Breyers Yogurt Company). The flow going to evaporator was used kept as a variable. That value was varied while calibration and the result corresponding to factor 1.1 were found appropriate hence that factor was used. It was assumed that when tank storing whey is 85% full the evaporator starts working.

Drainer, blender and storage: The curd formed in the vats goes to drainer and then to blender. Fruit dressings (if required) were added in blender. The cheese thus formed goes through packing machines and then stored in refrigerator. These operations were modeled as continuous unit operations without loss or addition of any mass (Figure 17).

Table 9 Details of Equipment and Unit Operations

No.	Equipment/Process	Temperature (°C)		Detention time (min)	Maximum capacity	Maximum number of units
		T_{in}	T_{out}			
1	Separator: Milk separation	4.5	4.5	0	20,455 kg/hr	2
2	HTST2: Pasteurization	4.5	54.5	0.5	19,545 kg/hr	1
3	HTST5: Pasteurization	4.5	54.5	0.5	3,636 kg/hr	1
4	Cheese vats: Cheese formation	54.5	82	180	9,469 kg 11,245 kg	3 10
5	Cheese starter tanks	54.5	82	1440	4,636 kg/hr	4
6	Drainer	+	21	0	+	2
7	Blender	21	60	0	3,864 kg 3,401 kg	5 1
8	Packing	60	60	+	+	1
9	Storage	60	4.5	+	+	+
10	Clarifier	+	+	+	+	1
11	Evaporator	+	+	+	+	1
12	CDCR: Milk storage	54.5	4.5	Varies	56,818 kg 77,278 kg 145,455 kg	1 2 2

Table 10: Mass and Energy Demands of Major Unit Operations

No.	Equipment /Unit operations	Mass (kg)	Heat demand (kJ/kg)	Power demand
1	Milk separator	(milk to cheese ratio) * (cheese to be produced)	0	25 kW
2	HTST2	0.909 * (milk in separator)	195	0
3	HTST5	0.091 * (milk in separator)	195	0
4	Cheese vats	Milk entering = milk entering milk separator Cheese curd formed = (curd to milk ratio) * (milk processed)	123	0
5	Cheese starter tanks	(starter dose)*(milk entering cheese vats)	109	0.04 kW/kg
6	Drainer	cheese curd formed	0	0.05 kW/kg
7	Blender	mass in drainer	128	10 kW
8	Packing	mass in drainer	0	25 kW
9	Storage and cooling	Cheese produced	0	1025 kW
10	Clarifier	(waste to milk ratio) * (milk processed in cheese vats)	0	37 kW
11	Evaporator	(1.1) * (whey to milk ratio) * (milk processed in cheese vats)	305,000	375 kW
12	CDCR	cream coming out from HTST2	0	0.03 kW/kg

Table 11: Details of Major Unit Operations (Breyers Yogurt Company)

Unit Operations	Temperature (°C)		Detention time (min)	Maximum Capacity	Maximum No. of Units
	T_{in}	T_{out}			
Milk Separator	4.5	4.5	~ 0	2.0E+4 kg/hr	2
HTST 2	4.5	60	0.5	1.95E+4 kg/hr	1
HTST 5	4.5	60	0.5	3.6E+3 kg/hr	1
Yogurt Batch tanks	4.5	4.5	20	1.1E+4 kg	2
HTST 3	4.5	60	0.5	1.2E+4 kg/hr	1
Yogurt Set tanks	60	60	300	1.3E+4 kg 1.1E+4 kg	1 6
Yogurt Starter tanks	60 82	82 4.5	660 2220	2.0E+3 kg 4.6E+3 kg	1 2
The Cooling Press	60	4.5	~ 0	1.1E+4 kg/hr	1
Packing	4.5	4.5	-	-	-
Storage	4.5	4.5	-	-	-
CDCR	60	4.5	Varies	5.7E+4 kg 7.7E+4 kg 1.5E+5 kg	1 2 2

Table 12: Mass and Energy Requirements for Major Unit Operations (Breyers Yogurt Company)

`	Mass (kg)	Heat Demand (kJ/kg)	Power Demand
Milk Separator	(milk to yogurt ratio) × (yogurt to be produced)	0	25 kW
HTST 2	90.9% × (milk in separator)	195	0
HTST 5	9.1% × (milk in separator)	195	0
Yogurt Batch tanks	95%× (milk in separator)	0	0
HTST 3	Milk in the batch tanks	195	0
Yogurt Set tanks	Milk in separator	0	0
Yogurt Starter tanks	5%× (milk in separator)	87	0.03 kW/kg
The Cooling Press	Mass in the set tanks	0	0.05 kW/kg
Packing	Yogurt base produced	-	-
Storage	Yogurt Produced	0	1025 kW
CDCR	Cream from HTST 2	0	0.03 kW/kg

Electricity cost module

This module calculates electricity cost based on the tariff for the class SC-3A (large general). Tariffs prescribed by National Grid were explained in detail under Task 2. An attempt was made to predict the various fixed and variable rates presented in Table 5. The electricity cost was calculated in dollars per day ($/day) based on the output of the energy demand module and various rates used in tariff given by National Grid. All the applicable rates used were converted into equivalent amount per day.

Modeling of fixed and variable rates: Amongst all the rates, on peak and off peak electricity supply rates vary hourly and Transmission Revenue Adjustment (TRA) varies monthly. These variations depend on season, availability, demand and few other factors. The rates are decided by National Grid. Since the rates vary with time it was difficult to predict them for the future. The past rates for the one year (from September 2005 to August 2006) were studied and that data was used to predict the future rates.

Figure 19 shows on peak supply rate as a function of month. Though the rate did not vary much there was no specific trend observed with respect to time. A trend line was developed with the past data and represented by a continuous function (Figure 10) in order to predict future supply rates.

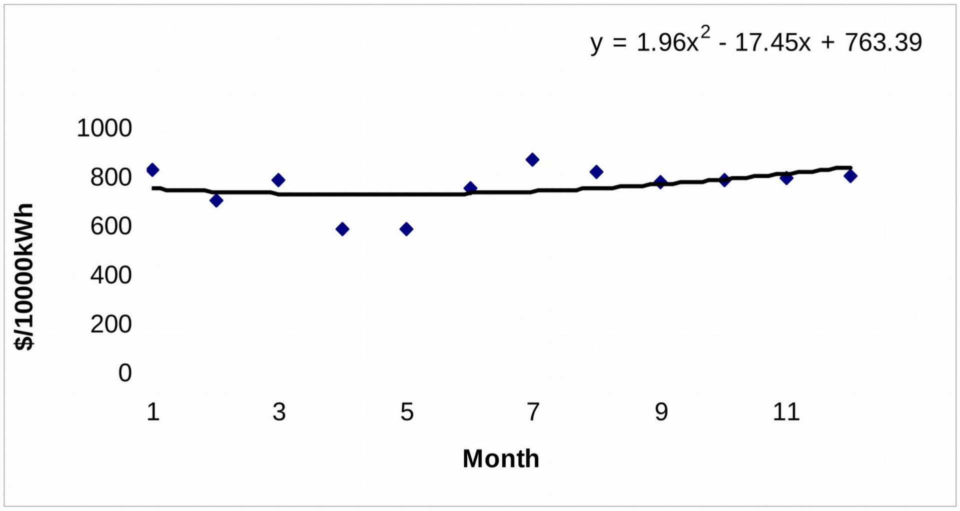


Figure 19: On peak supply rate

Similarly Figure 20 shows variation of off peak supply rate with respect to time. It can be observed that the rate was decreasing with time. A continuous line developed based on the past data was used to predict the rate.

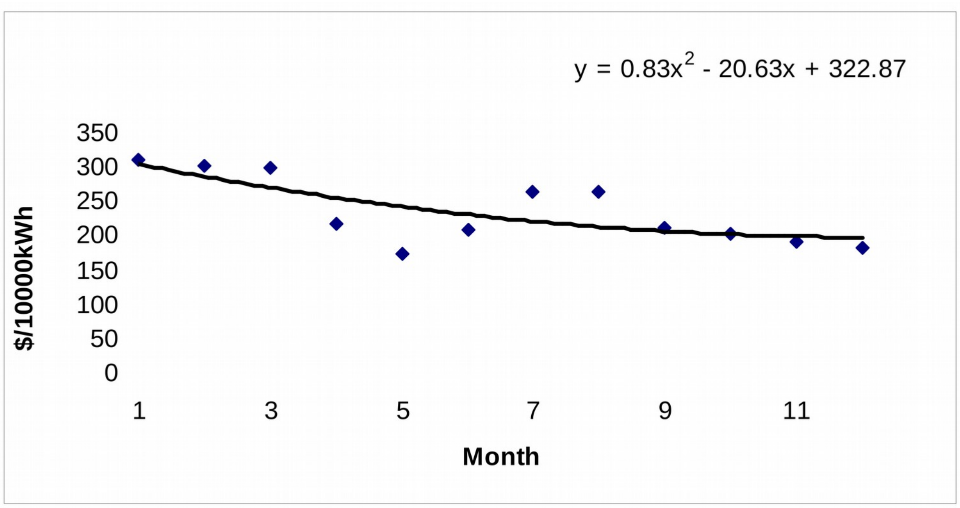


Figure 20: Off peak supply rate

Off peak weekend supply rate did not vary much with time but there were fluctuations observed in 2 nd and 8 th month. The past data is shown in Figure 21. The data for transition revenue adjustment (TRA) was in the scattered (Figure 24). There was large variation observed in these values. However, even so there was significant scatter in the data the overall impact on the overall electricity cost was relatively small as the absolute numbers were small relative to the other cost components. Hence the approximated trend line can be used to predict the TRA.

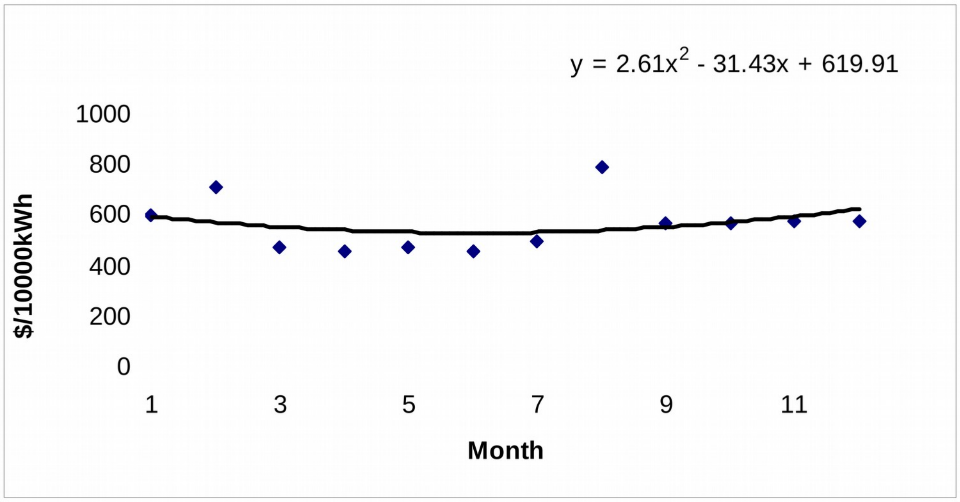


Figure 21: Off peak weekend energy supply rate

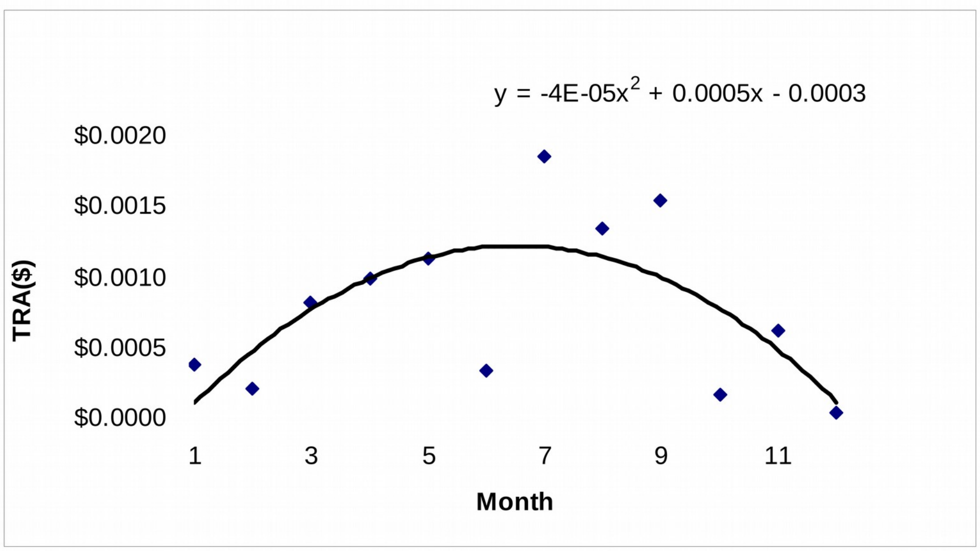


Figure 22: Transition revenue adjustment charge (TRA)

The rate data provided in Figure 19 to Figure 22 were used to generate empirical cost function to predict the future electricity rates (Table 13).

Table 13: Equations used for power costs

No.	**Rate** ($/kWh)	**Expression used**	R^2
1	Transition revenue adjustment (TRA)	$y = -4E\text{-}5x^2 + 0.0005x - 0.0003$	0.46
2	Energy supply on peak	$y = (1.996x^2 - 17.458x + 763.39)/10000$	0.16
3	Energy supply off peak	$y = (0.8391x^2 - 20.632x + 322.87)/10000$	0.53
4	Energy supply on weekends	$y = (2.6168x^2 - 31.436x + 619.91)/10000$	0.08

The module takes power demand values (in kW) calculated in the total energy module and divide them into on-peak and off-peak demand based on the time of the day. Peak time starts at 8 am and ends at 10 pm on weekdays while on weekends whole day is considered as in off peak hours. These values of demand were considered separately and multiplied by corresponding modeled unit rates. Thus the tariff corresponding to class SC-3A was modeled and the model can calculate approximate electricity cost in dollars per day. The electricity cost was calculated considering national grid power tariff of class SC-3A (large general) and bill for January 2006.

Economics module

Two energy generation alternatives were evaluated in the model. Any decision made regarding use of the alternatives will have economic implication. This module describes economic implications, in terms of cash flow which may be possible while choosing particular technology.

Fuel cells have relatively higher capital cost. Breyers Yogurt Company will need initial investment in order to use fuel cells for energy generation. It was assumed that external funding will be available through funding agency to install this renewable energy generation technology. The annuity for the capital cost was calculated. Interest rate of 6% and repayment period of 20 years was assumed for the calculations. It was assumed that fuel cells will need maintenance for replacement of the stacks after each 5 years of use. Annuity for this maintenance cost was also calculated. The sum of these annuities for capital and maintenance costs was considered as expense for Breyers Yogurt Company. In the case of alternative of direct combustion of biogas no such costs were applicable.

There will be generation of heat or electricity or both when fuel cells or direct combustion alternatives are used. The energy generation will reduce the total energy demand of a plant. There will be savings on power cost or on fuel oil costs or both. These savings on energy costs (as applicable) were calculated for a given day and savings were extrapolated for a year. The net annual savings corresponding to energy generation alternative were the difference in expenses and savings for each year. Thus possible economic implications for a particular decision can be clearly identified.

Model Calibration

Calibration of the model was required in order to fit the unknown six variables to actual data (variables and data shown in Table 14). All the calculations from various modules were based on the energy consumption data given by total energy module hence the entire module was calibrated.

It was very difficult to predict all unit operations accurately as there were uncertainties involved in it. In addition to that, it was not possible to include each and every unit operation or running equipment in the model. Hence a few assumptions were made and values of uncertain parameters were kept as a variable while developing the model. These assumptions were verified when modeled results were compared to actual data.

Calibration was carried out in two steps. First, data for a day (for 12/16/2005) was considered and sum of square errors with different values of unknown variables was calculated (Table 14). Sum of square error corresponding to each value of variable was computed for actual and calculated power demands. The lower the sum squares errors the better the fit. Values giving lesser sum squares errors for a given variable were chosen. Other variables and input to model were kept constant at that time. In the second step the chosen values of unknown variables were used with the data of a week and corresponding sum square errors were calculated. These values of unknown variables were verified for ten different days.

Table 14: Variables and corresponding sum square errors (SSE) for 12/16/2005

No.	Variable	Value	SSE
1	Milk to cheese ratio	2.0	9.77e6
		2.1	5.12e6
		2.3	5.80e6
2	Whey to milk ratio	1.0	9.85e6
		1.1	5.12e6
		1.2	6.89e6
3	Flow of fines	0.05	5.12e6
		0.1	6.39e6
		0.3	5.70e6
4	Cooling time	15 min	1.05e7

		30 min 60 min 75 min 180min	 4.43e6 5.12e6 6.15e6 8.74e6
5	Refrigeration efficiency	30% 40% 50%	4.29e6 5.12e6 7.51e6
6	Starting time of evaporator	When whey storage tank is 60% 80% 85% 90% full	7.42e6 6.16e6 5.12e6 9.61e6

The variable value of the lowest sum square error was used in the model except cooling time and refrigeration efficiency. The values for these two variables, cooling time 30 minutes (60 minutes used in model) and refrigeration efficiency of 30% (40% used in model) were not used because those were giving higher sum square errors for few other days. Thus the developed model was used to calculate actual power demands of 16, 17, 18, 19, 20 th of December 2005.

The model for electricity consumption consists of two parts: the yogurt and cheese manufacturing which were initially developed separately and then combined. The production data of 16th December 2005 was used to examine the combined model. The power demand estimated by the model was compared with actual power demand provided by National Grid (Figure 23). When the estimated consumption from the model and the actual demand for December 16th were similar, a few other days from winter as well as summer were used to examine the model. Predictions of the calibrated model were compared with actual power demand data of six different days and presented in Figure 23 through Figure 28.

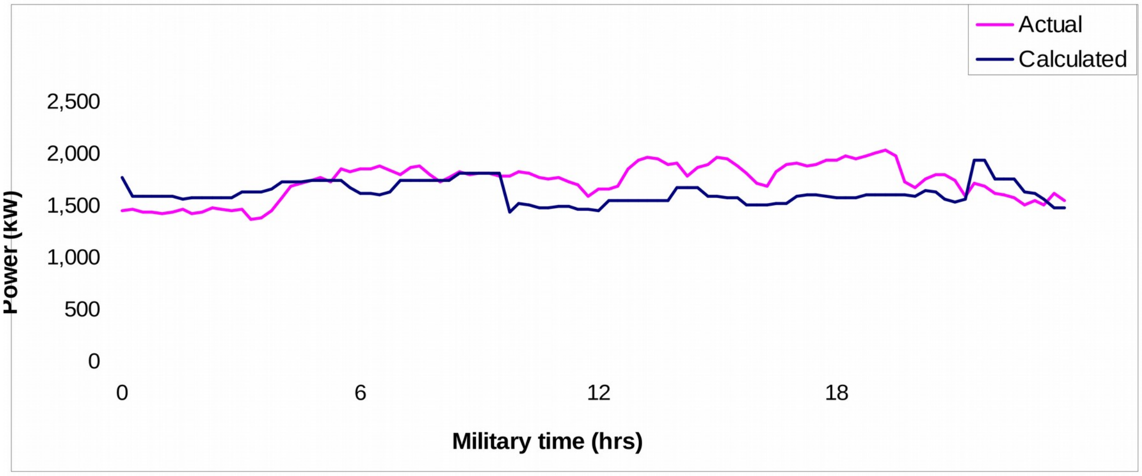


Figure 23: Comparison of predicted and actual power demand for 12/16/2005

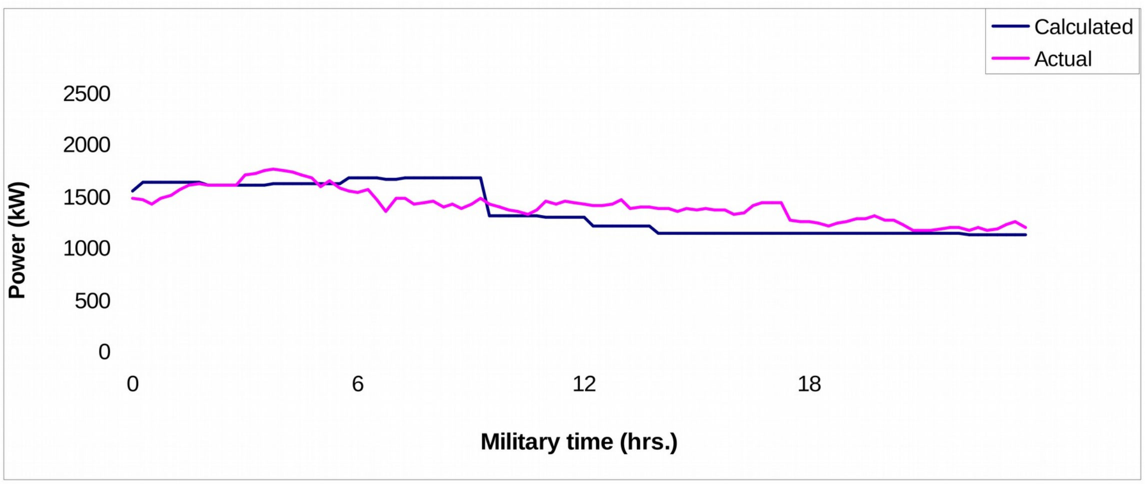


Figure 24: : Comparison of predicted and actual power demand for 12/17/2005

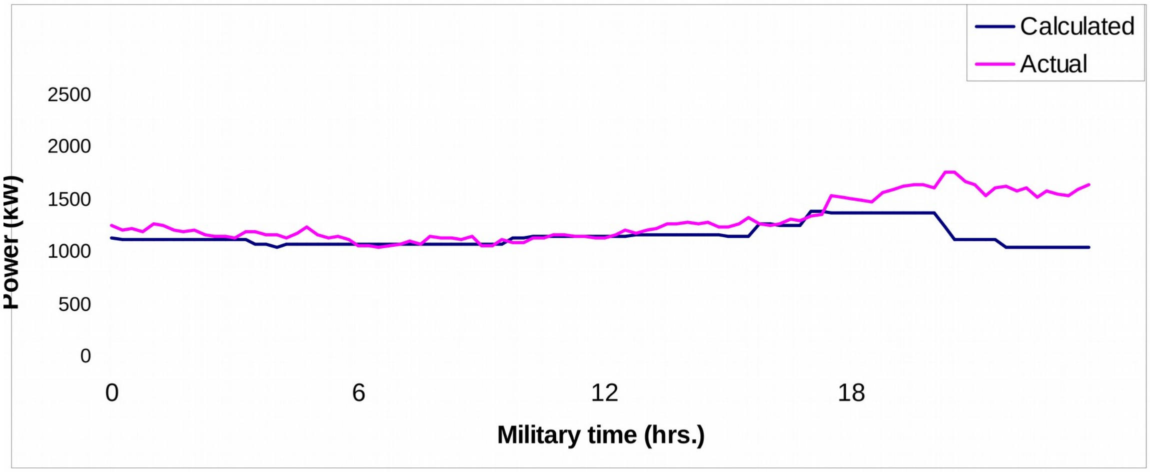


Figure 25: Comparison of predicted and actual power demand for 12/18/2005

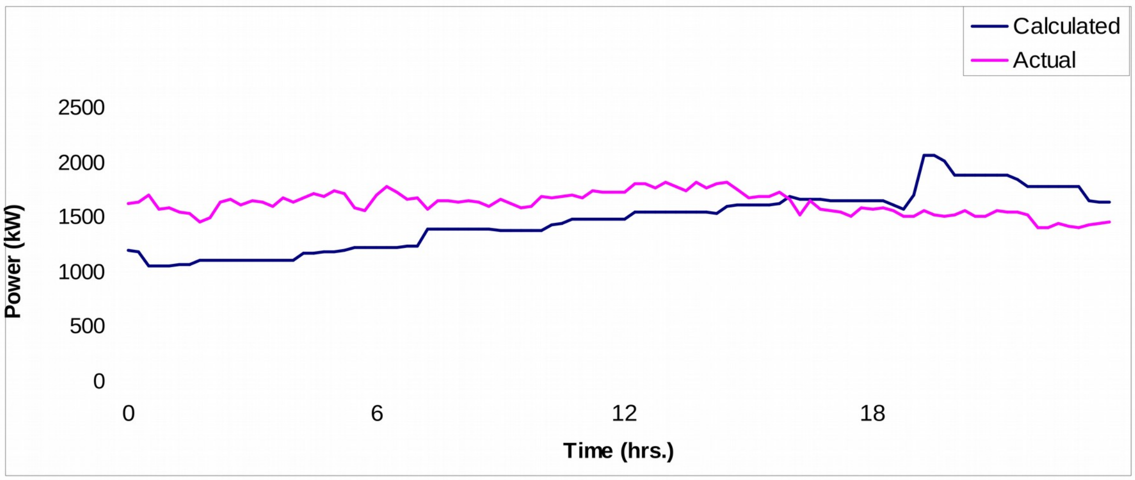


Figure 26: Comparison of predicted and actual power demand for 12/19/2005

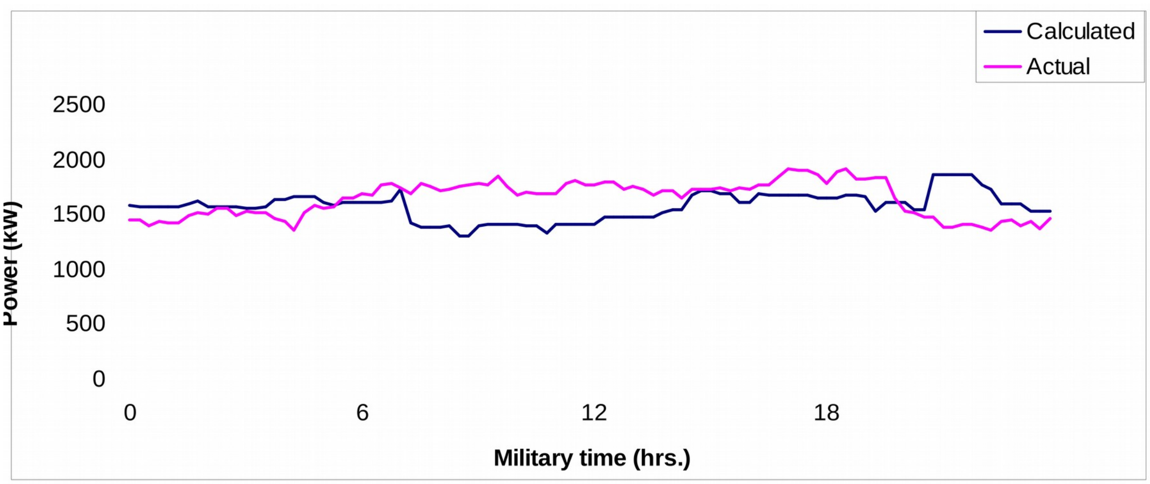


Figure 27: Comparison of predicted and actual power demand for 12/20/2005

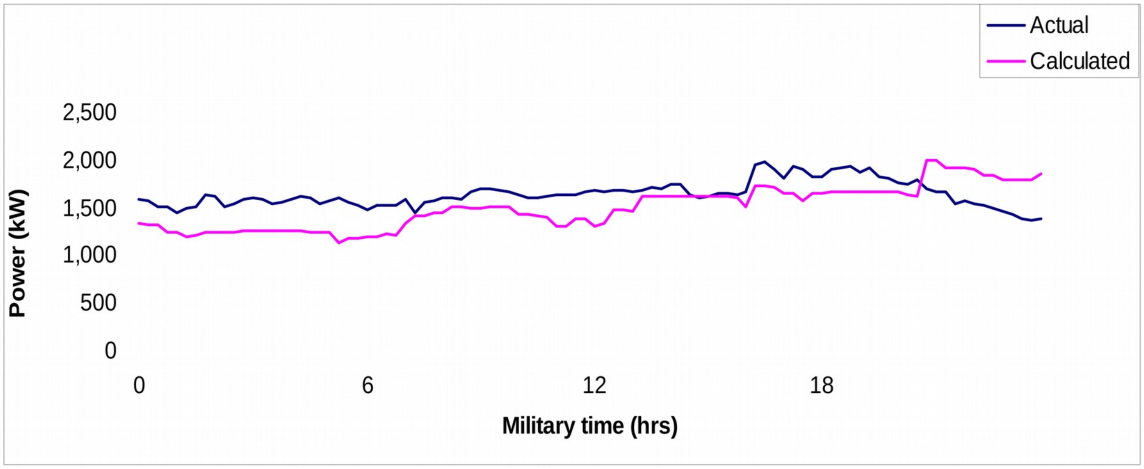


Figure 28: Comparison of predicted and actual power demand for 6/15/2006

Actual power demand for December 16, which was a weekday, was compared with the output of the model (Figure 23). Qualitatively the model successfully predicted general power demand of that day. The calibrated model was verified for four days. (17^{th}, 18^{th}, 19^{th} and 20^{th} of December 2006, Figure 24 to Figure 28).

There was relatively less cottage cheese and yogurt production on 17^{th} and 18^{th} as it was a weekend and the power demand of the plant was lower as compared to weekday. Since there was lower production the predicted profile was relatively flat. The calculated power demand for these two days was relatively similar to the actual power demand (Figure 24, Figure 25). Though the model did not reflect each peak of actual power demand, the model was sufficiently reliable to predict power demands of each day.

The inconsistency in actual and calculated power demand was observed after 20.00 hours on 18^{th} of December. While the calculated value remained constant and then declined the actual power demand was increasing (Figure 25). The model assumed that in a day the evaporator would not work for more than 12 hours. As the production is lower on weekend the evaporator would not have been used on 17^{th} December. In order to remove the waste resulting from 17^{th} and 18^{th} of December the evaporator may be running for longer time. There may be additional operations as cleaning, especially on a weekend. The same cause may be responsible for the inconsistency observed till 7 am on 19^{th} December (Figure 26). For the rest of the day on 19^{th} model predicted power demand which was consistent with the actual once.

The actual and calculated power demand for 20^{th} of December was compared in Figure 27. One sharp jump at around 20 hours was predicted by the model when there was no such drastic increase in actual power demand. The probable reason for this inconsistency is assumption made for working of evaporator.

In addition to six winter days the model was verified for five summer days. When the results were compared for the data from summer it was observed that the model succeeded to portray major trends of actual power demand of a plant. Sometimes there was inconsistency observed in predicted and actual power demand (Figure 26, Figure 27). Power demand of an evaporator may be responsible for the observed spikes. The evaporator was the major electricity consuming unit as compared to other equipment. In addition to that there were few dynamic loads present in the plant which may be responsible for the observed inconsistency. An attempt was made to make the model more accurate by selecting optimum values of six unknown variables (Table 14) and keeping sum square errors to minimum. The sum squares errors were calculated for each particular day and were mentioned in Table 15. All errors are of the same magnitude indicating total statistical fits between predicted and actual power demand curves were similar.

Table 15: Sum square errors (SSE) for a day

Date	SSE	Date	SSE
12/16/2005	5.12E6	6/15/2006	6.67E6
12/17/2005	2.54E6	6/16/2006	6.77E6
12/18/2005	5.10E6	6/20/2006	6.24E6
12/19/2005	1.17E7	6/21/2006	1.17E7
12/20/2005	5.59E6	6/22/2006	8.55E6

Though a few inconsistencies were observed between the modeled and actual values of power demand overall, the model predictions were reasonable and therefore it can be can be used to predict the power demands of Breyers Yogurt Company at any production level.

Model validation

Daily power and heating costs could be predicted using the model. The electricity cost was calculated for the given production of cottage cheese and yogurt for the particular days. Actual electricity costs were based on actual electricity consumption for particular day and the daily averaged energy usage cost. Power costs were compared for six days in December 2005 and five days in June 2006 (Figure 29and Figure 30).

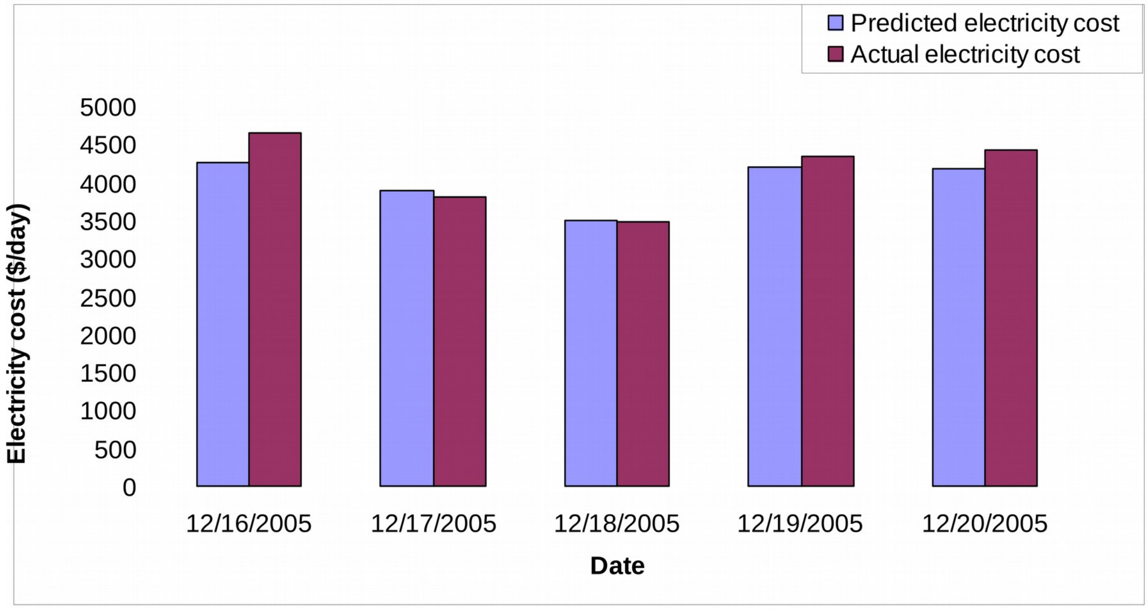


Figure 29: Electricity cost of December 2005:

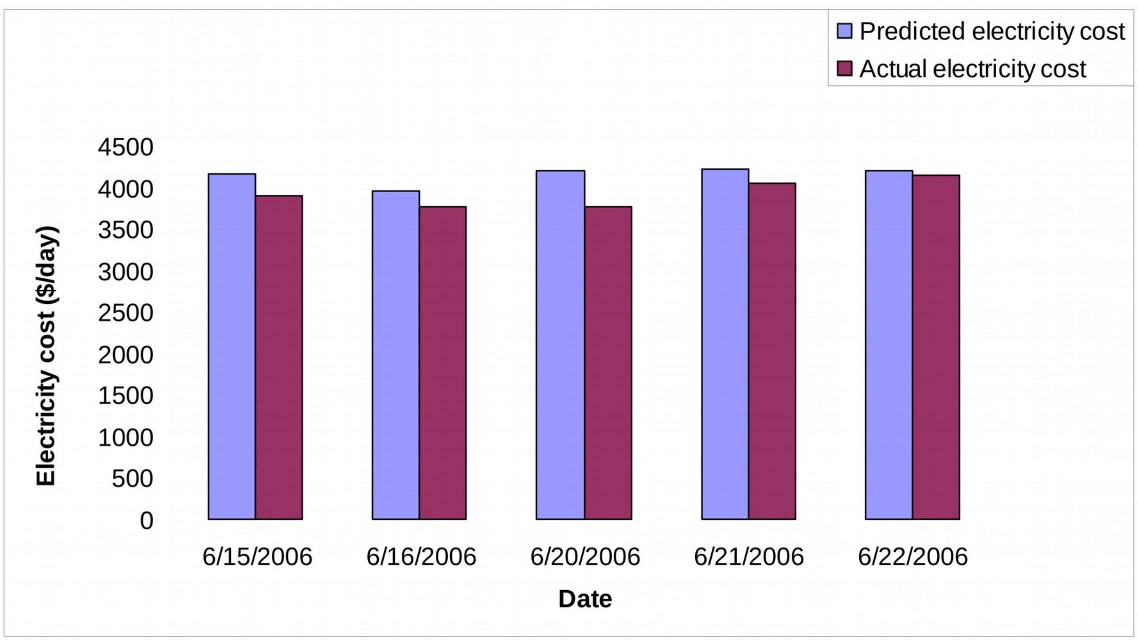


Figure 30: Electricity cost of June 2006

Predicted electricity costs for December 2005 were similar to actual costs (Figure 29). The calculated costs were slightly lower and slightly higher than actual ones for December 2005 and June 2006 respectively.

Electricity cost per day is dependent on production. On 17 th and 18 th December (both weekend days) electricity costs were less than other days (Figure 29) because during weekends the production was significantly less than the production during the week. The data for June 2006, actual and predicted electricity costs were compared in Figure 30. Overall, predicted electricity costs were within -2.8% and 5.6% of actual electricity costs for December 2005 and June 2006 respectively.

Predicted and actual electricity costs for December 2005 and June 2006 were plotted in Figure 31. The slope of the regression line was 0.99 + 0.35 which is statistically significant within 95% confidence (R2 = 0.54, p = 0.0013 < 0.05, n = 10).

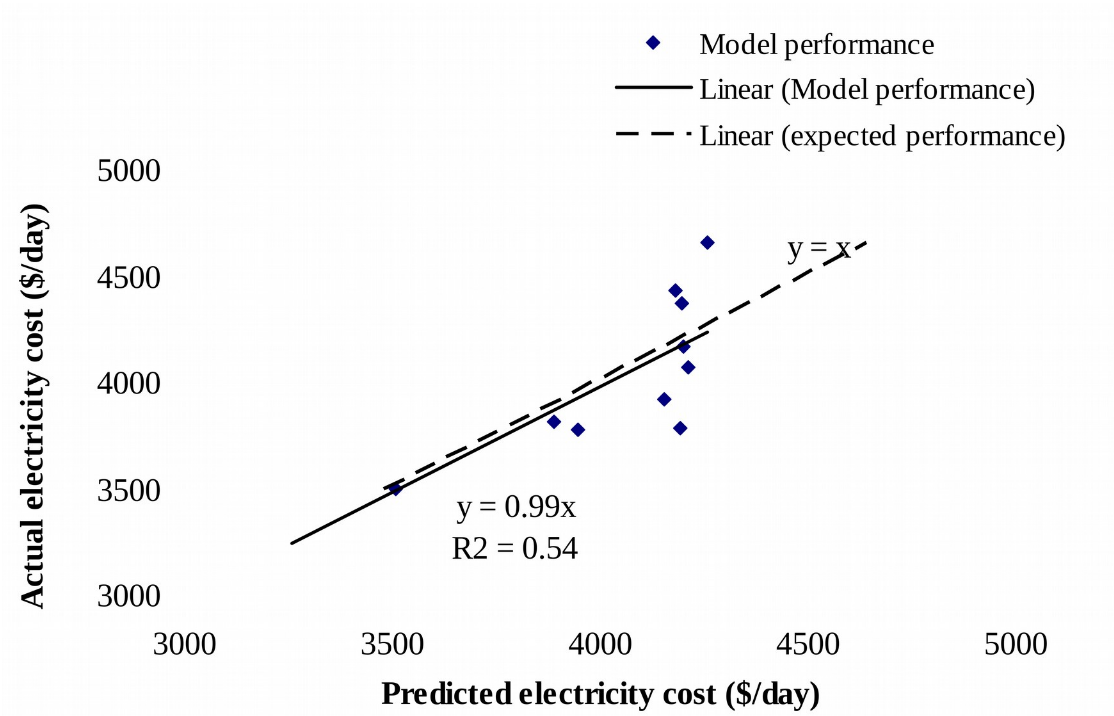


Figure 31: Comparison of actual and predicted electricity costs

Similarly predicted heating costs and actual heating costs for a day were compared for the same days in December 2005 and June 2006. Actual heating costs were based on actual fuel oil consumption for that day.

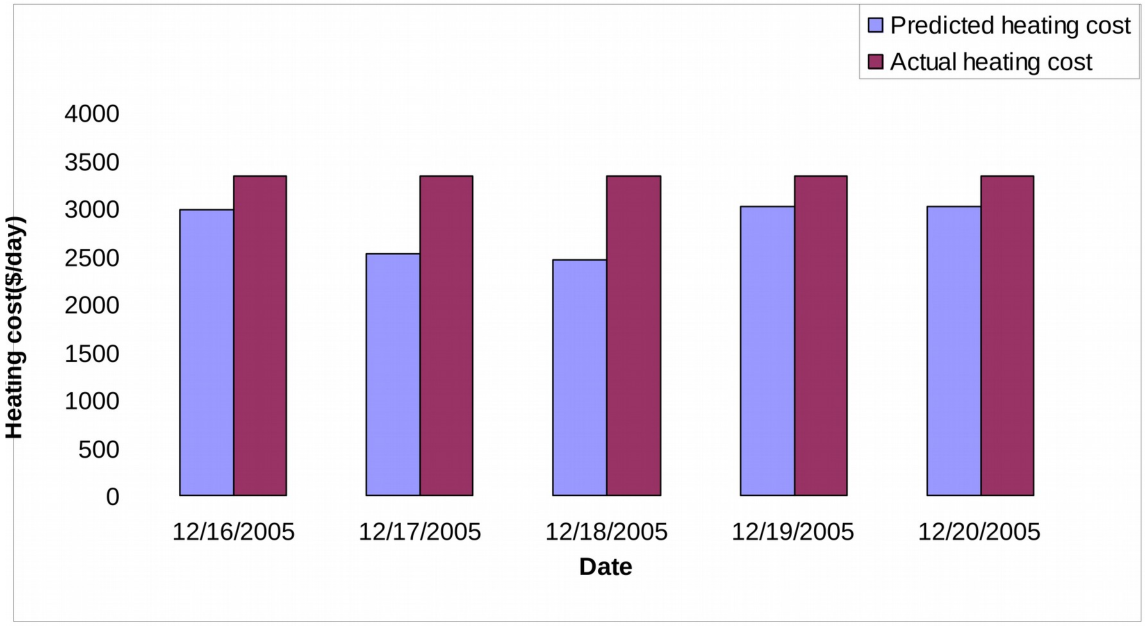


Figure 32: Heating costs for December 2005

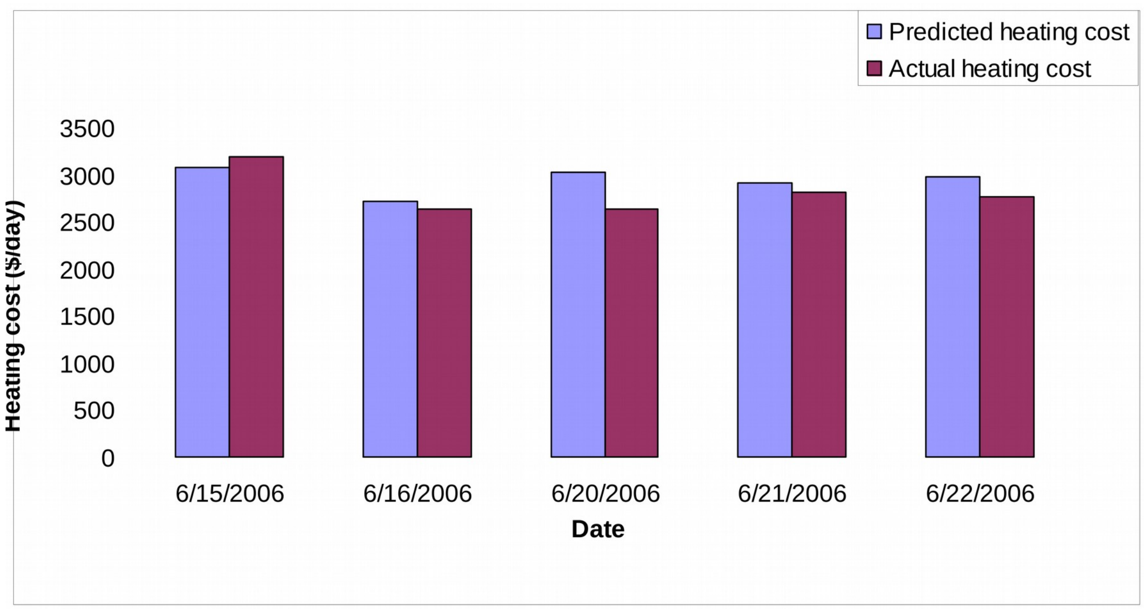


Figure 33: Heating costs for June 2006

Predicted heating costs were similar to actual heating costs (Figure 32, Figure 33). The difference between the heating costs was 5.1% for June 2006 and 25% in December 2005.

Actual and predicted heating costs for June 2006 were plotted in Figure 34 and expected behavior and its performance was compared. The slope of regression line was 0.95 $\pm$ 2.41 which is statistically insignificant (R^2 of 0.34, p = 0.3 > 0.05, n =5). The reason for the data to be statistically insignificant is the data set has only five points.

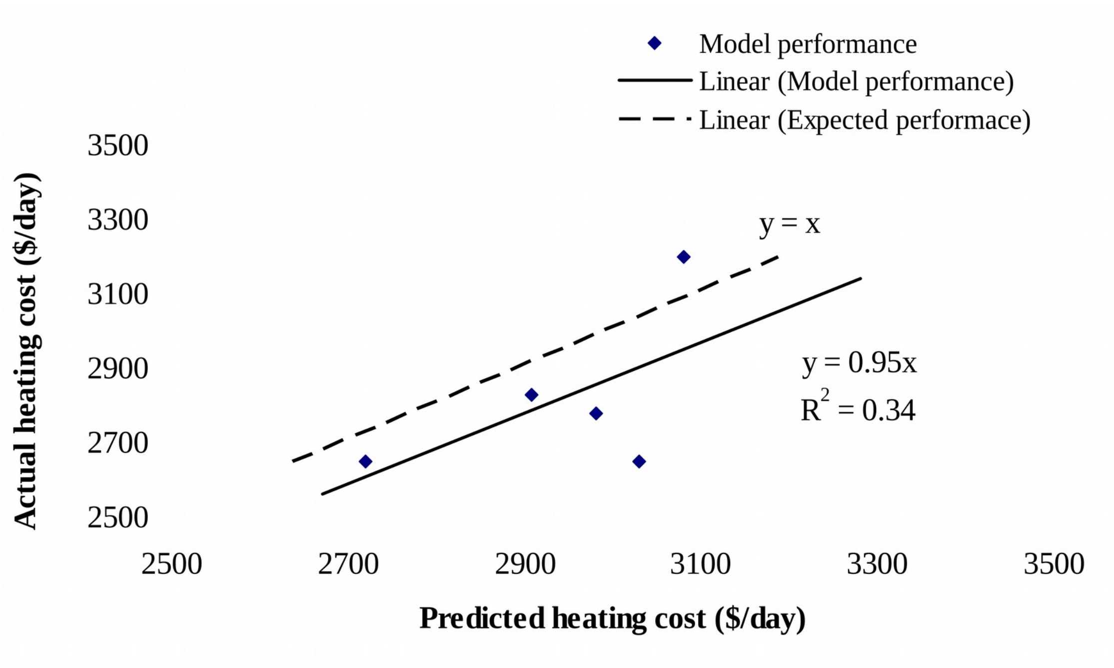


Figure 34: Comparison of actual and predicted heating costs

Since the actual daily fuel consumption data was not available for December, those daily costs were estimated using the monthly fuel bill and hence the difference between predicted and actual costs was higher. Thus data for December 2005 was not considered while plotting Figure 34, restricting analysis with only five data points (n = 5). It is clear from the previous discussion that the model predicts energy demand reasonably well and associated costs of Breyers Yogurt Company. Therefore the model can be used to evaluate various scenarios for beneficial biogas utilization at Breyers Yogurt Company.

Total energy per unit production

Since the model is based on energy and mass balance around major unit operations of the cottage cheese and yogurt manufacturing process, product specific total energy usage can be calculated using the model. While this feature was not included in the main objective of the model development, this information is particularly interesting to determine the impacts of fluctuating energy loads on product cost.

The energy usage per unit production was calculated from energy usage (kWh) of a day and total production of that day (Figure 35). This total production includes cottage cheese as well as yogurt varieties produced.

The average difference in predicted and actual energy usage per unit production was 6% in December and 5.6% in June 2006. The energy usage per unit production on 17 th and 18 th December were higher than all other days being considered. These two days were weekend days while other days were weekdays. The production on weekends was approximately 50% less than production on weekdays yet few unit operations continue to consume energy (e.g. cleaning). There was no equivalent reduction in energy usage and the energy usage per unit production was higher. Fixed major power demands such as refrigeration of product are not sensitive to production, thus inflating specific energy usage during low production days (i.e. weekends).

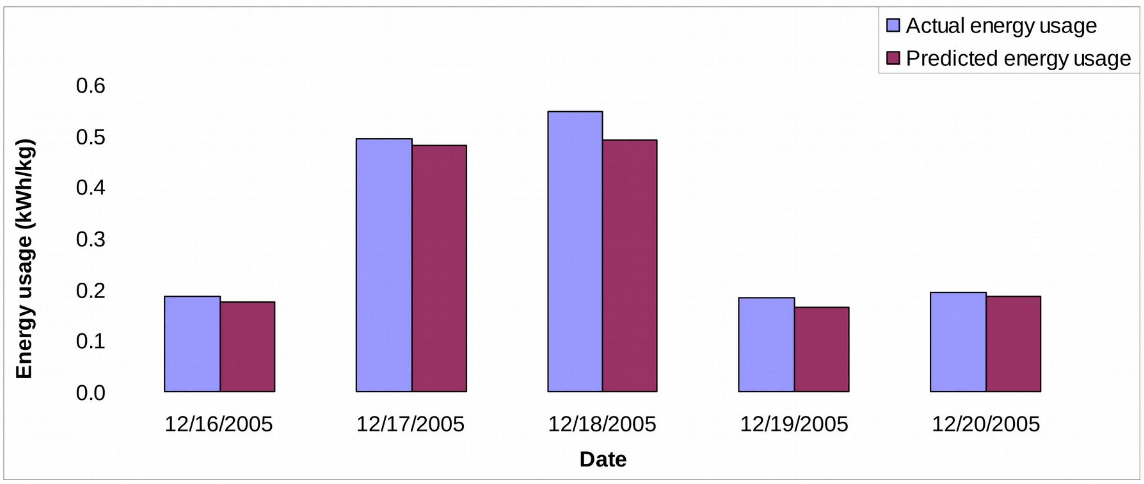


Figure 35: Electric energy usage per total product (cottage cheese and yogurt) for December 2005

Figure 36 shows electric energy usage per unit production of cheese as well as yogurt. Similarly heat requirement per unit production of cottage cheese and yogurt was presented in Figure 37.

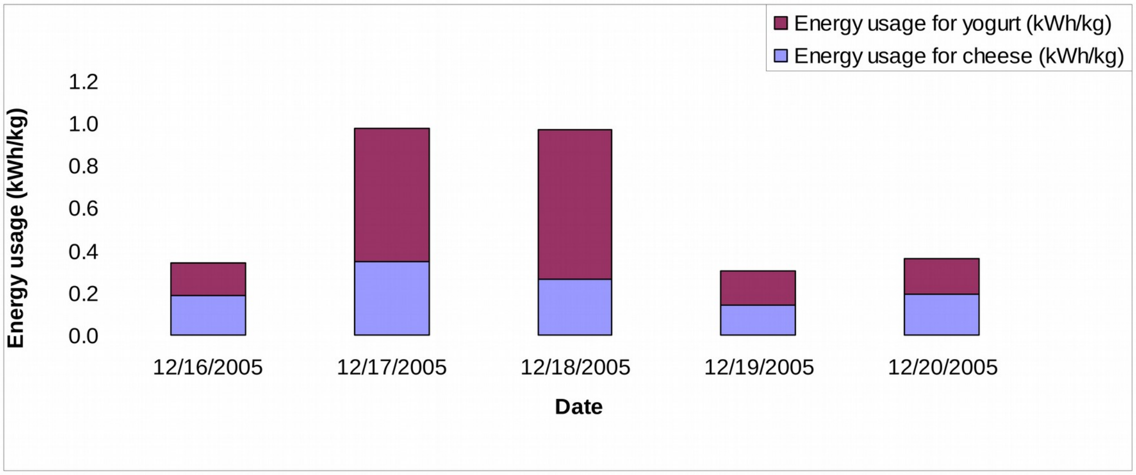


Figure 36: Predicted electric energy usage per unit cottage cheese and yogurt production

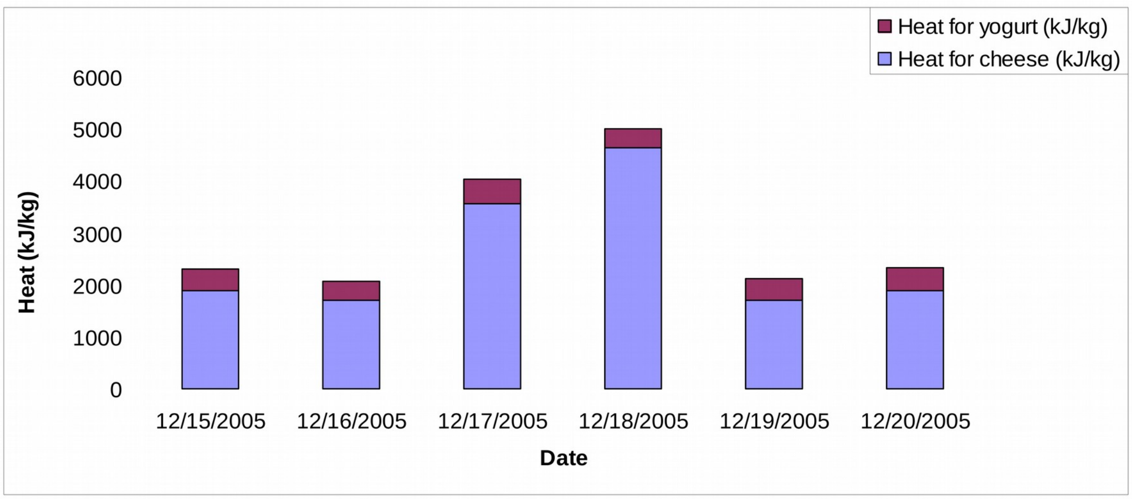


Figure 37: Predicted heat consumption per unit cottage cheese and yogurt production

Electric energy usage per unit production was higher on weekends (Figure 36). The similar trend was explained previously. Yogurt manufacturing seemed more electricity intensive than cottage cheese however cottage cheese manufacturing consumes majority of the heat at the plant (Figure 37). In cottage cheese manufacturing curd formations takes place in cheese vats at 82 ^{o}C (detention time 2-3 hrs) while yogurt manufacturing does not involve any unit operation requiring heating at elevated temperature for extended periods. This represents the major heat requirement for cottage cheese production. Hence cheese manufacturing has relatively higher heat requirement per unit production than yogurt production.

Based on the presented results the model can calculate energy (electric and fuel oil) demands of the plant for a given production level and schedule. Though these energy costs differ slightly (within 5%) from actual values the estimate is reliable and can be used for further analysis. The process model only considers the 13 predominant unit operations at the plant. Energy demand due to extra material processing, heating the building or other additional processes have been accounted for during the calibration of the model. Uncertainty in these external energy demands may explain the small but consistent difference between actual and predicted energy demands.

Modeling of an Anaerobic Digester/CHP System

In 2007, animals on U.S. dairy operations produced an estimated 225 million metric tons of manure (Liebrand et al., 2009). This manure can be viewed both as a challenge and liability and as an energy and nutrient resource. Anaerobic digestion technology, which is a biochemical process employing microbial communities to breakdown organic wastes, is gaining favor as a manure management practice and has been supported by the AgSTAR program, a joint effort by the U.S. Department of Agriculture, the Environmental Protection Agency, and the U.S. Department of Energy (U.S. AgSTAR, 2007). Anaerobic digestion has been shown to have the potential for biogas and energy recovery, odor and pathogen reduction, and nutrient management (Narula et al., 2011; U.S. AgSTAR, 2002). Recent research indicates that codigestion of substrates such as food waste and cheese whey in conjunction with manure can increase biogas production (Li et al., 2010; Venkiteshwaran, 2010; Lehtomäki et al., 2007).

Two major impediments to the implementation of anaerobic digestion technology are high capital costs and energy costs associated with maintenance of digester temperature. The AgSTAR program estimates that the capital cost of an anaerobic digester in the United States for an animal feeding operation with a dairy head size of 1,000 would be between $0.9–1.2 million (U.S. AgSTAR, 2010). Further, maintaining digesters at optimal mesophilic temperatures (37°C) is especially energy intensive in colder climates.

Digester costs may be offset by the implementation of a combined heat and power (CHP) system. The components of a CHP system may vary depending on the priorities of the operation, but a typical CHP system implemented with an anaerobic digester will include an engine-generator set to burn the biogas and produce electricity. Heat exchangers capture cogenerated heat from the engine coolant and exhaust to maintain digester temperature. Electricity production usually offsets the entire electrical load of the digester and possibly that of the farm as well. Certain operations will also capture heat in excess of that required by the digester. Smaller operations may utilize a water heater instead of an engine generator (U.S. EPA, 2007). A heat exchanger to capture heat from the digester effluent has also been suggested as a way to reduce the external heat demand of the digester (Gebremedhin and Inglis, 2007). Because anaerobic digesters with combined heat and power cogeneration systems are so complex and have great potential benefit, accurate modeling of the entire system is imperative.

An anaerobic digestion model, the Dynamic Anaerobic Reactor & Integrated Energy System (DARIES) Model, has been developed and is presented here to be both an accurate predictor of biogas production and composition as well as a model electricity production. The model may be run in either a completely mixed flow (CMFR) or plug flow reactor (PFR) configuration. DARIES is dynamic rather than steady state. Heat losses are continuously calculated using hourly weather data, and heat transfer may affect the digester temperature, which in turn will affect biogas production.

Little work with a similar scope has been previously reported. Biogas production models typically predict biogas as a function of the volatile solids (VS) content of the influent. Alternatively, other models use chemical oxygen demand (COD), a measure of the organic carbon in a sample, to predict biogas production.

The best known and widely available model of biogas production in farm digesters is the VS-based model FarmWare, which provides a "preliminary assessment of the benefits of integrating a biogas production and utilization system into an existing or planned dairy or swine manure management systems" (U.S. AgSTAR, 2007). FarmWare, currently available in Version 3.4 (April 2010), is provided by the AgSTAR program.

Numerous simple models of biogas production have been developed, but models of increasingly effective complexity are beginning to appear (Keshtkar, 2003; Blumensaat and Keller, 2005; Wu, 2009). Notable among these is the three-dimensional computational fluid dynamics (CFD) plug flow model based on principles of species transport and conservation of mass and energy described by Wu et al. (2009), for which predictions utilizing simplified stoichiometric reactions were found to be within 5% of the observed biogas flow rate for the one compared case study. However, little has been done yet to demonstrate a model verified over a larger data set. It should also be noted that current models are not able to simulate codigestion of wastes well.

The objective of this study is to validate DARIES as a model of biogas production and electricity production and to identify those operational and design parameters that have the greatest effect on model output. In this study, DARIES predictions have been made and compared to recorded data for eighteen dairy farms in the Northeastern United States. This study verifies the efficacy of DARIES predictions of biogas, methane, and electricity production and compares this to the efficacy biogas prediction by FarmWare. Sensitivity analysis was performed on DARIES to determine which parameters have the greatest effect on output variability.

Model Development

The DARIES model was designed to provide accurate predictions of biogas production, heat requirements, and electricity production of an anaerobic digester–CHP system on a dairy farm so as to allow for the investigation of and experimentation with operational and design parameters. Coded in MATLAB® & Simulink® , it marries a biogas production model with a heat transfer model, including combined heat and power elements, to form a dynamic model of a full anaerobic digester system. A simplified block diagram of DARIES is illustrated in Figure 38.

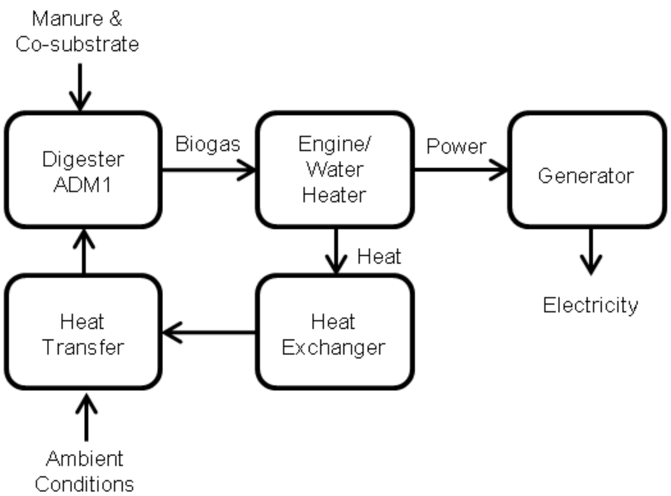


Figure 38: Simplified block diagram of DARIES.

DARIES implements a version of the Anaerobic Digester Model No. 1 (ADM1) to predict biogas production. ADM1 was developed by the International Water Association Anaerobic Digestion Task Force as a model for the anaerobic digestion of municipal waste (Batstone et al., 2002). Although developed for single-stage municipal wastewater digesters, ADM1 has been adapted to model two-stage (thermophilic followed by mesophilic) anaerobic digestion of municipal wastewater (Blumensaat and Keller, 2005), agricultural and food waste (Zaher and Chen, 2006), and dairy manure (Page, 2008a). More recently, work has been done to optimize the kinetic parameters of ADM1 for anaerobic digestion of dairy manure (Zhang et al., 2009). In addition to these improvements, the version of ADM1 incorporated in DARIES includes temperature-dependent (Arrhenius) kinetics as described by Rittman and McCarty (2001). Further, because ADM1 characterizes its mass flows on a chemical oxygen demand (COD) rather than volatile solid (VS) basis, the model is flexible enough to incorporate co-digestion if the necessary kinetic and stoichiometric parameters are known. A method of approximating certain feed parameters from total COD of the influent was adapted from Page (2008), while other feed parameters were not changed from work done by Rosen and Jeppsson (2006) in their MATLAB® implementation of ADM1.

Heat transfer models for anaerobic digesters were also developed for inclusion in DARIES. Heat transfer models for plug flow reactors including Gebremedhin et al. (2005), Wu and Bibieau (2006), and Xu (2007) have dominated recent research. However, since CMFRs are growing in popularity, a CMFR heat transfer model was developed for inclusion in DARIES. The CMFR heat transfer was developed from first principles, and the plug-flow heat transfer was largely adapted from Xu (2007). The engine model used by DARIES was adapted from model FC_SI186.m developed by the National Renewable Energy Laboratories (Markel, 1998) and verified against PowerTech 8.1L engine model 6081HFN02 engine performance curves (Deere & Company, 2001). The heat exchangers are modeled using the effectiveness-NTU method (Holmam, 1981).

Model Predictions

Prediction Methods

Observed biogas and methane flow rates for several manure digesters, listed in Table 16 in the Northeastern United States, predominantly in New York and Pennsylvania, were compared to predictions made by DARIES and FarmWare 3.4 (AgSTAR, 2010). Biogas at these farms was assumed to be 60% methane, a typical, though perhaps conservative value (Liebrand et al., 2007), when no composition was given. FarmWare and DARIES predictions were made for eighteen digesters each, with sixteen systems in common. Both total biogas and methane were considered. The data for observed biogas and methane production were collected from the New York State Energy Research and Development Authority (NYSERDA) Distributed Generation and Combined Heat and Power (DG/CHP) Integrated Data System (IDS) (NYSERDA, 2010), the Cornell Dairy Environmental Systems Program case studies (Cornell, 2010; Gooch and Pronto, 2009), and the Penn State University Department of Agricultural and Biological Engineering case studies (PSU, 2010).

Table 16: Influent data for twenty digesters in the Northeastern United States.

Farm Name	Location	Digester	Approx. size	Influent (m^3/d)	HRT (d)	COD[a] (g/L)
Freund Dairy	East Canaan, CT	PFR	250	14	30	NA
Morrisville State College	Morrisville, NY	PFR	275	NA	NA	NA
Oregon Dairy	Litiz, PA	PFR	385	28	20	NA
Brookside Dairy	Homer City, PA	PRF	425	38	30	NA
Reinford Farm	Mifflintown	CMFR	470	42	48	NA
Ridgeline Dairy	Clymer, NY	CMFR	525	95	25	201[b]
Sheland Farm, 2008	Ellisburg, NY	CMFR	560	53	17	75[c]
Sheland Farm, 2009	Ellisburg, NY	CMFR	650	69	13	75[c]
AA Dairy	Candor, NY	PFR	600	42	37	126
Hillcrest Saylors Dairy	Rockwood, PA	PFR	610	65	25	NA
Shrack Farms	Logantown, PA	PFR	650	76	30	NA
Penn England Farm	Williamsburg, PA	CMFR	800	69	23	NA
New Hope View Farm	Homer, NY	PFR	850	76	20	103
Patterson Farms	Auburn, NY	CMFR	1000	170	19	NA[b]
Noblehurst Farms	Pavillion, NY	PFR	1100	106	25	NA
Emerling Farm	Perry, NY	PFR	1100	182	25	NA[d]
Twin Birch Farm	Owasco, NY	PFR	1200	110	20	NA
Sunny Knoll Farms	Perry, NY	PFR	1400	163	18	NA
Zuber Farms	Byron, NY	CMFR	1550	NA	NA	NA
Aurora Ridge Farm	Aurora, NY	PF	2000	231	31	NA

a. NA = not available. Assume 80 g/L unless otherwise stated.
b. Influent includes food waste.
c. Solids separation before digestion.
d. Assume 50 g/L COD to account for dilution.

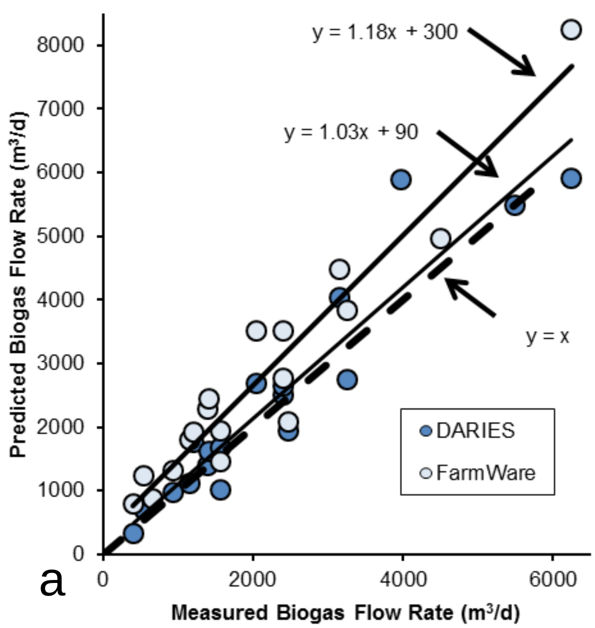
DARIES predictions of electricity based on the influent parameters for the eighteen AD/CHP sets were compared to daily observations of electricity produced per volume of biogas for nine digester gas engine-generator systems in New York. The measured daily electricity production and biogas utilization rate for the nine biogas engine-generator sets was accessed from the NYSERDA DG/CHP IDS (NYSERDA, 2010).

FarmWare predictions are based on herd type and size, whereas DARIES predictions are made based on type of digester, influent flow rate, hydraulic residence time, and, if known, COD. Table 16 lists the characteristics of the twenty farms used in this study. The approximate number of dairy cows contributing waste to the digester is given, although manure from other animals (e.g. heifers) may be included in the influent stream and was considered when modeling with FarmWare.

For DARIES, a default value for COD of 80 g/L for manure was used when relevant data was not available. No DARIES predictions were for farms that did not have reported influent flow rate since herd size was found to be an insufficient predictor of influent flow rate. Dairy manure is assumed to be 50% biodegradable. FarmWare assumes biogas is 57.5% methane when evolved from dairy manure and assumes an HRT of 20 days (U.S. AgSTAR, 2007). Since FarmWare is not capable of modeling codigestion, no FarmWare predictions were possible for the Ridgeline or Patterson Farms.

Model Predictions

The quality of DARIES and FarmWare predictions of biogas and methane flow rate are presented in Figure 39. In most instances, FarmWare over predicts both methane flow rate and total biogas flow rate (additional information may be found in Supplementary Information). DARIES, on the other hand, predicts biogas very well and consistently under predicts methane as a percent composition of the biogas. Real biogas is approximately 60% methane, while DARIES predicted biogas is closer to 50–55% methane, which may in part be due to an over prediction of carbon dioxide. Difference in predicted and observed methane volume (approximately 12% on average), may be due to differences between the assumed COD and the unknown actual COD of the influent at that farm, or due to uncertainty in methanogenic kinetic parameters.



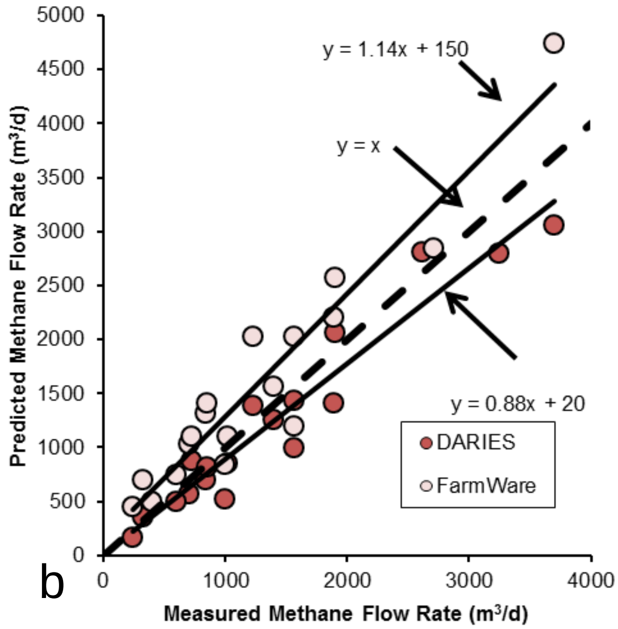


Figure 39: DARIES and FarmWare model predictions are evaluated by comparison of predicted to measured (a) biogas and (b) methane production.

Figure 40 shows both the daily actual electricity production per volume of biogas for nine NYS biogas engine-generators, as well as the DARIES predictions of biogas and electricity for the eighteen dairy farms. Regression lines for both data sets are also included, the statistics of which are discussed later.

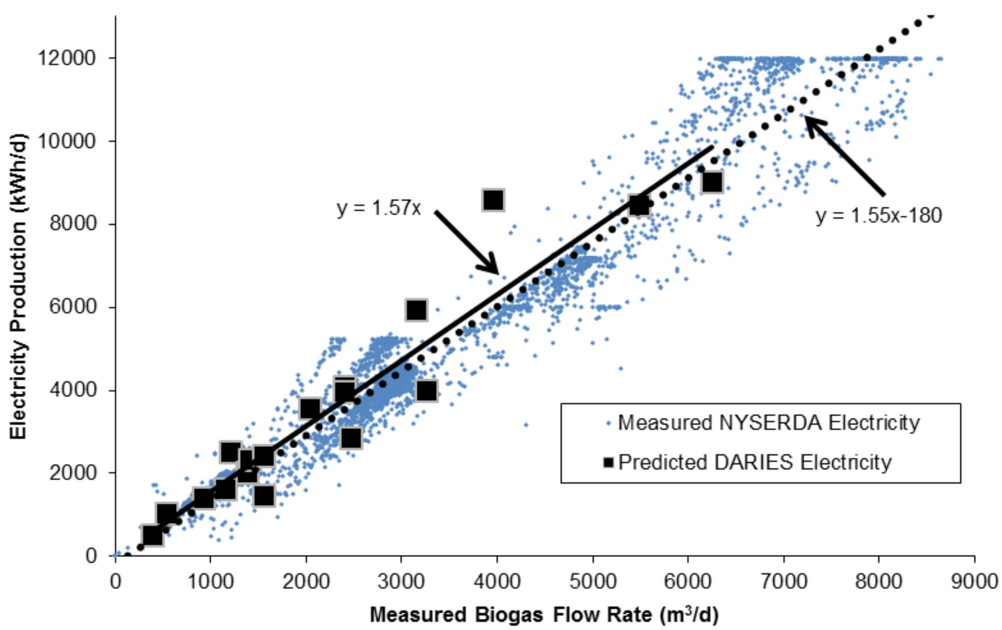


Figure 40: Comparison of DARIES predictions of electricity production (kWh/d) to NYSERDA data set as function of measured biogas flow rate data (m3/d).

Model Verification

Verification Methods

A statistical method adapted from Larsen (2006) and Neter et al. (1996) was used to assess the efficacy of FarmWare and DARIES as appropriate models for the example farms. This was done for each of the FarmWare and DARIES models for both biogas and methane production. To verify or reject a model, the predicted and measured data sets were treated as functions of the measured data, and it was determined whether or not the resultant measured and predicted regression lines were statistically coincident. Note that the line predicting measured biogas as a function of measured biogas is y=x. Thus, from a graphical perspective, in a plot of predicted vs. measured biogas/methane, the closer (in both slope and intercept) the regression line of the predicted data is to the y=x line, the better the prediction.

The method to test for coincidence involves reimagining the observed and predicted data sets, which are considered functions of the measured data, as being part of a single, larger data set whose values are functions of both the measured data and a dummy variable. An equation is developed to represent this larger data set. In this study, it is a function of the dependent variable x (measured biogas flow rate) and the dummy variable z that takes the value $z_i = 1$ if a data point i came from the model predicted group and $z_i = 0$ if point i came from the group of observed data. The least squares regression equation that encompasses this new data set has the following general form

$$y = \hat{\beta}_0 + \hat{\beta}_1 x + z(\hat{\beta}_2 + \hat{\beta}_3 x) \qquad (1)$$

This equation simplifies to

$$y_1 = (\hat{\beta}_0 + \hat{\beta}_2) + (\hat{\beta}_1 + \hat{\beta}_3)x \qquad (2)$$

$$y_2 = \hat{\beta}_0 + \hat{\beta}_1 x \qquad (3)$$

when $z = 1$ (predicted) and $z = 0$ (measured) respectively.

To test for coincident of these two regression lines, the following hypothesis is used:

$$H_0: \beta_2 = \beta_3 = 0$$

Thus, this is a test to see if the variable z (note that parameters β_2 and β_3 are those associated with z), the variable that distinguishes between the predicted and measured sets, is significant. If it is not, the line y=x describes the predicted data set, and the model is verified.

For this method to be valid, the assumption of equal variance between the measured and predicted data was verified in all instances. A level of significance of $\alpha = 0.05$ was used throughout this study. That is, a null hypothesis is rejected (and so the model is not accepted) if the p-value calculated for an equation is less than $\alpha = 0.05$.

Verification of Biogas Prediction

Plots of predicted vs. measured biogas/methane can be seen in Figure 39. In both cases, it can be observed that the DARIES prediction regression line is closer to the y=x line than is the FarmWare prediction regression line. Confidence bands for DARIES predictions may be found in Supplementary Information.The p-values for the test of coincidence with the y=x lines are as follows for each of the four predictions: DARIES Biogas (0.53), DARIES Methane (0.01), FarmWare Biogas (8.0E-6), and FarmWare Methane (2.9E-4), Using level of significance $\alpha = 0.05$, we only accept the coincidence of the DARIES biogas predictions with measured data and reject that of the FarmWare predictions and the DARIES methane predictions. Further analysis suggests that it is the slope rather than the intercept of the DARIES methane predictions that does not match that of the measured data. It may be worth noting that if the level of significance were lowered to 0.01 (corresponding to 99% confidence rather than 95%), we would not be able to reject DARIES methane predictions. FarmWare predictions would still be rejected.

Hence, DARIES is a more accurate predictor of biogas than FarmWare. For methane, DARIES under predicts methane by approximately 12%. Hence, predictions for smaller farms (less 1,000) are more accurate. Prediction of methane as a percent composition of biogas around 50–55% rather than the typical 60% has been previously observed in ADM1 (Page, 2008) and is likely due to the uncertainty in the methanogenic kinetic parameters.

FarmWare on the other hand is not found to be an effective predictor of biogas or methane. Its over prediction of methane, for example, as indicated by the regression line, varies between 18% to in excess of 50% over the range of observed values. It is not surprising that FarmWare fails to accurately predict biogas production in these real situations as it is meant as a preliminary tool. FarmWare is limited in that it predicts biogas production as a linear function of dairy cow herd type and size. This study found too much uncertainty in the relationship between herd size and influent flow rate to model the relationship in DARIES with confidence. Further, FarmWare assumes an HRT of 20 days, which is not always accurate, and it cannot account for co-digestion.

Verification of Electricity Production

The same method described above was adapted to determine whether the two regression lines in Figure 40 are coincident. The p-value for this test was 0.14, which indicates coincidence. Further, Figure 40 demonstrates that the DARIES predictions of electricity production are well within the expected scatter. Digester models generally do not include electricity production, and, thus, this result represents a significant advancement in that respect.

Sensitivity Analysis

Methods

Sensitivity analysis was performed to determine the sensitivity of an output parameter to variation in input parameters and to determine to the nature of the effect (i.e. degree of linearity) input parameters have on output parameters. The objective of performing sensitivity analysis was primarily to determine the relative importance of different input parameters on various aspects of the output. Further, sensitivity analysis is a way of factor screening for complex models. For example, if all output parameters are relatively insensitive to certain input parameters, those input parameters may be held at reasonable fixed values so as to avoid inordinate parameter configurations (Alam et al., 2004) and to concentrate future work on important parameters.

Sensitivity analysis was performed by Morris's Randomized One-at-a-Time (OAT) method, also known as the Elementary Effects (EE) method, as adapted from Alam et al. (2004) and Ekström and Broed (2006). The general idea of the EE method is to determine the change in an output variable when a single input variable is changed by a set amount. This change is the elementary effect of the input variable x_i on the output variable y_j. The elementary effect is calculated for a number of randomized input vectors and a predetermined, constant change in the input variable. Each calculation is one trial, and analysis is performed over several trials.

More formally, let $\boldsymbol{x} = (x_1, \ldots, x_k)$ be a randomly generated *k*-dimensional vector input to the DARIES function **y** = f(**x**) where *k* is the number of independent input variables. The input parameter space is discretized, that is, each x_i takes one of *p* discrete values from the set {0,1/(*p*-1), 2/(*p*-1),…,1}. A predetermined multiple of 1/(*p*-1) is chosen and designated Δ. This Δ is the determined amount by which an input variable is changed. It has been shown that a choice of an even *p* and Δ=*p*/(2(*p*-1)) is convenient (Alam et al., 2004). Then, the *i*th elementary effect is given by

$$m(x_i) = \frac{y(x_1, \ldots, x_i + \Delta, \ldots, x_k) - y(\boldsymbol{x})}{\Delta} \qquad (4)$$

An elementary effect is determined for each of the *k* input variables in each of *r* trials each beginning with a randomly assigned base value of **x**. A mean μ and standard deviation σ are calculated over the *r* trials for each input variable. If μ = 0, the variable has no effect on the output. If σ= 0, *y* is a linear function of x_i. A parameter with large μ relative to σ is considered mildly non-linear while parameters with large σ relative to μ are strongly non-linear. In general, a large μ indicates an overall importance of the variable to the output variability while a large σ indicates either non-linear effects or interactions with other variables (Ekström and Broed, 2006).

For this study, we present the sensitivity analysis for the DARIES CMFR model with p = 6, Δ = 3/5, and r = 10. These choices were made based on the recommendations of Alam et al. (2004) and Ekström and Broed (2006). The set of DARIES input parameters varied in this study are listed in Table 17. The lower and upper bound for each parameter were chosen based on likely distributions and a range of interest for each parameter (Page, 2008; U.S. EPA, 2010; Holman, 1981; Xu, 2007).

Table 17: DARIES input variables, bounds of tested variation, and effect evaluation for biogas production, electricity production, and usable energy recovery output parameters.

Parameter	Units	Lower Bound	Upper Bound	Biogas Production	Electricity Production	Usable Energy
Influent COD	g/L	60	120	Major	Major	Major
Influent total VFA	mg/L	1000	5000			
Influent biodegradability	%	20	70	Major	Major	Major
Influent methanogen concentration	$kgCOD/m^3$	0.5	3		Minor	Minor
Influent acetogen concentration	$kgCOD/m^3$	0.5	3		Minor	Minor
Flow rate of manure	m^3/d	20	200	Major	Major	Major
Hydraulic residence time	d	10	45	Moderate	Moderate	Moderate
Digester control temperature	C	20	40	Moderate	Moderate	Moderate
Engine efficiency	-	25	40		Major	Moderate
Engine coolant HX effectiveness	-	0.5	0.8			Minor
Engine exhaust HX effectiveness	-	0.5	0.8			Minor
Fluid-manure HX effectiveness	-	0.5	0.8			Moderate
Manure-manure HX effectiveness	-	0.5	0.8			Minor
Water heater efficiency	-	0.7	0.9			Moderate
Thickness of insulation	m	0	0.2			Minor
Thermal conductivity of insulation	W/m-K	0.02	0.2			Minor
Temperature of fluid in exhaust HX	C	25	50			
Biogas to engine rather than water heater	%	0	100		Major	Minor
Specific heat of manure	J/kg-K	3500	4000			

Sources include Page (2008), U.S. EPA (2010), Holman (1981), and Xu (2007)

Sensitivity Analysis Results

The sensitivity analyses of biogas production, electricity production, and usable energy recovery (the sum of electricity and excess heat evolved from the CHP system) are presented in Figure 41 as a graph of σ vs. μ. The most important (large μ) parameters are identified on the figure.

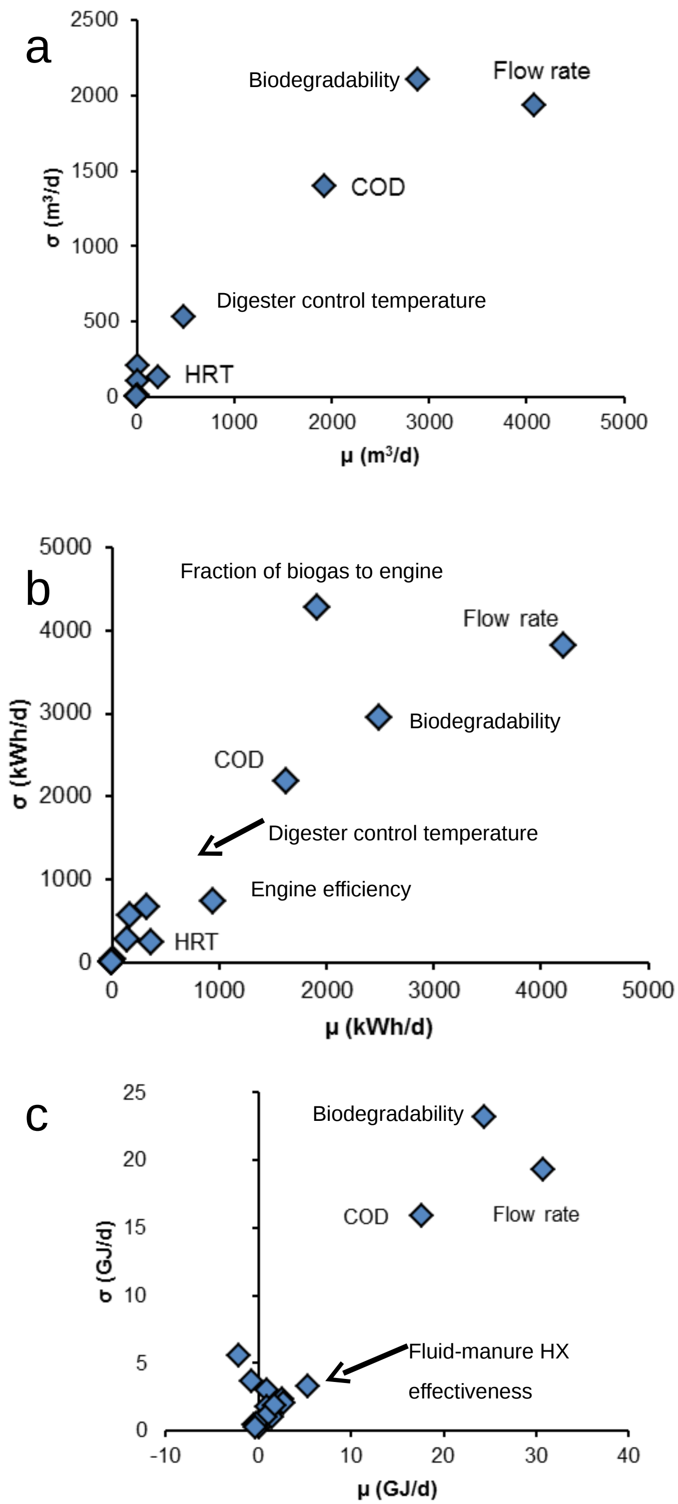


Figure 41: Elementary effects plot (¬ vs. μ) for (a) biogas production, (b) electricity production, and (c) usable energy recovery.

The results of Morris's elementary effects screening method suggest groupings of important parameters. Major effects include those parameters with large μ and σ of a similar order of magnitude. These factors include the major influent parameters, namely influent flow rate, biodegradability, and COD, and significant operational parameters such as the fraction of biogas sent to the engine-generator. This study considers a parameter with a μ greater than 20% of the largest observed μ for that output to have a major effect. Moderate effects include those with significant but not the largest μ. One may think of these parameters as fine tuning the output variable. Parameters in this category typically include HRT, digester control temperature, and relevant effectiveness of the heat exchangers. A parameter with a μ greater than 5% of the largest observed μ for that output is considered to have a moderate effect. Minor effects have small μ. The inherent uncertainty in some of the major and moderate parameters may affect the output to a degree that finding accurate values for minor parameters will not improve the accuracy of the output. Finally, certain parameters have negligible effects, being essentially irrelevant to the output parameter. Parameters with μ less than 1% of the largest observed μ for that output are considered negligible. Parameters found in these last two categories across the list of output variables are good candidates for being assigned fixed values and removed from further sensitivity considerations. For DARIES, influent VFA, acetogen, and methanogen concentrations fall into this category. A classification of parameters as major, moderate, or minor for each of biogas production, electricity production, and usable energy recovery is also found in Table 17.

The results of this sensitivity analysis are not unexpected. Biogas production will vary greatly with the volume of manure entering the digester daily. By proxy of herd size, manure volume is taken into account by FarmWare. Biogas production will also vary with the strength of the influent, as characterized by biodegradability and COD. Waste strength is assumed constant in FarmWare and may account for some of the error. It is not too surprising that certain influent constituents with low concentrations relative to the overall composition of the manure (e.g. VFA and bacterial concentrations) have minimal to no effect on most dependent parameters.

Conclusion

DARIES was verified as an accurate biogas model over a data set of eighteen farms while FarmWare was rejected as overly optimistic. DARIES under-predicted methane by approximately 12% on average while FarmWare over predicted both biogas and methane by 20% to more than 50% over the range of study. Although methane was under predicted, DARIES electricity production predictions were demonstrated to be well within expected variation. DARIES may now be used to investigate various AD-CHP scenarios such as the use of co-digestion or varying digester control temperature seasonally.

The parameters that contribute the most to output variability are influent flow rate, biodegradability of substrate, influent COD, digester temperature, and HRT. Future work must concentrate on better understanding and quantification of these parameters. This is especially true of biodegradability, for which there is no specific test. These results indicate that DARIES is a good predictor given information about the basic important parameters but that improved predictions may be effected by more detailed information about additional parameters.

This work is significant because it introduces a dynamic model of an anaerobic digester and integrated energy system, which is something that has not yet been seen in this field, and it provides a relatively wide verification of both biogas production and electricity production. It opens the door for future work optimizing design and operational parameter as well as the economic return for famers considering implementing anaerobic digestion technology.

Task 4 Extrapolation of Energy Economics

Background on Combined-Heat and Power (CHP) Systems.

Fuel cells

A fuel cell is an electrochemical device that converts chemical energy of fuel directly to electrical energy. It operates with high efficiency as it has no internal moving parts. Batteries store energy, while fuel cells can produce electricity continuously as long as fuel and air are supplied.

Modern power production consists of heat extraction from fuel, conversion of heat to mechanical energy and finally, transformation of mechanical energy into electrical energy. Our bodies oxidize hydrocarbon compounds from our food and release chemical energy without combustion. Fuel cells operate similar to our body.

Fuel cells consist of stacks which are enclosed in a container. Stacks have electrodes inside them. Arrangements are made for fuel and air to enter the container. Fuel reacts with air in presence of electrodes. Electrons start flowing and hot water and exhaust gases to come out of the container as a result of the reaction. Thus electricity is generated and extracted from the electrodes. Hot water comes out as a by-product of the reaction and heat energy can be extracted from it (National Fuel Cell Research Centre).

Working principal

A fuel cell consist of electrodes and electrolytes. Hydrogen flows to the fuel cell anode and protons are separated. Those flow through electrolyte towards cathode. Oxygen at the cathode reacts with protons to form water and heat. Thus ionic currents flows through the electrolyte while electronic current flows through external electric circuit. The whole reaction generates electricity and hot water is given out as a by-product. Figure 42 shows arrangement of fuel cell (National Fuel Cell Research Centre and Sames, Du and Bove 2005).

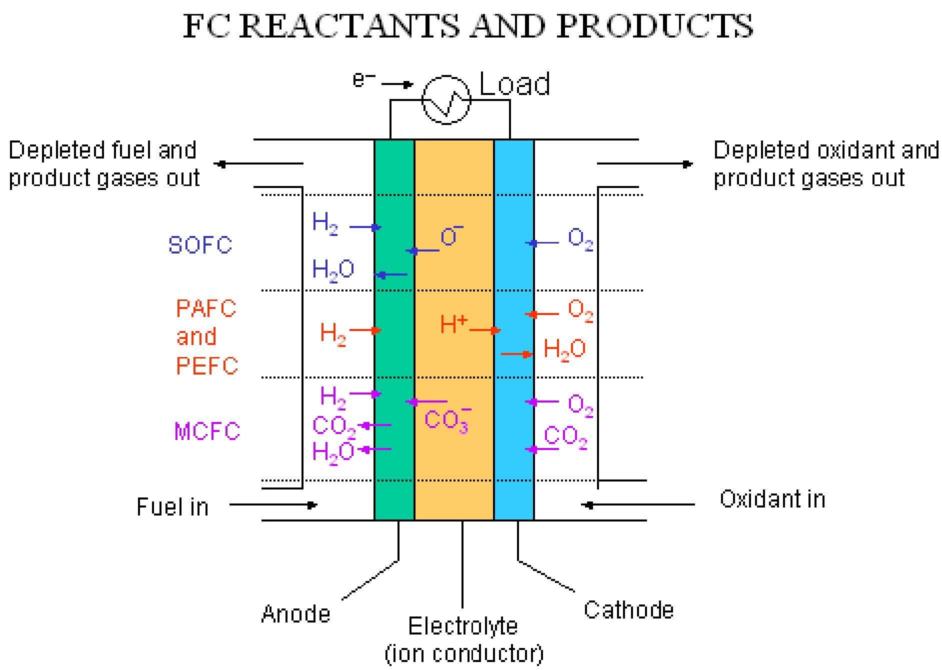


Figure 42: Fuel cell reactants and products

Types of fuel cells

Fuel cell types are generally characterized by electrolyte material. The electrolyte is the substance between the positive and negative terminals, serving as the bridge for the ion exchange that generates electrical current. There are five principle types of fuel cells as mentioned below. These types are significantly different from each other in many respects and the key distinguishing feature is the electrolyte material.

1) Alkaline Fuel Cell
2) Molten Carbonate Fuel Cell
3) Phosphoric Acid Fuel Cell
4) Proton Exchange Membrane Fuel Cell
5) Solid Oxide Fuel Cell

Table 18 compares advantages and disadvantages of four commonly used fuel-cells

Table 18: Comparison of various types of fuel cells (Christenson, 1997)

	Proton Exchange Membrane (PEMFC)	**Phosphoric Acid (PAFC)**	**Molten Carbonate (MCFC)**	**Solid Oxide (SOFC)**
Advantages	Tolerant to CO_2	Tolerant to CO_2	No Precious metal required	No Precious metal required
	Low working temperature	Most Advanced Stage	CO is a usable fuel	CO is a usable fuel
	Very High Current density	Applicable to small capacity plants and vehicular use	Internal Reforming in cells is feasible	Internal Reforming in cells is feasible
			High grade heat is available	High grade heat is available
				CO_2 recycling not required
Disadvantages	CO content is strictly prohibited	Catalyst needs precious metal	CO_2 source needed	High temperate puts severe constraint on cell material
	Fuel cleanup and external gas reformer required if pure hydrogen not available	Fuel cleanup and external gas reformer required if pure hydrogen not available	Phase change between working and ambient temperature	Relatively High electrode resistivity
	Water Management in cell is difficult	Pt Catalyst is deactivated by CO		
	Only Low grade heat is available	Low conductivity electrolyte management is necessary		

Molten Carbonate fuel cell: These fuel cells consist of two nickel based porous electrodes. The electrolyte used is an alkali carbonate (sodium, potassium, or lithium salts, i.e., Na_2CO_3, K_2CO_2, or Li_2CO_3) or a combination of alkali carbonates. An MCFC operates at 600 to 700°C electrolytes withstanding these temperatures are used.

The output range of these cells varies from kilowatt to megawatt. These cells offer greater fuel flexibility and higher conversion efficiencies. As they operate at relatively higher temperatures the exhaust heat can be recovered. High initial costs and short life time are the major drawbacks (National fuel cell research centre and Sames, Du and Bove 2005).

Solid oxide fuel cell: These fuel cells use electrolyte in solid form. They also operate at higher temperatures (800 – 1000^{O}C) and exhaust heat can be recovered. These cells utilize a non-porous metal oxide (yttria-stabilized zirconia, Y_2O_3-stabilized ZrO_2) electrolyte material. The anode of SOFC is cobalt or nickel zirconia and the cathode is strontium-doped lanthanum manganite. High-temperature operation, up to 1,000°C, allows more flexibility in the choice of fuels and can produce very good performance in combined cycle applications. Total thermal efficiency of 85% can be achieved in co-generation applications. They are manufactured using two different main designs as tubular and planar (National Fuel Cell Research Centre and Sames, Du and Bove, 2005).

Fuels used in fuel cells

The primary fuels that can be directly utilized within fuel cell stacks today are hydrogen, carbon monoxide, methanol, and dilute light hydrocarbons like methane, depending upon the fuel cell type (Table 19). Note that the presence of sulfur is not tolerated by fuel cells in general and that the SOFC is the most inherently fuel flexible of the fuel cell types. MCFC units are also quite fuel flexible.

Table 19: Fuels for fuel cells (Dayton and others, 2000)

Gas species	**PEMFC**	**PAFC**	**MCFC**	**SOFC**
CO_2	Diluent	Diluent	Consumed in cathode	Diluent
CO	Poison < 10 ppm	Poison <1%	Fuel	Fuel
CH_4	Inert, fuel with reformer	Inert, fuel with reformer	Fuel if reformed	Fuel if reformed
Sulfur	Poison < 1 ppm H_2S	Poison < 4 ppm	Poison (H_2S) < 10 ppm	Poison (H_2S) < 0.1 ppm
NH_3	Poison	Poison	Inert	Fuel < 5000 ppm
Halides	Poison	Poison < 4 ppm	Poison < 1 ppm	Poison < 1 ppm

Hydrogen is the optimal fuel for all types of fuel cells. Carbon monoxide is a poison for lower temperature fuel cells, but is used as a fuel in the high temperature fuel cells (e.g., SOFC, MCFC).

Methane can be oxidized directly using solid oxide fuel cell however, high concentrations of CH_4 lead to severe coking problems. Therefore, only fuels containing dilute concentrations of CH_4 can be oxidized directly in current SOFCs. In addition, the oxidation of CH_4 may not actually occur at active electrochemical sites within solid oxide fuel cells. Rather, CH_4 is probably reformed within the cell through steam reformation chemistry as follows:

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

Energy generation using biogas

A feasibility study was carried out to evaluate effectiveness of use of fuel cells for dairies in NY. The study says that fuel cell technology has the potential to help dairy waste management program. The technology can serve as a key component in a resource-recovery system. Anaerobic digestion of dairy wastes is facing few challenges. The fuel cell technology has matured to the point that it is considered a reliable technology on the farm. Thus it says there is a potential of energy generation using fuel cells from high strength organic wastes (Scott and others, 2000).

Biogas generated in the process of anaerobic digestion can be used in fuel cell to generate electricity. The major components of fuel cell units which can generate electricity using biogas are as follows.

1) Pretreatment unit for biogas: The biogas may contain other elements, compounds which are to be removed. Sulfates can cause damage to cell stacks if not removed from biogas. Thus pretreatment of biogas may be required

2) Reformer: This component converts various types of fuel to hydrogen gas. Hydrogen gas is extracted chemically from the fuel.

3) Fuel cell stacks: These are nothing but the actual fuel cell. The energy is generated by this component.

4) Heat exchangers: Hot water comes out off fuel cell after completion of reaction. Heat exchangers can be used to recover energy from the hot water.

Commercialized fuel cell units: Different types of fuel cells with different energy generation capacities are available commercially.

Preliminary studies show that methane from wastewater treatment plant of Breyers Yogurt Company has the potential to generate approximately 250 kW with fuel cell units. Hence the fuel cells with capacity ranging from 200-350 kW are pertinent for this case. The data collected from companies can be compiled as follows and is then integrated in the process model.

Fuel Cell Energy units can generate 300kW of electricity with the available methane gas. In addition to that heat can be recovered from the unit which can satisfy some of the heat demands of the plant. It seems that the company has installed fuel cell units of the capacity approximately 250kW and which uses methane gas generated from anaerobic digester. Two direct fuel cells, each of 250 kW capacity have been installed at wastewater treatment plant of Santa Barbara, CA. The fuel cells use methane gas generated in the process of anaerobic digestion. FCE will be installing fuel cell units at King's county south wastewater treatment plant at Renton, Washington. The unit will be having capacity of 1 MW (Fuel cell energy).

UTC Power replied saying they can generate 200 kW of power with the available methane. There will be high grade heat available for recovery and that can be used. The company said that they have not installed any fuel cell unit which works on methane gas from anaerobic digester but have the capability to commission such project (UTC Corporation).

Gencell Corporation has not commercialized the fuel cell with capacity around 250 kW. They have fuel cells available for application with capacity 40kW (Gencell Corporation). FCE has showed interest to work for such project and wished to come for preliminary discussions. FCE can manufacture customized fuel cell as per the requirements and available gas inputs. Hence they said that generation of 300 kW can be possible though their standard fuel cell unit has the capacity of 250 kW.

Use of molten carbonate fuel cell

Wastewater treatment plants using anaerobic digestion to stabilize and reduce pathogenic microorganisms can produce large quantities of biogas. The digester gas can be used at the site for heat or power. This digester gas can be used with a molten carbonate fuel cell, without CO_2 removal and has the potential to provide significant environmental and economic benefits. Engineering studies have shown the benefits of locating a 1 MW molten carbonate fuel cell at a wide variety in USA (Scroppo and others, 1999).

Microturbines

Microturbines are small combustion turbines, approximately the size of a refrigerator, which can generate electricity ranging from 20 to 500 kW (S.L. Hamilton 2003). Microturbines, which have been available for over 50 years have evolved from turbocharger technologies found in large trucks or auxiliary power units for airplanes to light weight, compact, and high powered generators in the military and aerospace industry (Pilavachi 2002).

Various technologies are applied in distributed generation including microturbines, fuel cells, solar systems and wind turbines. There is a particular interest in the potential of technology like microturbines. For microturbines and other distributed energy technologies to be competitive, the price of electricity today needs to be more attractive (Pilavachi 2002). Microturbines are important to the distributed power generation industry being researched at present. They can be used for stand-by power, power quality and reliability, peak shaving, and cogeneration applications. In addition, since they are developed to utilize a variety of fuels, they are being used for landfill gas as well as digester gas. Their capacity is well suited for small scale power generation such as on farms, or in the dairy industry (US DOE 2000).

The elements of microturbines. Microturbines are classified by the physical arrangement of their components: single-shaft or two-shaft, simple or recuperated (US DOE). Single-shaft is the more commonly used because it is simpler and easier to build. Microturbines can also be divided in two general classes: recuperated microturbines and unrecuperated (or simple cycle) microturbines. Recuperated microturbines recover the heat from exhaust gas to boost the temperature of the combustion and increase the efficiency. In simple cycle microturbines, there are no heat exchangers that recover from the exhaust stream, which make them have lower cost, higher reliability, and more heat available for cogeneration applications than recuperated units. However, recuperated units have a higher thermal-to-electric ratio than unrecuperated units and a higher electrical efficiency, as high as 20-40% compared to 15% for unrecuperated units (Romier 2004). The combined thermal electrical efficiency of microturbines with cogeneration applications can reach between 85 to 90% depending on the heat process requirements (Cleveland 2004).

As shown in Figure 43, single-shaft recuperated microturbines are composed of a compressor, a combustor, a turbine, a recuperator, and a generator (Pilavachi 2002). Incoming air is compressed and then passes through the recuperator to gain heat. Thus, preheated air is mixed with fuel and burned in a combustor under constant pressure. The resulting hot gas is allowed to expand through a turbine to perform work. A sheet metal heat exchanger is applied to recover some of the heat from the exhaust stream and transfer it to the incoming air stream, which is preheated and then used in the combustion process. The rest of the exhaust stream is passed through a waste-heat recovery device that captures more of the heat for use in industrial processes, space heating, and water heating.

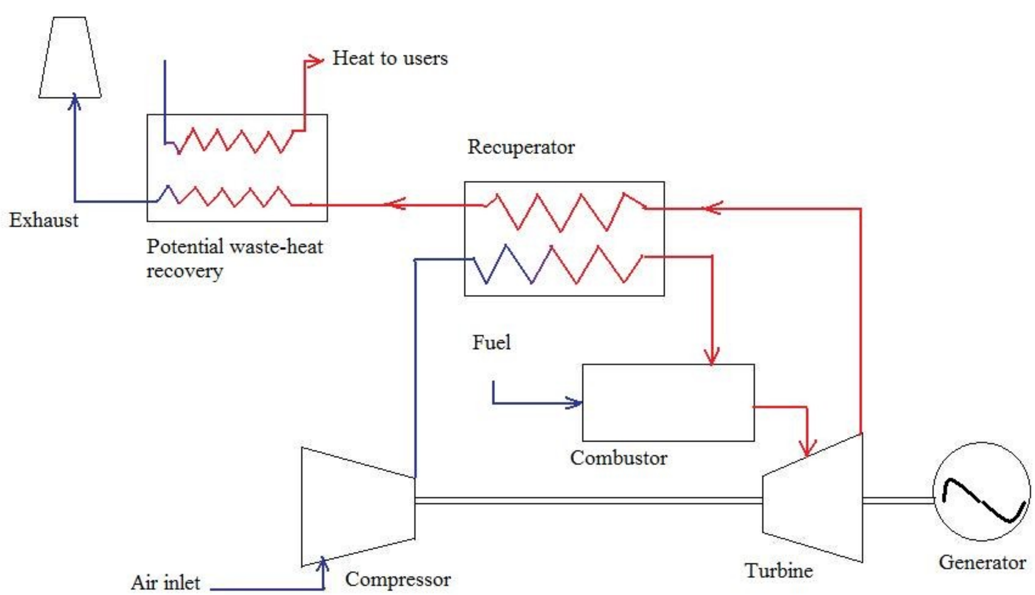


Figure 43: Schematic of single-shaft recuperated microturbine system (Capstone)

There are basically two types of microturbines with different engineering considerations regarding the utilization of recuperators. The first type is the close coupling of the recuperators and the other is an arrangement where the recuperator is positioned behind, above or alongside the rotating machinery.

Advantages and disadvantages of microturbines. Microturbines offer many potential advantages for distributed power generation (Pilavachi 2002). These include a small number of moving parts, compact size, light weight, good efficiency in cogeneration, low emissions, and multi-fuel capability. In addition, microturbines have low maintenance cost, low vibration level and short delivery time. Compact size and light weight per unit power lead to reduced engineering costs. Fuel options include natural gas, diesel, landfill gas, industrial off-gases, ethanol, and other bio-base liquids and gases.

The disadvantages of microturbines include technical barriers such as low fuel to electricity efficiencies, loss of power output and efficiency with higher ambient temperatures and elevation. There are also non-technical barriers to the implementation of microturbines. More skilled personnel are required for maintenance of microturbines (Pilavachi 2002). Grid connection standards are also a non-technical barrier. The costs of a grid connection are high and the access to electricity network at reasonable price is not always possible.

Current and future status. The beauty of current microturbines is their simplicity. However after decades of development, compressor and turbine aerodynamic efficiencies have little potential for advancement. Combustion, mechanical and generator efficiencies are already at high level (McDonald 2003). Thus increased turbine inlet temperature and higher recuperator effectiveness are changes that can be made to advance microturbine performance. Advanced materials, such as ceramic and thermal barrier coatings, are potential technologies to improve the performance of microturbines. A 7.5 kW ceramic microturbine was designed with the potential for efficiencies of over 40% (McDonald 2007).

The size of microturbines varies from 5 kW to 500 kW or even 1000 kW are being planned. Existing sizes range from 25 kW to 250 kW. The capital costs of microturbines range from $700/kW to $1,100/kW according to the size of the units. The addition of a heat recovery system adds between $75/kW to $350/kW. With fewer moving parts, the manufacturers expect the maintenance to be once a year and the maintenance intervals to be 5,000-8,000 hours (US DOE 2000). The aim of US DOE microturbines program in 2000 is to design microturbines with high efficiency and environmental superiority, durability, lower cost. In order to reach full market for microturbines and compete with grid-connected powers and other distributed energy resource options, improvements must be made in the technology. Base on the existing technology, the areas that need to be improved are application of advanced materials, power electronics, grid interconnection, sensors and controls (US DOE 2000).

Internal combustion engines

An internal combustion (IC) engine is a device that runs on an open thermodynamic cycle and is used to convert chemical energy of a fuel to rotational mechanical energy (Taylor 1979). This rotational mechanical energy is mostly often used directly to provide motive powers. Alternatively, the internal combustion engine may be mounted to a generator to provide electric power. IC engine can also be used in a heat and power cogeneration system that uses recuperators to capture and return waste exhaust heat. Commercially available IC engines produce power from 0.5 kW to 10MW, have efficiency between 27 to 40%, and can operate down to NO_x level of less than 1 g per horsepower-hour. The efficiency varies according to the engines size and engine materials. An efficiency as high as 40% can be achieved by using advanced materials. IC engines in cogeneration systems can have an overall efficiency between 80 to 85%. According to different engine types, sizes and materials, the installed costs of IC engines are about 300- 1500 $/kW while the O&M costs are about 0.0075- 0.02 $/kWh (Cleveland 2004).

Types and principles of operation. IC engines may be generally classified by the method of initiating combustion as either spark ignition or compression ignition engines. IC engines may also be classified based on whether the rotational mechanical energy is obtained via the rotational motion of a rotor in a rotary engine, or more commonly via reciprocating piston motion (Kutz 2006). All these IC engines include five general processes:

1. An intake process, during which air or a fuel-air mixture is inducted into the combustor.
2. A compression process, during which the fuel–air mixture is compressed to higher temperature, density and pressure.
3. A combustion process, during which the chemical energy of the fuel is converted to thermal energy.
4. An expansion process, during which a portion of the thermal energy of the working fluid is converted to mechanical energy.
5. An exhaust process, during which most of the products of combustion are expelle from the combustion chamber.

Advantages and disadvantages. IC engine generators offer many advantages for small scale power generation, including the ability to provide highly reliable, inexpensive backup power; provide power for remote locations; and generate one-site power during peak periods when utility charges are highest. IC engines can run on traditional fuels including diesel, natural gas, gasoline as well as fuels generated from waste treatment (methane) and other biofuels. The disadvantages of IC engines include corrosion of engines parts and catalysts, particulate matter buildup on exhaust gas filters, and high emission of atmospheric pollutants: NO_x, CO.

Biogas generation: Wastewater is being generated because of the manufacturing activity. Process flow diagram of a cheese manufacturing process showed that whey was generated in cheese vats and rinse water coming out of them contributes for the major part of wastewater and treated in the anaerobic digester.

Based on the information provided by Breyers Yogurt Company the wastewater generation was expressed as a function of cheese being produced and the milk being processed. The flow and characteristics of wastewater were used to calculate expected gas generation in digester. Average COD was 49945 mg/l and methane generated per mass of COD was assumed to be 0.447 m^3/kg COD (Breyers Yogurt Company). The ratio of methane used to methane generated was 0.95 and methane content was considered to be 57% (Breyers Yogurt Company).

Energy generation potential using fuel cells: There are different types of commercialized fuel cells. The units which can be used for Breyers Yogurt Company were solid oxide fuel cells or molten carbonate fuel cells. It was necessary to evaluate commercial fuel cells units. Hence technical enquiries were sent to several fuel cells manufacturers. Fuel cell energy, UTC Corporation and Gencell Corporation replied for these enquiries.

Table 20: Operating conditions and estimated capital cost

Fuel cell manufacturer	Gas flow (m^3/hr)	Maximum heat generation (kJ/hr)	Maximum power generation (kW)	Equipment cost ($)
Fuel cell energy, Danbury, CT	66	316500	300	1,008,000
UTC Corporation South Windsor, CT	99	316500	200	1,100,000
Gencell Corporation Southbury, CT	28	395625	125	450,000

Based on estimates given by fuel cell manufacturers Table 20 was constructed. Different fuel cell units have different biogas requirements. The output delivered by them was also different. The required flow of biogas and the delivered output in terms of heat as well as power was correlated. Maximum possible power generation and required gas flow were shown in Figure 44. As the gas flow increased output of the fuel cell also increased except the last data point. Fuel cell unit of UTC Corporation delivers less power though it requires maximum gas flow amongst all other fuel cell units. Figure 45 shows possible quantity of heat which can be generated as a function of gas flow. As the gas flow increased heat generated from the fuel cell was decreased and then remained constant.

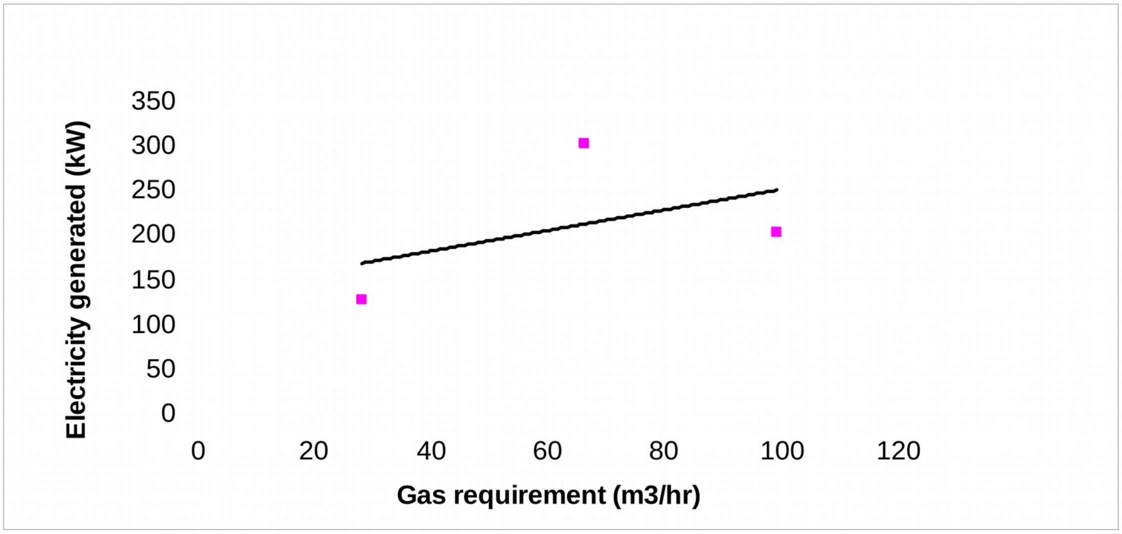


Figure 44: Electricity generation and gas flow

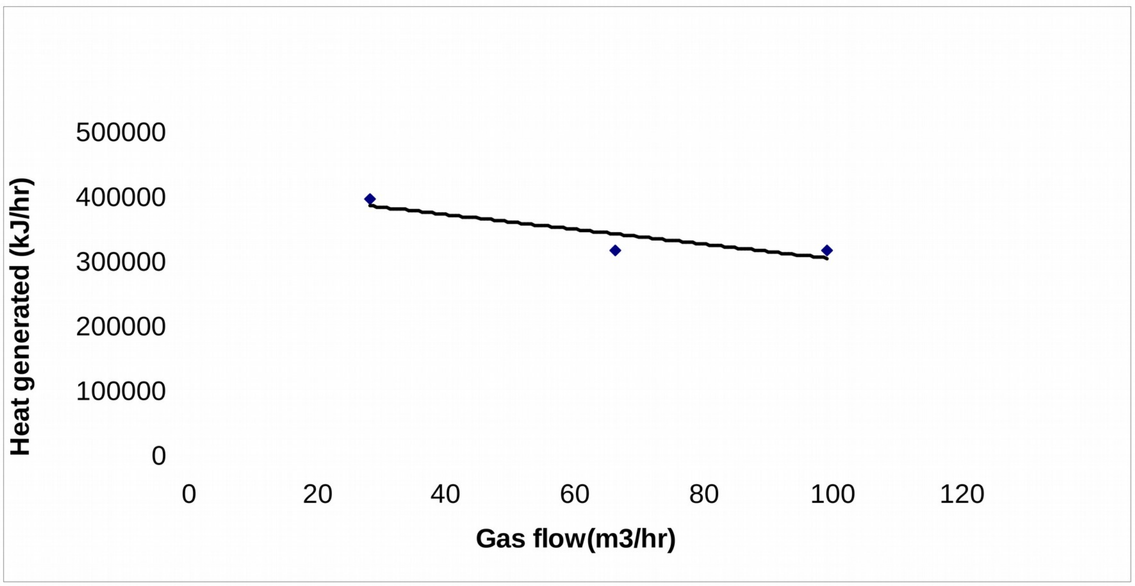


Figure 45: Heat generation and gas flow

The expressions used to model output of fuel cell units and its costs are mentioned in Table 21, where x is the gas flow rate from the digester in m^3/hr. The modeled equation for power was of the form y = m * x + c. That equation gives a value equal to c when x = 0. That means fuel cell can produce electricity equal to c when the gas flow equals zero, which is not correct. Hence linear relation between power and gas flow was assumed where the actual data was not available (for gas flow less than 28m^3/hr). Similar approximation was made for heat and gas flow also.

Table 21: Empirical equations used to calculate power and heat generated by commercial fuel cells

No.	Description	Expression	R^2
1	Maximum expected	= 1.1562x + 134.12 (for x > = 28)	0.216

	power (kW)	= 4.46x (for x < 28)	
2	Maximum expected heat (kJ/hr)	= -1141x + 416495 (for x > = 28) = 14129x (for x < 28)	0.785

If production is remaining same as before and auxiliary power is being generated then there will be reduction of expenses incurred for fuel oil and electricity. Those savings on the electricity and heating costs were also calculated. It was important to calculate the cost associated with the fuel cell technology to generate the predicted energy. The cost of energy generation was expressed in terms of the capacity of the fuel cell unit.

Direct combustion: The model evaluates the alternative of direct combustion by using biogas. The possible heat generation from the biogas was calculated using quantity and calorific value of bio-gas. Calorific value of methane was considered to be 802.65 kJ/mol and combustion efficiency of 70% was assumed. Thus possible heat generation from the biogas can be quantified.

Sensitivity Analysis

Net annual savings of alternatives

The net annual savings of biogas utilizing technology alternatives evaluated in the model was expressed in Figure 46. The figure shows possible net annual savings per year for each alternative. As shown in Figure 46, direct combustion has the highest net savings and is considered to be the optimum alternative. Because of higher initial cost and maintenance cost, microturbines are not as profitable as direct combustion.

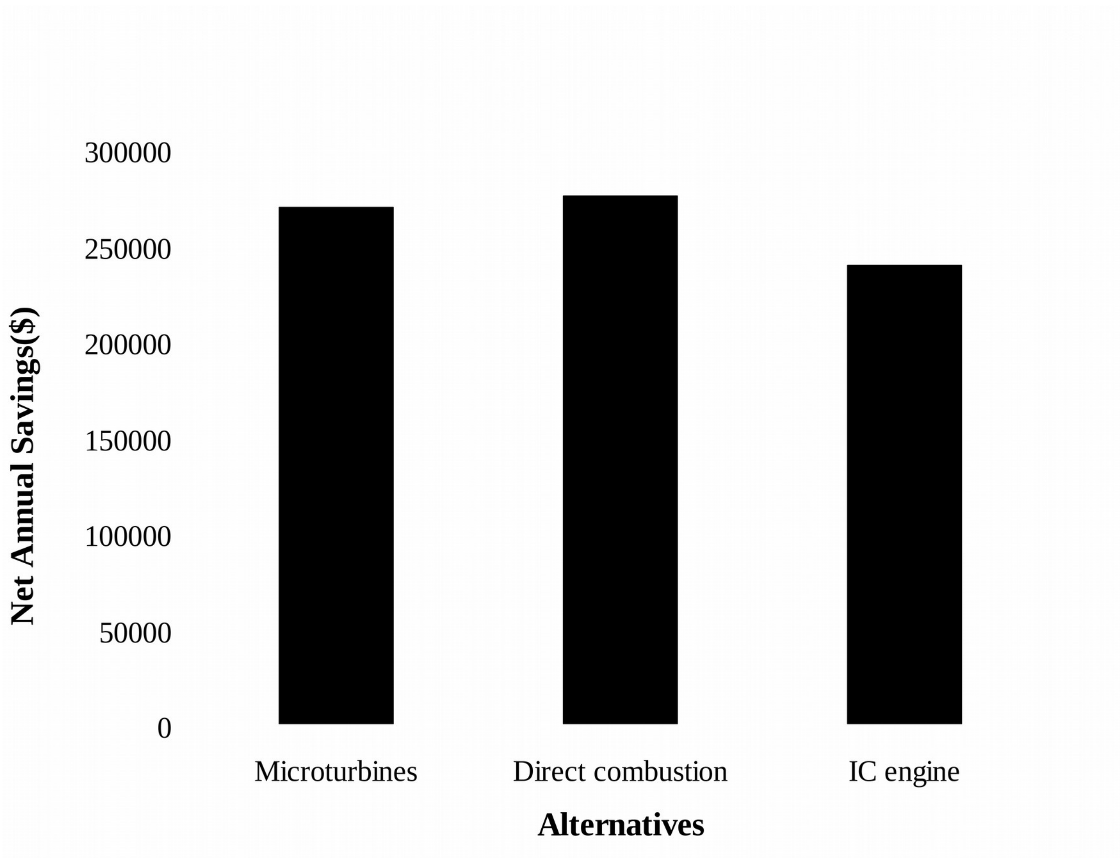


Figure 46: Net Annual Savings for Alternatives

Net annual savings and electricity price

An attempt was made to show the effect of a few parameters by changing their values in the model. The corresponding net annual savings for each alternative were estimated with the changes in electricity price in the model. Figure 47 represents the net savings with the reduction and increase in electricity price value respectively.

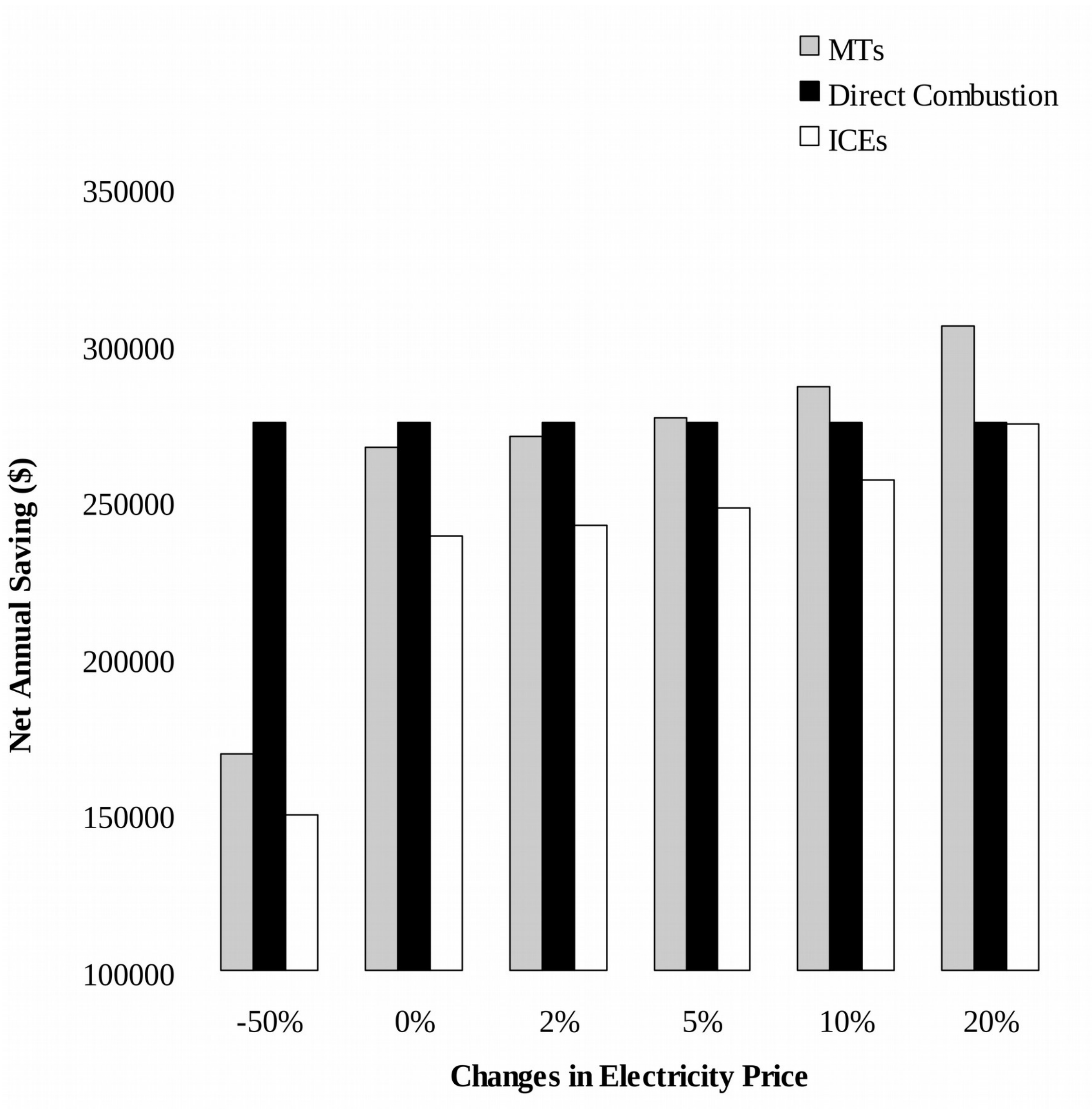


Figure 47: Net Annual Savings with Changes in Electricity Price

There are no changes in net annual savings for direct combustion since no electricity was generated under that condition. An increase of 5% in electricity price causes approximately 4% increase in net annual savings for MTs which makes MTs the optimum alternative economically. On the other hand, reduction of 50% in electricity price causes approximately 40% of drop in net annual savings for MTs and ICEs which makes direct combustion the optimum alternative. Above all, in the case of an increasing electricity price, more net annual savings can be obtained for the utilization of MTs. Direct combustion stays optimum with reduction in electricity price. MTs become optimum with a more than 5% in electricity price.

Net annual savings and fuel oil price

The corresponding net annual savings for each alternative were estimated with the changes in fuel oil price in the model. Figure 48 shows the corresponding net annual savings with the reduction and increase in fuel oil price respectively.

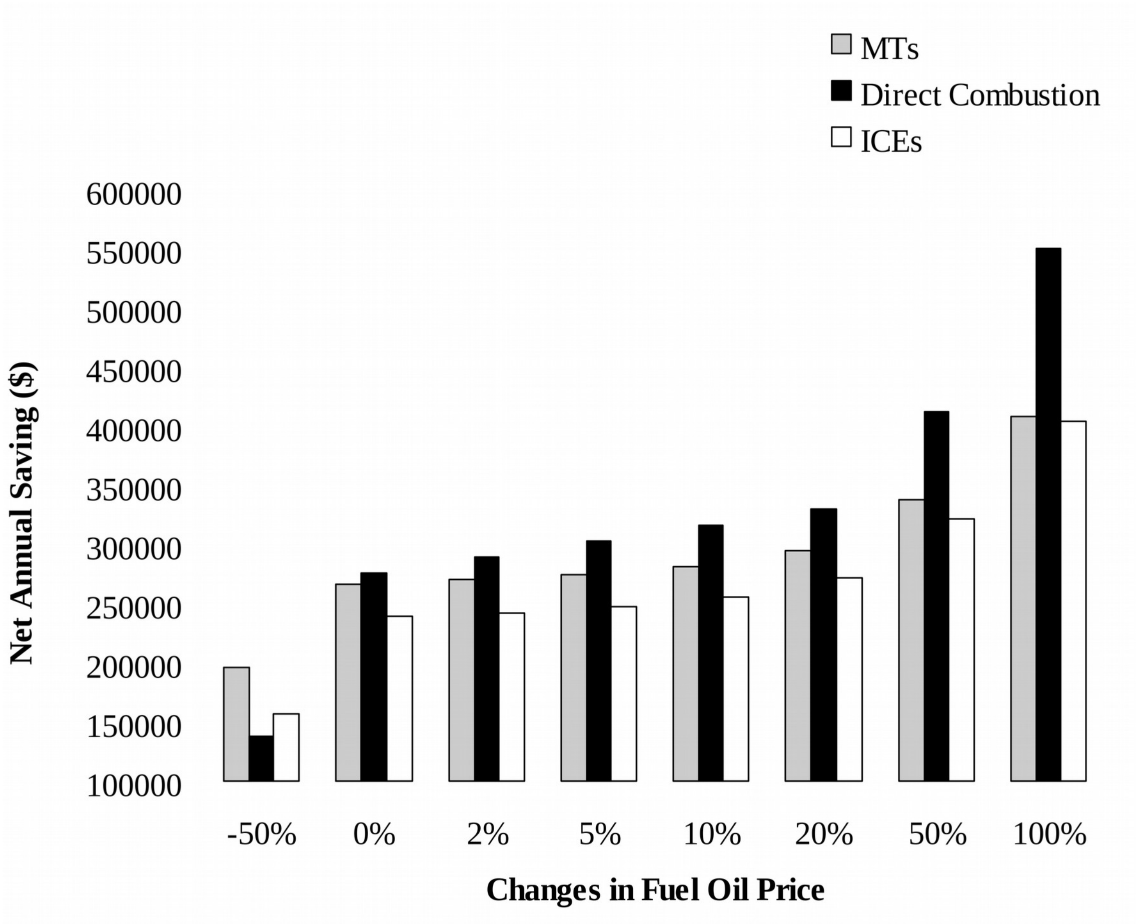


Figure 48: Net Annual Savings with Changes in Fuel Oil Price

An increase in the fuel oil price causes an increase in net annual savings for all alternatives while a reduction in fuel oil price causes a decreased net annual savings. With a 50% increase in fuel oil price, there are 26%, 50%, 35% increases in net annual savings for MTs, direct combustion and ICEs respectively. The percentage increase in net savings for direct combustion is more than that for MTs and ICEs, which means that direct combustion is always an optimum alternative with increase in fuel oil price. With a 50% reduction in fuel oil price, the MTs become optimum alternative with highest net savings.

Net annual savings and capital price

The corresponding net annual savings for MTs and ICEs were estimated with the changes in capital costs in the model. Figure 49 shows the corresponding net annual savings with the reduction in capital price in MTs and ICEs respectively. Reduction of 20% in capital cost causes increase of 5% in net annual savings for MTs and increase of 2.7% in net annual savings for ICEs. MTs need about 15% reduction in capital cost to make the optimum alternative.

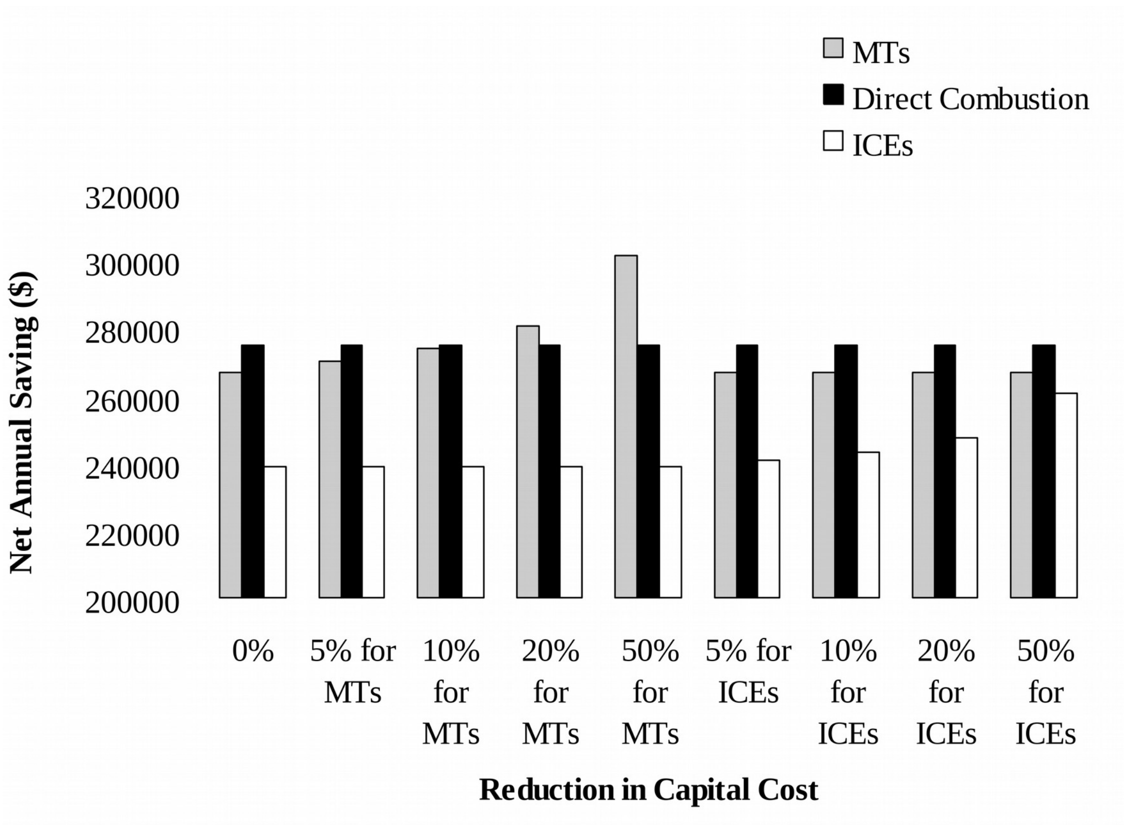


Figure 49: Net Annual Savings with Reduction in Capital Price

Annual savings and production level

Using the model, the effect of various independent production and environmental variables on the process economics could be evaluated. Production level, scheduling of yogurt and cheese lines, electricity prices, fuel oil prices and capital cost of energy generation alternatives were one of the important variables. The model was used to study the effect of these variables on the cash flows and the profitability was measured in terms of net annual savings.

The biogas generated in the digester is dependent on cottage cheese production and thus the savings on energy costs. Hence the savings corresponding to each alternative were evaluated for a given production level. Installments for initial investment, maintenance costs may be necessary for these energy generation alternatives. The project costs were annualized assuming interest rate of 6% and an evaluation period of 20 years. Thus higher the net annual savings better the choice.

Figure 50 shows the effect of cottage cheese production on net annual savings when biogas is used at the plant for fuel cells or direct combustion to generate energy.

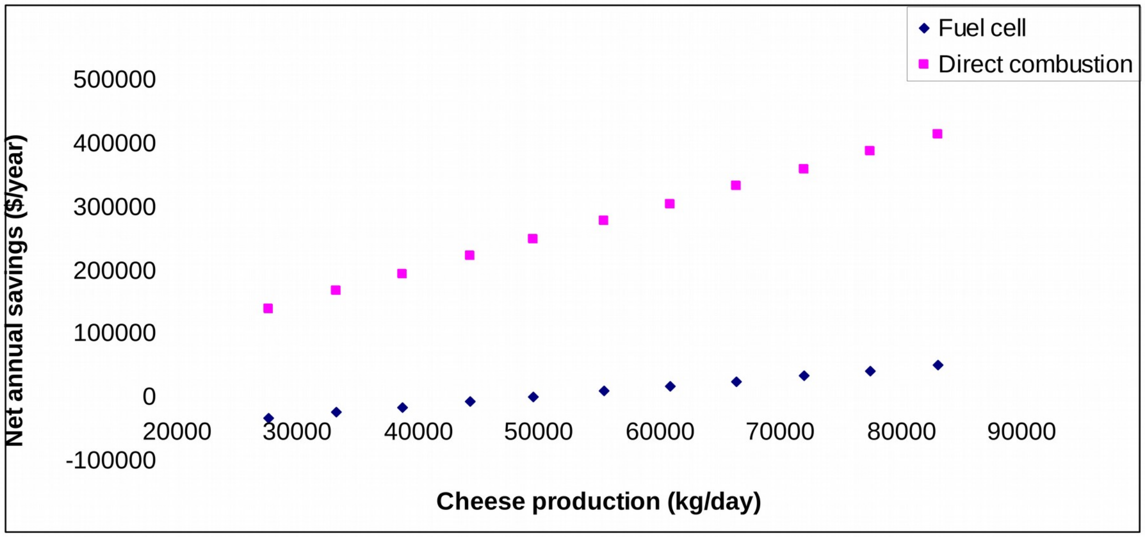


Figure 50: Net annual savings and cottage cheese production

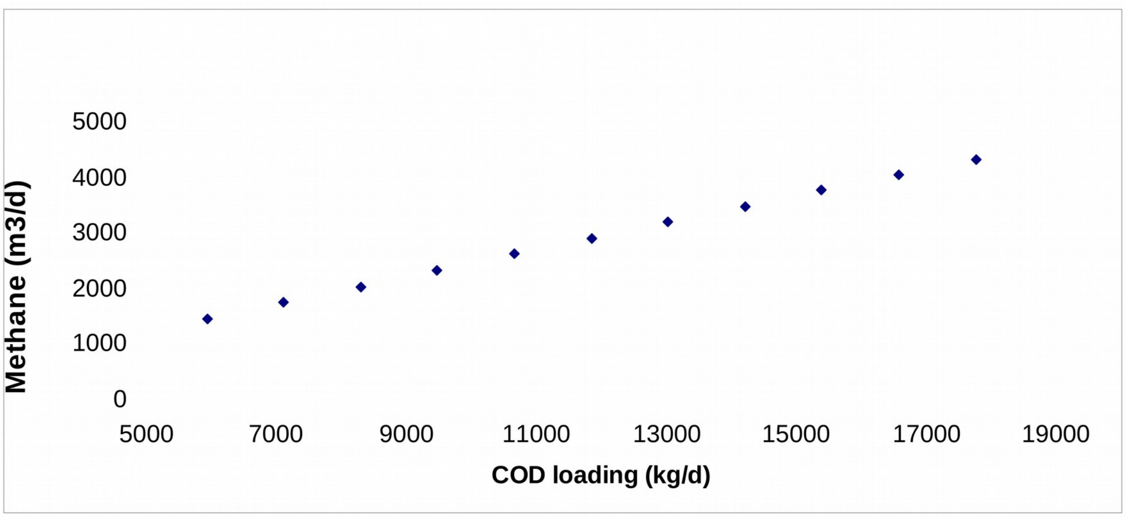


Figure 51: Gas generation and cottage cheese production

Figure 50 shows savings in dollars per year for a specific cottage cheese production per day. As the production was increased the net annual savings for fuel cells and direct combustion were increased. The present electricity price is considered as 0.12$/kWh (considering total usage and electricity cost of January 2006). Capital cost for fuel cell unit was calculated as approximately 4000$/kW whereas direct combustion do not need any capital investment. It was assumed that cottage cheese manufacturing was responsible for wastewater generation. As the quantity of wastewater increases, organic loading increases and digester can produce more biogas which can result in more energy available.

Net savings from fuel cells were always lower than from the alternative of direct combustion. Fuel cells have very high capital cost whereas no additional cost was required for direct combustion. Thus use of fuel cells is more expensive alternative for energy generation than direct combustion. If fuel cells are used when the cottage cheese production is approximately 50000 kg/d, there will not be any profit.

Thus biogas generation increases linearly with increase in production level. Past data for wastewater, organic loads and gas generation was used in the model. It calculates expected gas generation based on average gas generation per COD load, thus a linear trend was observed (Figure 51).

The model can compute total energy costs of a plant for a day. Figure 52 shows electricity and heating costs per day for a given cottage cheese production. These costs were calculated by model using the production data. When the cheese production varied the other parameters were not changed.

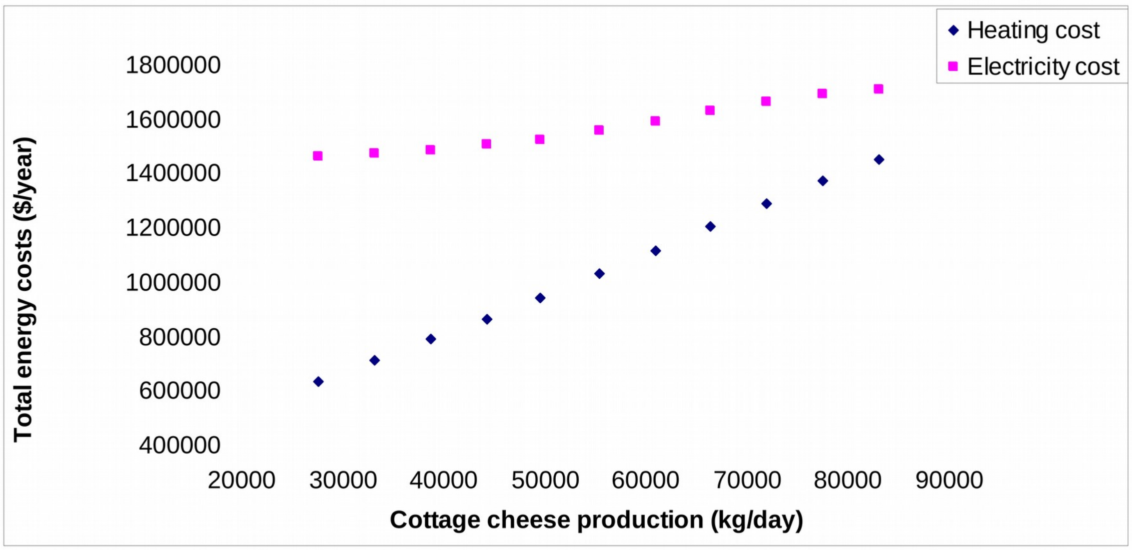


Figure 52: Total energy costs and cottage cheese production

Total energy costs increase as cottage cheese production increases. Heating costs increased faster than electricity cost however electricity cost remained higher than heat for all scenarios tested. As mentioned before cottage cheese manufacturing has higher heat requirements. It does not exert power demands with the same rate. Thus heating cost increases rapidly as compared to electricity cost with increase in cottage cheese production.

The effect of cottage cheese production scheduling on net annual savings

Electricity prices and rates vary with respect to time i.e. for weekday and weekend, peak and off peak timings. Thus the model was used to examine effect of scheduling of cheese production on electricity costs. Electricity cost for 19 th December 2005 was calculated by moving the production of a day by 8 hours earlier. There was reduction in power cost by 190$/day and thus scheduling of production in off peak hours (10 pm to 8 am) may reduce power costs.

Similarly the cottage cheese production from weekday was scheduled on weekend and its effect on electricity costs was observed. The electricity cost was $4260 for the weekday which became $ 4351 for the weekend, for the same cheese production. Higher supply rate for weekend was responsible for this increase in cost. On weekend, there was no differentiation as off peak and on peak supply rate. The off peak supply rate for weekend was lower than on peak supply rate for weekdays but higher than off peak supply rate on weekday. As a result there was increase in electricity cost.

Two lines (L2 and L7) were used only for cheese production at the plant. Model was used to observe the effect of variation in production on savings and energy costs. Figure 53 and Figure 54 show the effect of variation of production from line 2 on net savings and electricity costs. The production on one line was varied at a time and production on other was kept constant to value which was production on 16 th December. Similar results were observed when production on line 7 was varied. The total energy cost shown on y axis is the energy cost of a plant when production on of the cheese producing lines was varied while other values remained constant.

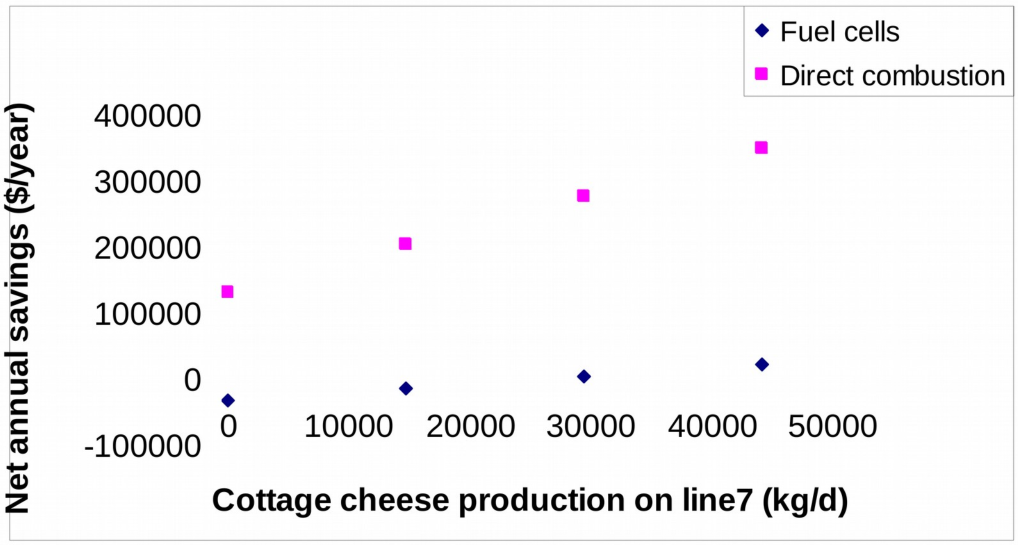


Figure 53: Net annual savings and cottage cheese production on line 7

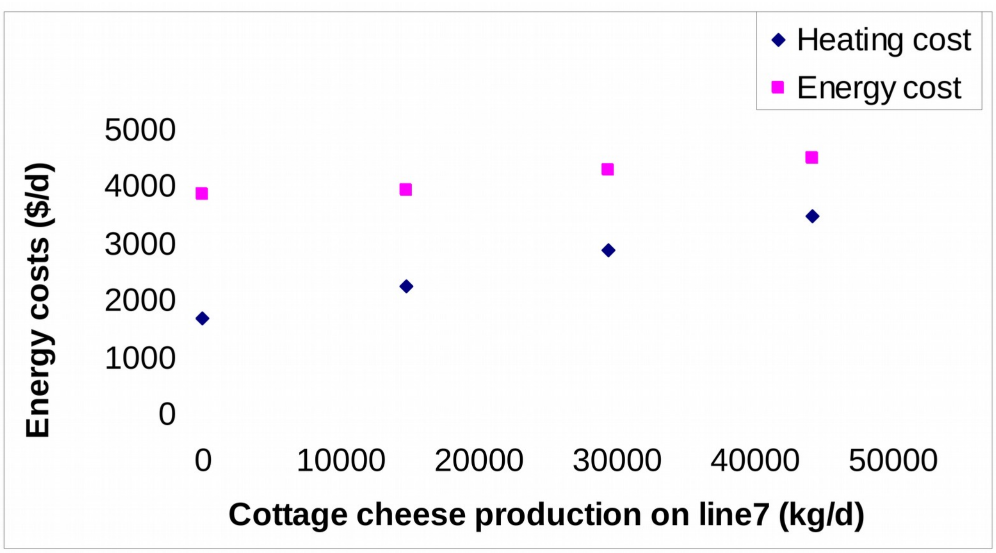


Figure 54: Total energy costs and cottage cheese production on line 7

Figure 53 and Figure 54 show the similar results to those were obtained by variation in total production. Thus irrespective of the line increase in production increases net savings and total energy costs. Variation of production on line 2 or line 7 is similar to variation in total cheese production and will produce similar effect on net savings and total energy costs.

The effect of energy price on annual savings

Variation of Electricity Price. Generally the heat and electricity prices will be increasing in the future due to limited availability and increasing demands. It was interesting to see the effect of change in those prices on the net annual savings of the plant. Thus power price was increased by 2%, 5%, 10% and the net savings were calculated. 0% price corresponds to tariff (0.12$/kWh) used by National Grid on January 2006 for Breyers Yogurt Company.

Net annual savings increase as electricity price increases (Figure 55). As electricity price increases savings on electricity cost ($/day) which may be possible using fuel cells, also increase, as a result adding net annual savings. Thus if there is any possibility of increase in electricity prices then use of fuel cells may be beneficial.

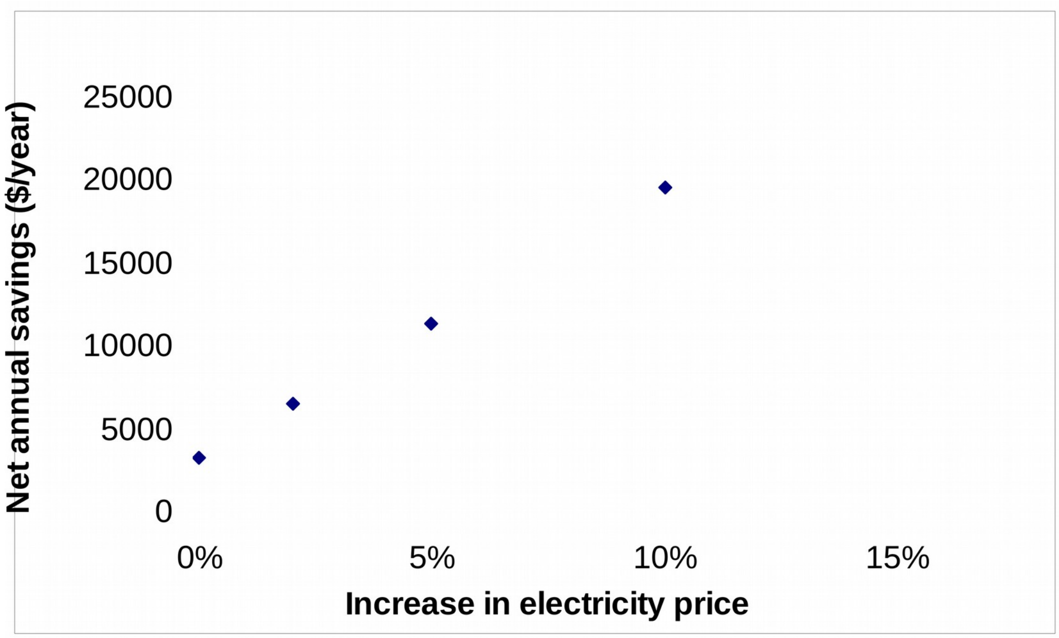


Figure 55: Net annual savings and electricity price

Variation of Fuel Oil Price. Effect of fuel price on the net savings was portrayed in Figure 56. Unit rate of 1.24 $/gal (based on the data from Breyers Yogurt Company) for fuel oil was considered which corresponds to 0% increase in fuel oil price. Figure 56 shows linear increase in savings with rise of fuel oil prices. Savings which can incur from fuel cell were lower than those from direct combustion. Fuel cell generates power and heat. The heat produced by fuel cells can satisfy part of total heat demand of a plant. Savings on heating costs correspond to the heat produced. Electricity produced adds more savings than heat if fuel cells are considered. Net savings from direct combustion were higher than fuel cells and it seemed to be the beneficial alternative with increase in fuel prices.

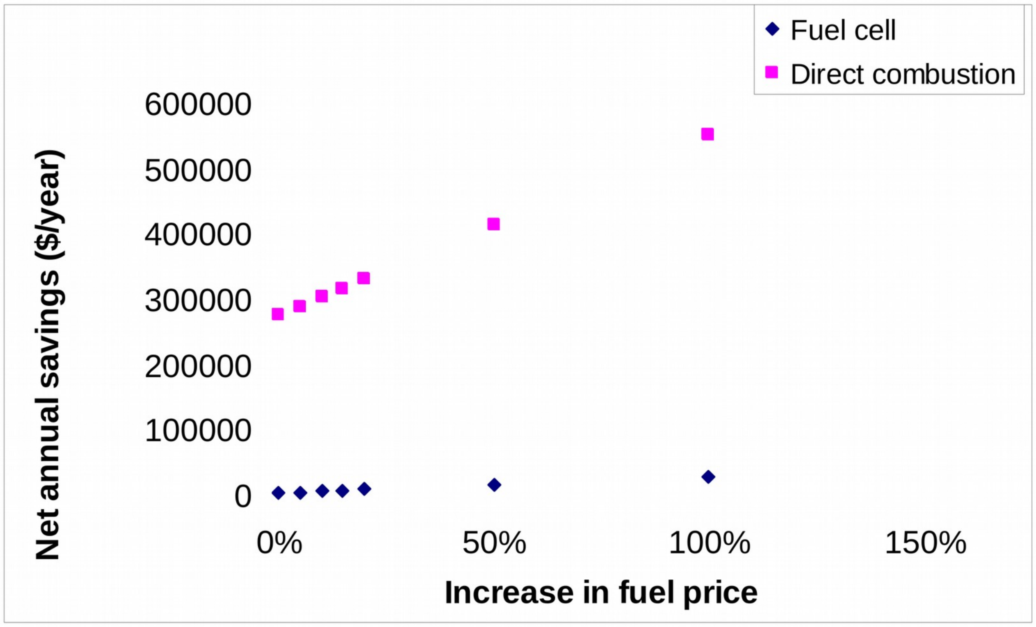


Figure 56: Net annual savings and fuel prices

Effect of capital cost of fuel cell on annual savings

Fuel cell technology is growing and there is possibility that fuel cell prices will reduce in near future. Current savings of a fuelcell installation are significantly lower than for microturbine, ICE of direct combustion (Figure 57). The model was used to study the effect of reduction of fuel cell prices in future. The base case (0% reduction of initial cost) corresponds to initial cost of fuel cell cost which is 1.1 million dollars.

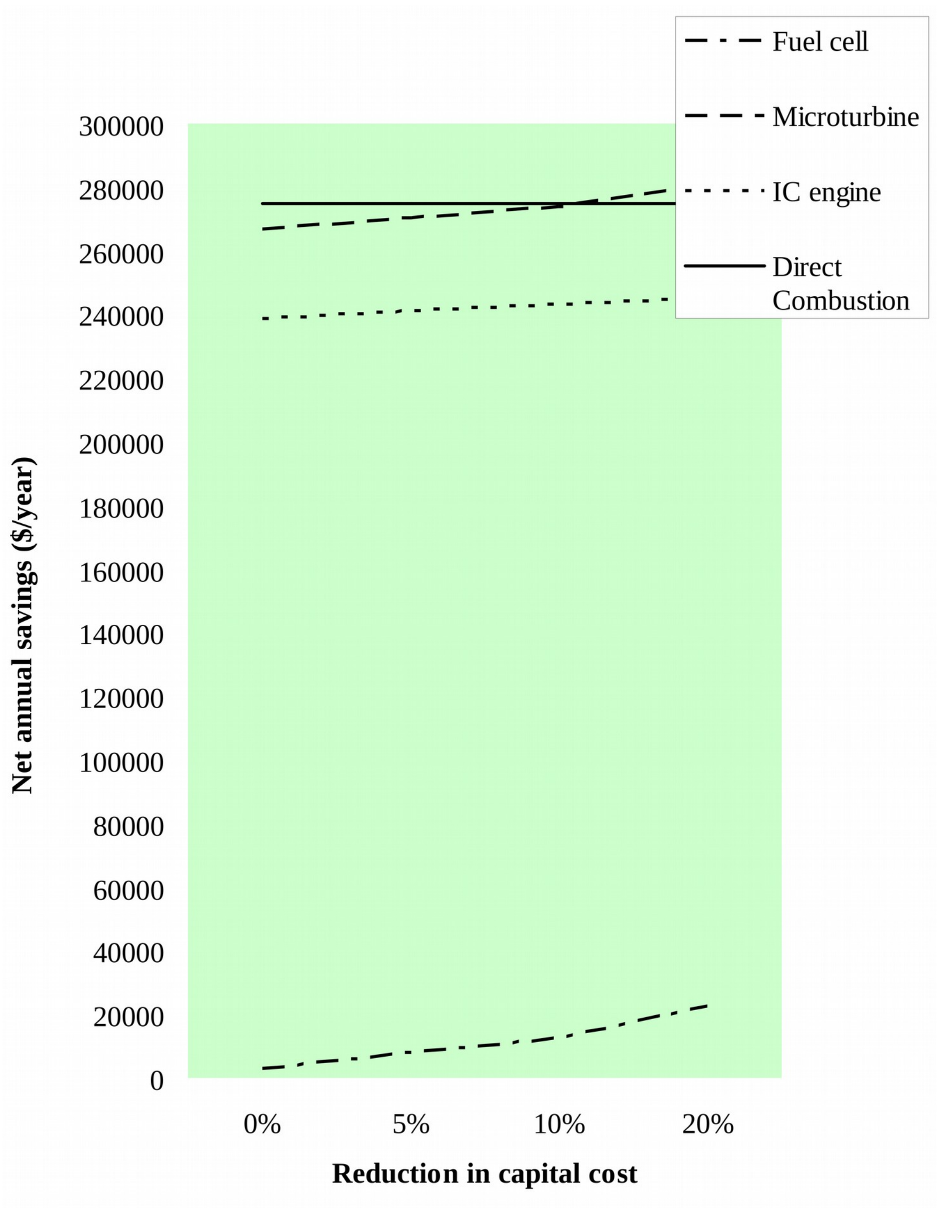


Figure 57: Net Annual Savings of Alternatives and Capital Cost

Higher net savings will be possible if initial cost of fuel cell drops. The higher initial cost is the major reason for the economic inefficiency of fuel cells (Figure 58). Further reduction in initial cost can make fuel cell as one of the efficient energy generation technology.

The model evaluates various energy generation alternatives. The comparison of alternatives considered was expressed in Fig. 6. The graph shows initial cost and cost per unit capacity of power generation ($/kW) of each alternative. Fuel cells have higher energy conversion efficiencies but have very high capital costs. Direct combustion of methane gas for heat generation was also one of the options available for Breyers Yogurt Company. It was assumed that there was no additional cost associated with this alternative as methane can be used with existing set up.

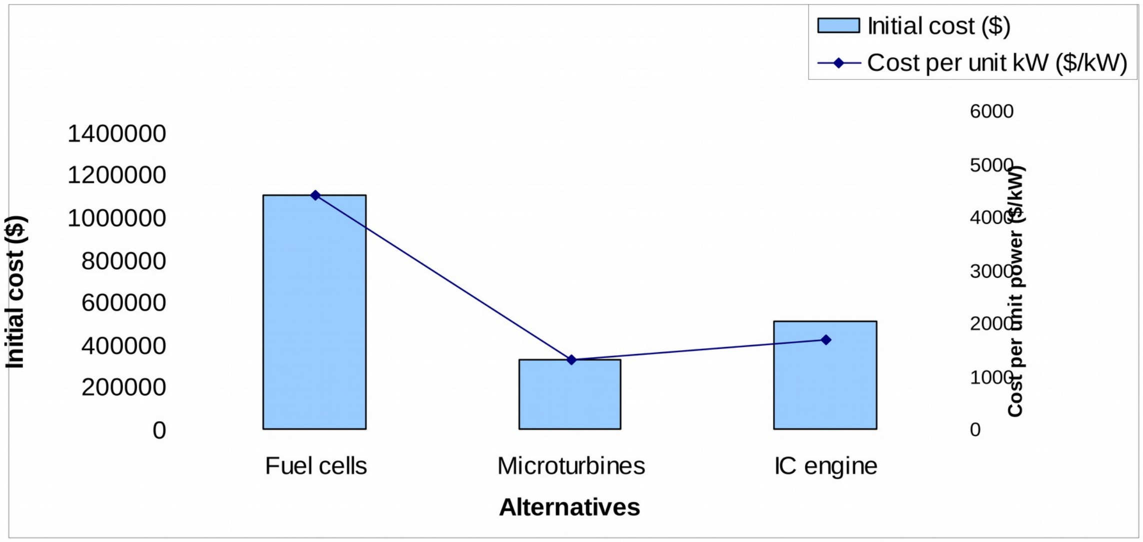


Figure 58: Initial (Capital) cost of energy generation alternatives

When evaluating the effect of fuel oil and electricity cost changes versus net realizes annual savings it was assumed that electricity was increased by 2%, 5% and 10%. The net annual savings of the plant were calculated as shown in Figure 59. Net annual savings increase as electricity price increases except for direct combustion which is not affected by electricity price. The increasing rates of net annual saving for microturbines, IC engines and fuel cells are similar. Direct combustion stays as the most beneficial alternative with the increasing of electricity price, while IC engines and microturbines are getting closer to be the most beneficial alternatives if electricity price increase. After 5% of increase in electricity price, MTs become the optimum alternative.

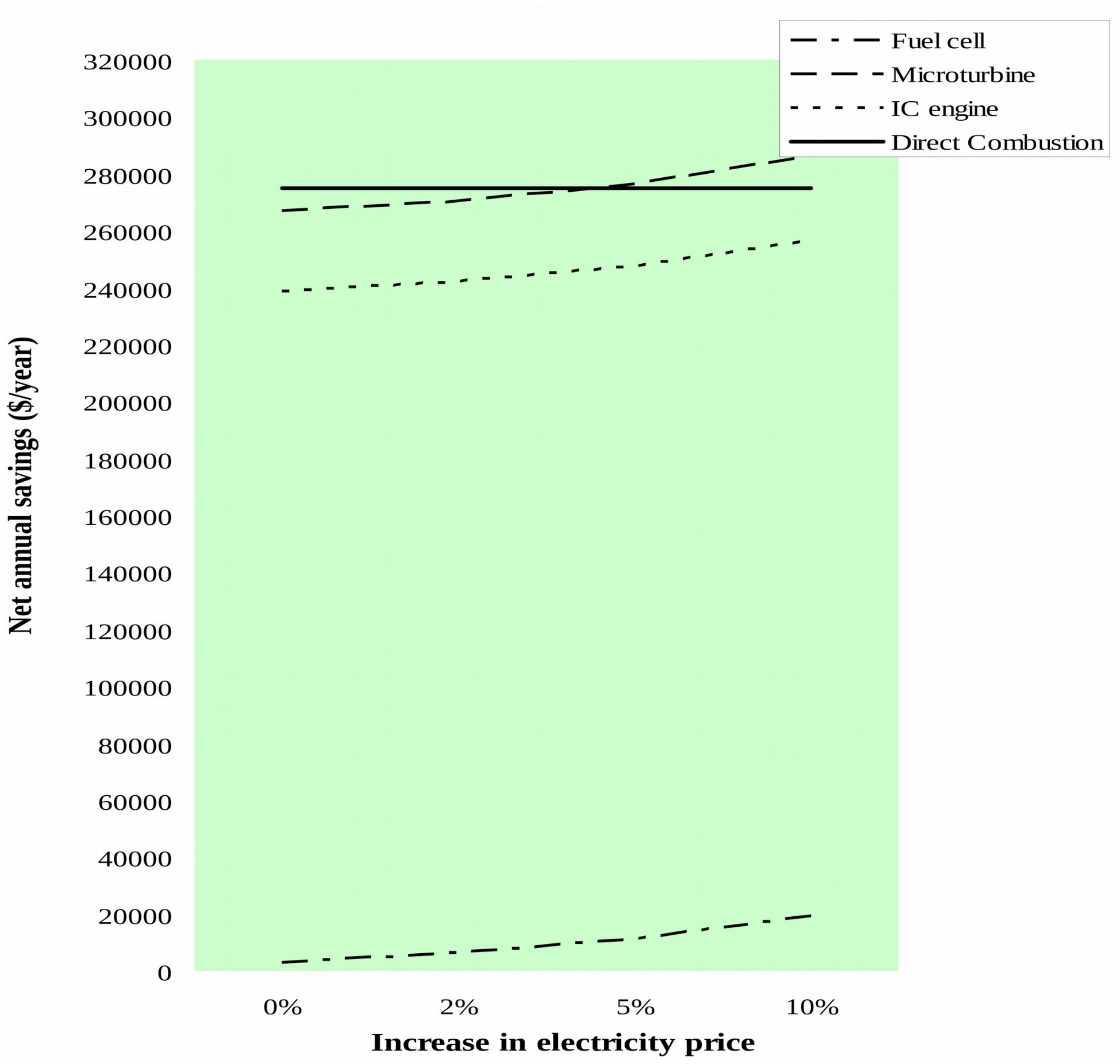


Figure 59: Net Annual Savings of Alternatives and Electricity Price

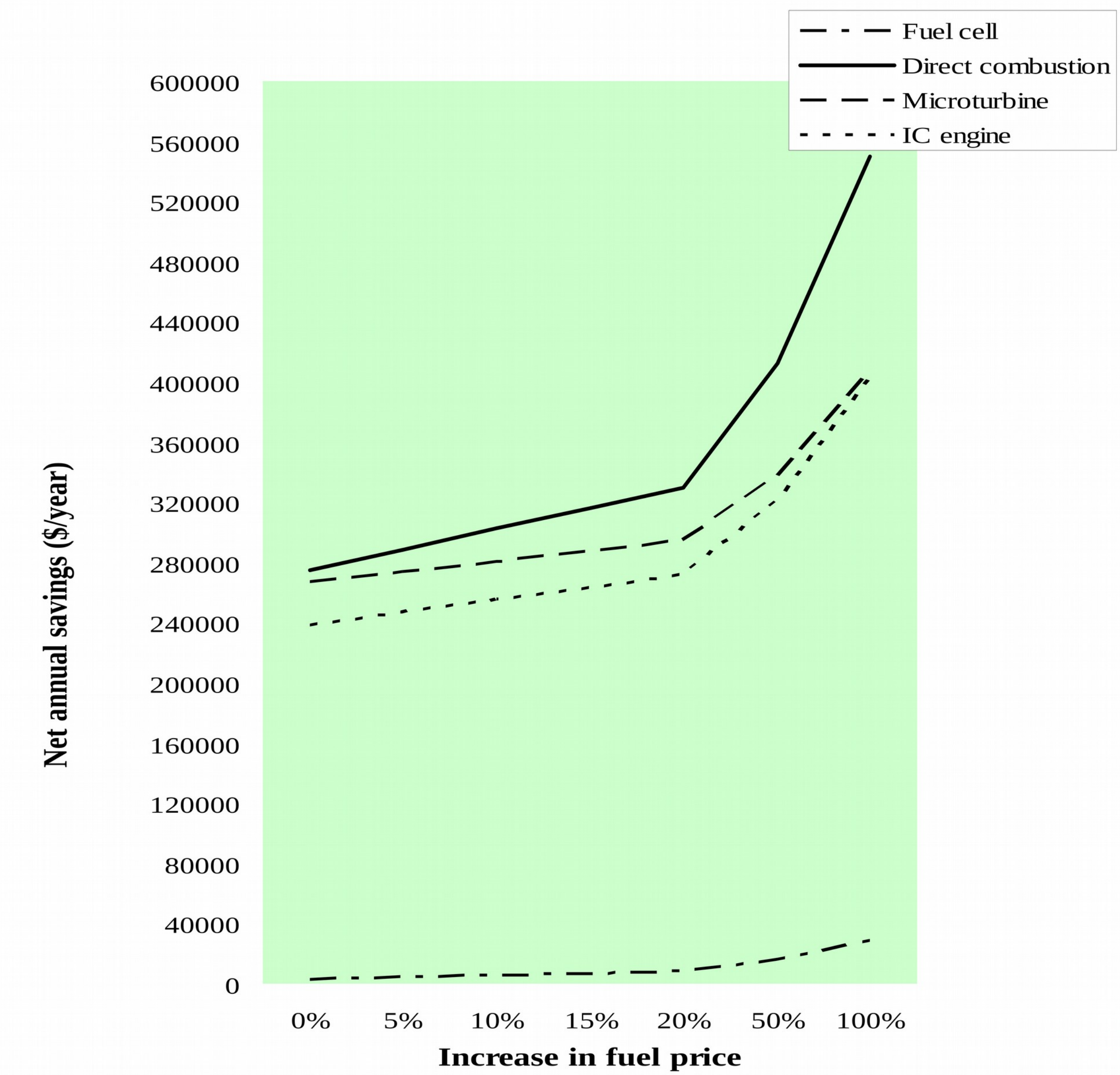


Figure 60: Net Annual Savings of Alternatives and Fuel Oil Price

Fuel oil price was assumed to increase by 5%, 10%, 15%, 20%, 50% and 100%. Figure 60shows linear increase in net annual savings with rise of fuel oil price. Increase rate of net savings for direct combustion is approximately 7 times of that for fuel cells, 5/3 times of that for microturbines and 3/2 times of that for IC engines. As far as the fuel oil price is increasing, direct combustion is the optimum alternative for the plant.

Annual savings and cheese production

In addition to evaluate different CHP systems for the most economic use of the biogas at the dairy the model was also used to evaluate how changes in the production environment may affect CHP system economics. Independent parameters considered in this research part include changes in daily production levels, production schedule, electricity and fuel oil costs. For example, annual net savings as a function of cottage cheese production level for direct combustion of biogas and fuel cells is presented in Figure 8. Direct combustion of methane rich biogas proves more beneficial than use of fuel cells. Cottage cheese manufacturing generates high strength wastewater which is used as feed to generate biogas via anaerobic digestion. Due to the high capital cost a minimum of approximately of 50,000 kg/d of cottage cheese would have to be produced in order to generate any annual savings using fuel cells. Lower capital costs for the direct combustion alternative, which displaces fuel oil only, also resulted in a higher annual savings rate compared to fuel cell systems.

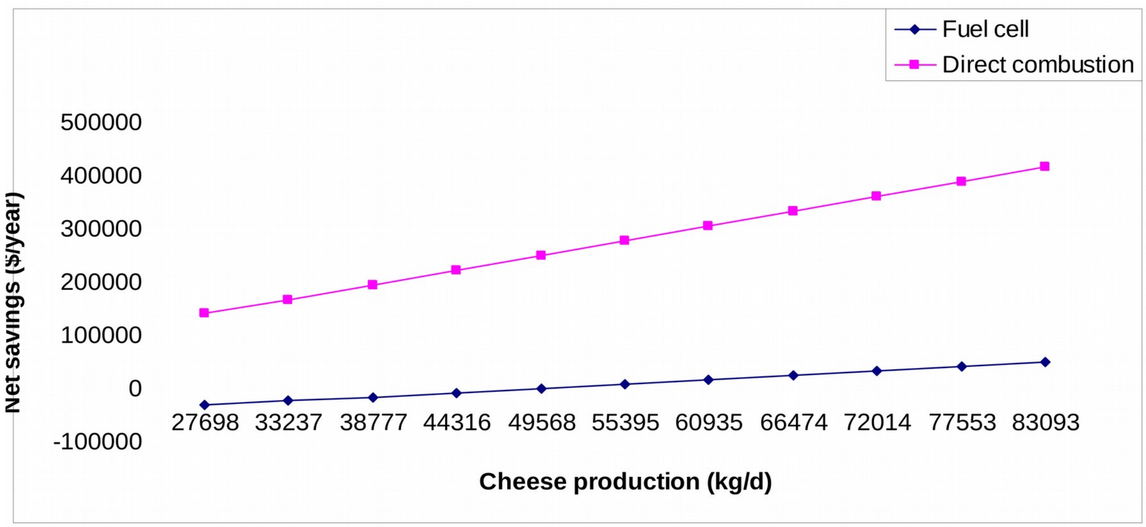


Figure 61: : Annual net savings as a function of cottage cheese production for direct combustion and fuel cell CHP systems.

Task 5 Dissemination

Dissemination of the project results occurred primarily in form of publications, conference presentations and presentations to lay audience. Publications and conference presentations are listed in the following section (Accomplishments). Presentation to general audience and other stakeholders are tabulated below.

Outreach (general communication):

1. Poster: 2005 visit of Sen. Clinton to Clarkson University (Potsdam NY)
2. Poster: 2006 Fuel the Future Bioenergy Summit (Potsdam NY) (sponsored in part by NYSERDA)
3. Poster: 2006 New Jobs for New York conference sponsored by Sen. Clinton (Rochester NY)
4. Presentation to stakeholders and USDA officials on the economic assessment of two manure digesters in the Malone region. (2005-2006, Malone NY)

5. Grimberg, S.J. (2007) Energy from Cows – Biogas Digesters for Dairy Farms. *Presented* at 2007 North Country Sustainable Energy Fair & Home Tours. State University of New York, Canton, NY, April 27-29, 2007.
6. Grimberg, S.J. (2007) From Dairy Waste to Electric Power. *Presented* at the Clarkson University Alumni Reunion, July 13, 2007.
7. Poster: 2007. Dairy Waste to Energy. *Presented* at the Clean Energy & Transportation Expo, Clarkson University, Potsdam, NY 10/4/07
8. Grimberg, S.J. (2009) Farm Waste to Energy: Potential Windfall and Challenges. *Presented* at Clarkson University Alumni College 2009, July 7-8, 2009.

Accomplishments

This project was part of a larger collaborative research effort funded by several funding agencies. The overall goal of the project was to build a farm digester that will also receive cheese manufacturing waste. After construction the goal was to monitor the system to validate any models that were developed throughout the research. Since the full-scale digester was never built due to the economic down turn and as a result the farmer's unwillingness to incur more dead for the capital project the digester model was validated using data from operating systems. To this date seven publications and six conference proceedings resulted from the research partly funded through this project.

The research on the economic feasibility of renewable energy systems at the Breyers Yogurt Company was presented to company officials and submitted in form of a report. The company seized to operate in 2010, however, and the local digester was decommissioned. At the end of 2011 the Breyers Yogurt Company was purchased by Upstate Niagara Cooperative, Buffalo, who are now operating the plant under new leadership and with different product lines. The results from this research are therefore of limited use.

Three Masters students (Nandan Prabhune, Zhongbo Sang, Yotam T. Weldetnsae) were supported for their work on the energy assessment of the plant and for the initial digester model. Each of the students defended successfully their thesis in front of a panel of researcher. Their work served as the basis of the subsequent peer reviewed publications listed below.

Two models were developed throughout this research. DAIRIES, is a model that can predict the biodegradation and biogas production for organic mixtures. In addition, DAIRIES will predict energy production for given ambient conditions. The energy assessment model for Breyer's Yogurt Company allowed for the evaluation of three different biogas utilizing technologies (fuel-cell, micro turbine, direct combustion) given plant production, economic incentives and energy prices. Modeling results showed that direct combustion of the biogas was most cost effective for the plant in 2009. Given that energy and capital prices are significantly different today the model could be easily used to determine whether for similar production rates direct combustion still would be the most economical solution.

Publications

1. Brouwer, A. F; S.J. Grimberg; S.E. Powers. In press. The Dynamic Anaerobic Reactor & Integrated Energy System (DARIES) Model: Model Verification and Sensitivity Analysis. J. Water Environ. Res., July 2012.
2. Narula, R.; S.J. Grimberg; S. Rogers; S. Mondal (2011) Pathogen Reduction and Factors Responsible for Pathogen Reduction in Dairy Farm Operations Treating Agricultural Waste. Biological Engineering Transactions, 4(3), 115-131.
3. Zhang, B.; K.R. Fowler, S. Mondal, S.J. Grimberg Model Calibration and Sensitivity Analysis of ADM1 Simulating Non-Steady State Anaerobic Digestion of Dairy Manure. *In Press Wat. Sci. Technol.*.
4. Welsh, R; S.J. Grimberg; G.W. Gillespie; M. Swindal (2010) Technoscience, Anaerobic Digester Technology and the Dairy Industry: Factors Influencing North Country New York Dairy Farmer Views on Alternative Energy Technology. *Renewable Agric. Food Sys.* 25(2), 170-180.
5. Swindal, M.G., G.W. Gillespie, R.J. Welsh (2009) Community digester operations and dairy farmer perspectives. *Agric. Hum Values*, DOI 10.1007/s10460-009-9238-1.
6. Page, D.I., K.L. Hickey, R. Narula, A.L. Main, and S.J. Grimberg (2008) Modeling Anaerobic Digestion of Dairy Manure Using the IWA Anaerobic Digestion Model No. 1 (ADM1). *Wat. Sci. Technol.* 58(3), 689-695.
7. Grimberg, S.J. (2008) Anaerobic treatment of farm waste: opportunities and challenges. *Water. Environ. Res.*, 80:3, 195.

Conference Proceedings

1. Narula, R., **S. J. Grimberg**, S. Rogers, S. Mondal (2010) Quantification of Selected Pathogens in Agricultural and Municipal Wastes. In *Proceedings* of the 83rd Annual Water Environment Federation Technical Exhibition and Conference, New Orleans, LA, October 4-6, 2010.
2. Venczel, M.Z., S.E. Powers, "Anaerobic Digestion and Related Best Management Practices: Utilizing Life Cycle Assessment." In: *Proceedings* of the XVIIth World Congress on the International Commission of Agricultural Engineering (Quebec City, June 2010).
3. Narula, R., S. J. Grimberg, S. Rogers, S. Mondal (2010) Pathogen Reduction And Correlation To Factors Responsible For Pathogen Reduction In Dairy Farm Operations Treating Agricultural Waste. In: *Proceedings* of the 2010 ASABE Annual International Meeting (Pittsburgh, PA, June 20-23, 2010)
4. Linder, G; S.J. Grimberg (2010) Comparison of Monitoring Systems for Anaerobic Digesters. In *Proceedings* of the 2010 IEEE PES T&D Conference & Exposition in New Orleans, LA, April 20-22, 2010.
5. Venzcel, M. N. Dejeuny, J.M. Kusiima, S.E. Powers (2009) Environmental Impacts and Costs for Manure Management with and without Anaerobic Digestion for Heat and Power (Paper Number: 096173, Reno, Nevada, June 21-24, 2009).
6. Zhang, B; K. Fowler, M. Grace, S. Mondal, S.J. Grimberg (2009) Optimization of Anaerobic Digestion Model No. 1 (ADM1): Simulation of Dairy Manure Digestion. In: *Proceedings* of the 2009 ASABE Annual International Meeting (Paper Number: 096618, Reno, Nevada, June 21-24, 2009).
7. Linder, G; S.J. Grimberg, P. Pillay, E. Thacher (2009) Implementation of a distributed standard anaerobic digester control system based on observations from real world failure analysis. In:

Proceedings of the 2009 ASABE Annual International Meeting (Paper Number: 09577, Reno, Nevada, June 21-24, 2009).

Abstracts/Presentations

1. Narula, R., *S. J. Grimberg*, S. Rogers, S. Mondal (2010) Quantification of Selected Pathogens in Agricultural and Municipal Wastes. *Presented* at the 83rd Annual Water Environment Federation Technical Exhibition and Conference, October 5, 2010, New Orleans, LA.
2. Brouwer, A.F. S.J. Grimberg, S.E. Powers, E.F. Thacher, A Dynamic, Systems Approach to Modeling Anaerobic Digester Systems, abstract submitted for presentation at the Northeast Agricultural/ Biological Engineering Conference (Geneva NY, July 2010).
3. Brouwer, A.F. S.J. Grimberg, S.E. Powers, E.F. Thacher (2010) Assessing the economic viability of anaerobic digesters on dairy farms in NYS through the use of mathematical models. Poster presented Syracuse Center of Excellence in Environmental and Energy Systems grand opening, March 5, 2010, Syracuse NY.
4. Zhang, Y and S.J. Grimberg (2010) Feasibility to reuse recycled bedding sand at dairy farms. P*resented* at the 82st Annual Winter Meeting of the New York Water Environment Association, February 1-3, 2010, New York City, NY.
5. Venkiteshwaran, K, M. DiGennaro, S.J. Grimberg (2010) Two stage anaerobic co-digestion using crude glycerol or cheese whey with dairy manure for improving biogas production. P*resented* at the 82st Annual Winter Meeting of the New York Water Environment Association, February 1-3, 2010, New York City, NY. (received 2nd place award for student presentation)
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Conclusions

Two models were developed throughout this research. DAIRIES, is a model that can predict the biodegradation and biogas production for organic mixtures. In addition, DAIRIES will predict energy production for given ambient conditions. The energy assessment model for Breyer's Yogurt Company allowed for the evaluation of three different biogas utilizing technologies (fuel-cell, micro turbine, direct combustion) given plant production, economic incentives and energy prices. Modeling results showed that direct combustion of the biogas was most cost effective for the plant in 2009. Given that energy and capital prices are significantly different today the model could be easily used to determine whether for similar production rates direct combustion still would be the most economical solution.

The digester model accurately predicted the biodegradation of agricultural wastes of 26 full-scale digesters operating in the North Eastern U.S. Model predictions proved to be more accurate than the Farmware Program promoted by U.S. EPA.

Recommendations

Both models were validated separately. If one could locate an digester that receives both dairy manure and cheese processing waste the combined models could be validated. The models represent a general framework on how energy assessments can be used in decision making. Energy and mass balances throughout the manufacturing process have been completed. Given inputs of energy prices, production rates, capital coste

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