COMBINING ANAEROBIC DIGESTION AND HYDROTHERMAL LIQUEFACTION IN THE CONVERSION OF DAIRY WASTE INTO ENERGY: A CENTRALIZED CASE STUDY FOR NEW YORK STATE

A Thesis

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ABSTRACT

In this report, the economic feasibility of implementing a centralized bioenergy system in New York state was investigated. It has been shown that the feasibility of the project depends on many factors, with system scale being the most determinant factor. Increasing the system size from 157 farms and 130,000 cows to 407 farms and 260,000 cows increases the NPV from a negative $19 million to $162 million (considering a 40-year project lifetime). The hybrid AD/HTL centralized system generates around 560 million liters of manure - equivalent to 575 million kWh of electricity – 120,000 liters of biocrude oil and 70,000 kg of hydro-char per day. Other variables such as discount rate, electricity selling price, tax incentives and subsidies greatly impact the economics of the project.

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LIST OF ABBREVIATIONS

AD: Anaerobic Digester
ASABE: American Society of Agricultural and Biological Engineers
BETC: Biomass Energy Tax Credit
BITC: Biomass Investment Tax Credit
BOD: Biological Oxygen Demand
BP: Breakeven Point
CC: Capital cost
CHP: Combined Heat and Power
COD: Chemical Oxygen Demand
CSTR: Continuously Stirred Tank Reactor
DCF: Discounted cash flow
eeq: electron equivalent
EOS: economies of scale
EPA: Environmental Protection Agency
ER: energy recovery
FID: Farm ID
GIS: Geographic Information System
HHV: high heating value
HRT: Hydraulic retention time
HTL: Hydrothermal Liquefaction
IRR: internal rate of return
LCA: Life Cycle Assessment
LCOE: Levelized cost of electricity
NPV: Net present value
NYSERDA: New York State Energy Research and Development Authority
O&M: Operating and Maintenance cost
REV: Reforming the Energy Vision
SRT: Solids Retention Time
STP: Standard Temperature and Pressure
TS: Total Solids
UASB: Upflow Anaerobic Sludge Blanket
VFA: Volatile Fatty Acids
VS: volatile Solids
WGS: World Geographic System (coordinate system)

LIST OF SYMBOLS

Q: Flow rate
Y: Yield
Y_n: Net yield
$\hat{q}$: maximum specific substrate uptake rate
K:half saturation constant
b: decay rate
Y_c: Composite yield
$\hat{q}_c$: Composite specific substrate uptake rate
K_c: Composite half saturation constant
b_c: Composite decay rate
f_s^o: fraction of eeqs going to cell synthesis
f_e^o: fraction of eeqs going to energy
$\hat{\mu}$: maximum specific growth rate
S_o: Influent Soluble BOD concentration
P_o: Influent Particulate BOD Concentration
S: Effluent soluble BOD concentration
P: Effluent particulate BOD Concentration
θ_x: Solids Retention Time
θ: Hydraulic retention time
K_h: Hydrolysis rate constant
X_v: Biomass concentration in reactor/effluent
F_d: Biodegradable fraction of biomass
ΔG_o: Gibbs free energy
ΔG_c: Free energy required to convert pyruvate to cell carbon
ΔG_p: free energy consumed in the conversion of a carbon source to pyruvate
ΔG_r: Energy released per electron equivalent of electron donor substrate used in catabolism
A: electron equivalent of electron donor converted to energy per electron equivalent of cells synthetized
ε: efficiency of energy transfer to or from an energy carrier
R_e: Energy reaction
R_c: Cell synthesis reaction
$\hat{q}_e$: Maximum flow of electrons to the electron acceptor
X_1: Lactate fermenters
X_2: Acetate fermenters
S_L: effluent/reactor Lactate
S_A: effluent/reactor Acetate
S_L^o: Influent Lactate concentration
S_A^o: Influent Acetate Concentration
ΔBOD: digested BOD
V_{acetic}: acetic acid volume
V_{lactic}: lactic acid volume
m_{acetic}: acetic acid mass

m_{lactic}: lactic acid mass
ρ_{acetic}: Acetic acid density
ρ_{lactic}: lactic acid density
P: present value
F: future value
i: discount rate
PV_n: present value at year n
C_o: initial capital cost at year 0
n: economic lifetime of the project

1. Introduction & objectives

The dairy industry is one of the major industries in New York state and contribute greatly to its economy. In fact, NY state is the # 1 producer of yoghurt, sour cream and cottage cheese and # 4 in cheese production in the United State. There has been tremendous growth in dairy product manufacturing in the state, generating employment and creating wealth. Behind this agricultural success, however, lies an important environmental problem. Waste generated during the production process of dairy products is significant. Dairy farms' main waste product is cow manure. Without proper treatment and/or adequate storage facilities, manure can represent a significant source of methane emissions. A waste by product of dairy processing facilities is acid whey. According to a Cornell University report (2013), for every 7,000 gallons of milk used in making Greek yoghurt, 4,900 gallons of acid whey are produced. Moreover, the treatment of dairy waste water produces sludge, another solid waste of concern. Handling, disposal and treatment of the waste streams is costly and proves to be a burden to farmers and industry alike. As such, dairy waste management is a complex challenge that must be addressed in order to ensure a sustainable dairy industry.

One way to tackle this problem is to view the wastes as a resource (for carbon and nutrients). Carbon recovered through anaerobic digestion results in methane gas production which can be used as an electricity source or as feedstock for fertilizer production. Nutrient recovered (Nitrogen and Phosphorous) as fertilizers can offset the costs of purchasing synthetic fertilizers in farms. The recovery and recycling of waste by products creates a circular dairy economy which contributes in increasing the overall sustainability of the dairy system.

This report will examine energy recovery in the context of a centralized dairy bio-energy system. The system consists of a series of biological and thermochemical conversion processes to treat dairy manure from New York State farms. The centralization of such an energy system will be evaluated using geographic information systems (GIS) and spatial analysis tools. Finally, the feasibility of the bioenergy system will be assessed by performing a techno-economic analysis.

1.1. Description of the centralized bioenergy system

In a centralized dairy manure bioenergy system, dairy manure is collected from multiple farms, blended together and digested in anaerobic digesters (AD) (Gooch et al.), producing methane gas and digestate, a waste byproduct with significant carbon content. The digester effluent (digestate) is usually stored on-site at the centralized facility and then shipped to nearby farms as fertilizers (Gooch et al.). Manure can also be co-digested with other non-farm biomass such as food waste and organic industrial wastes. Digestion of other biomass materials is function of material handling, biodegradability, and economics (Gooch et al.). Co-digestion of manure with other organics can actually increase biogas generation (Gooch et al., N. Scott). However, in the scope of this study, only manure will be considered.

Because of its high organic matter and nutrient contents, land spreading the digestate can be subject to stringent environmental regulations regarding nutrient control and management (excess nutrient supply, seepage of growth-limiting nutrients and risks of eutrophication in nearby water bodies). The digestate will then be further treated using hydrothermal liquefaction (HTL), producing in the process hydro-char, biocrude oil and a carbon/nutrient rich aqueous phase. To further recover carbon, a secondary, smaller scale anaerobic system will be used to treat the aqueous phase, generating more methane and a high nutrient concentration waste stream. The centralized bioenergy plant consists of an AD-HTL-AD system. A process flow diagram showing the different unit processes of the hybrid AD/HTL system can be shown in figure 1.

Centralized biorefineries should be strategically placed so as to minimize manure feedstock transportation distance and maximize economic output (energy and other platform chemical products). In this study, HTL units and small-scale ADs will be added to existing ADs in NY state. Centralized bioenergy systems can benefit from economies of scale, where operating and maintenance costs per unit of influent treated ($/liter) is less in large centralized systems than smaller decentralized systems (Gooch et al.).

1.2. Methodology

This study started by conducting a spatial analysis using ArcMap®, a GIS based software, to assess the centralization of the bioenergy system (grouping farms and AD/HTL facilities into centralized systems). Using the centralized system layout (i.e. relative distribution of farms and integrated AD/HTL facilities), the manure input into each centralized facility was computed. The energy potential of the bioenergy system was determined by conducting simple mass balances around the AD and HTL plants to determine the relative amount of methane gas, biocrude oil and hydro-char produced. A kinetic modeling was then conducted on different anaerobic systems to select the optimal secondary AD system to treat the aqueous phase. The work would entail in searching in the literature for common kinetic parameters for microbial communities that degrade carboxylic acids, the main aqueous product composition (Posmanik et al., 2017), to determine design Solids Retention Time (SRT), steady state substrates and biomass concentration, substrate removal efficiency and methane production in each of the different anaerobic systems. The optimal anaerobic system was determined according to practicality (SRT times), and treatment efficiency (substrate removal). Finally, the economic feasibility of the bioenergy system was evaluated by conducting a cash flow analysis and determining key financial parameters such as the net present value (NPV), internal rate of return (IRR), and levelized cost of electricity (LCOE). A sensitivity analysis was performed to measure the effect of different technical and economic variables on those parameters.

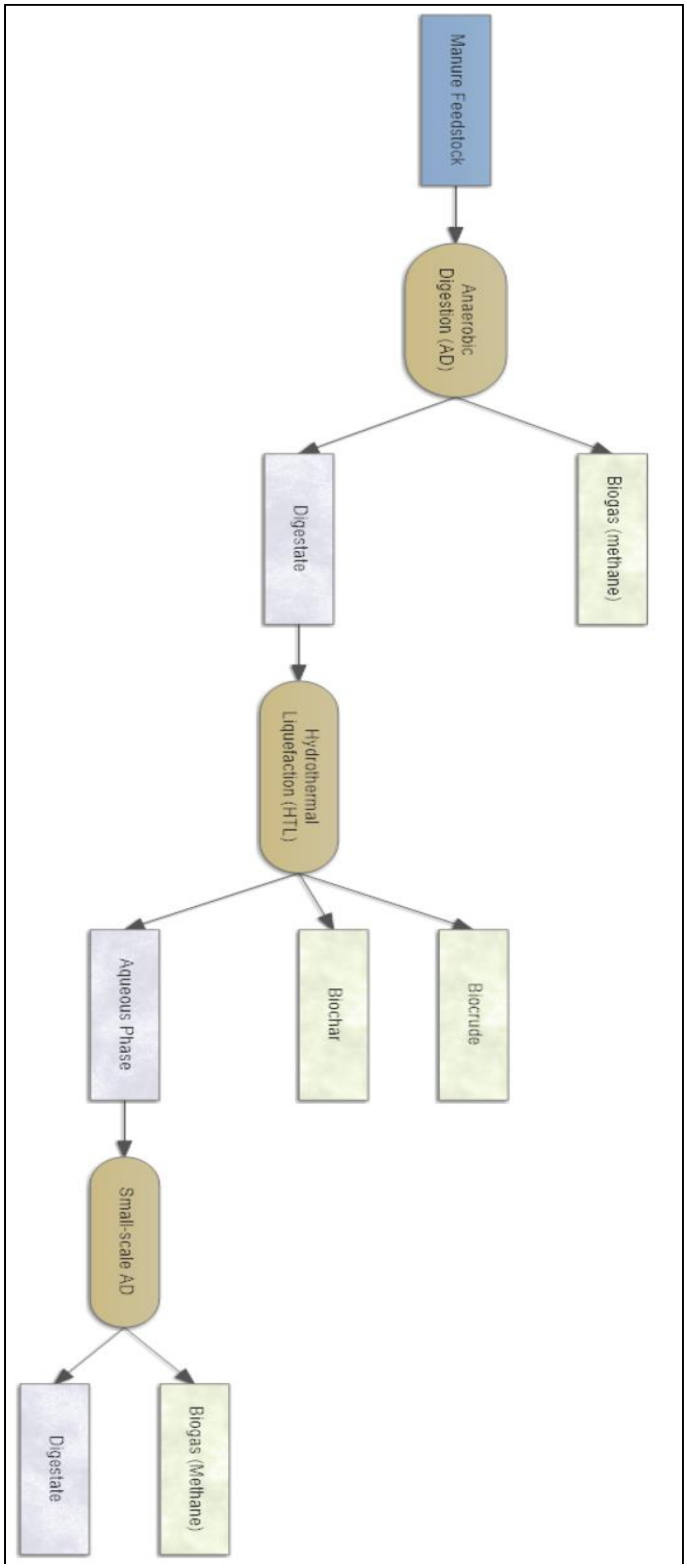

Figure 1-Process flow diagram showing mass flows between anaerobic digester, HTL reactor and secondary anaerobic treatment system

2. Spatial Analysis

2.1. Data collection

In this section, the centralization of the biomass waste-to-energy system is evaluated. A centralized bioenergy system, or 'energy village' is defined as a collection of farms that share a common digester. The boundaries of such bioenergy systems will be defined using ArcMap®.

Data on all dairy farms locations in New York state were collected. Coordinates of the digesters were obtained from the EPA's AgSTAR database. The decimal degree coordinates were imported to ArcMap for analysis, and were projected onto the geographic WGS 84 coordinate system. Every digester was assigned an identification number (FID). We used ArcMap's 'near' tool to match every farm with its closest digester, and thus 30 clusters were created, with each cluster consisting of a certain number of farms and a shared centralized digester. A list of all digesters in NY state along with their FIDs is shown in table 1 below. Note that each FID represents a farm that has an anaerobic digester on site, hence each FID is associated with a certain number of cows.

Table 1-Anaerobic Digesters in NY state

Farm (AD)	FID (ArcMap)	#cows
AURORA RIDGE DAIRY, LLC	0	590
FESSENDEN DAIRY, LLC	1	850
PATTERSON FARMS	2	2240
RIDGECREST DAIRY, LLC	3	1,255
SPRUCE HAVEN FARM LP	4	1500
SUNNYSIDE FARMS, INC.	5	400
THE ROACH FARM	6	1525
WILLET DAIRY LLC	7	680
CAYUGA REGUONAL BIOENERGY ENTEPRISE	8	670
NEW HOPE VIEW FARM LLC	9	1220
LAMB FARMS, INC. (FARM #1)	10	725
ZUBER FARMS	11	1800
SHELAND FARMS	12	650
COYNE FARMS, INC.	13	280
NOBLEHURST FARMS INC.	14	1085
CREEK ACRES FARM	15	1150
TWIN BIRCH DAIRY, LLC	16	600
HALF DUTCH FARM	17	1775
LAWNHURST FARMS	18	710
WILL-O-CREST FARMS	19	1200
WAGNER FARMS	20	840
GREENWOOD DAIRY FARM LLC	21	1840
AA DAIRY	22	850
WALKER FARMS LLC	23	1350
EL-VI FARMS	24	1000
BOXLER DAIRY FARM	25	1000
EMERLING FARMS LLC	26	370

SUNNY KNOLL FARMS	27	1000
SWISS VALLEY FARMS LLC	28	4000
SYNERGY, LLC	29	650
MORRISVILLE STATE COLLEGE(EQUINE FACILITY)	30	940

2.2. Spatial Assessment

Not all farms within a cluster are near enough the digester so that manure can be economically hauled. Dohler and Schliebner (2006) showed that as the distance exceeds 5-10 km, it is more viable (economically) to fertilize the lands by land spreading manure than to transport manure. In that respect, a 7 km buffer zone was created around all the digesters. All farms that are located outside the 7 km radius were deemed too far for manure transport and will thus not be part of the centralized bio-energy system. Although the 7 km buffer scenario represents an upper economic limit to the farmers, it only accounts for 84 out of all 442 dairy farms in NY state and therefore limits the resource potential. The larger the buffer radius, the more cows are included in the analysis (table 1), the higher the potential to recover carbon and generate electricity. Since the main focus of this study is to evaluate the energy potential of dairy farms in NY state, higher buffer distances will be considered for the analysis. A higher buffer radius implies higher transportation costs but also indicates higher economies of scale. Table 2 below shows farm and cow counts for different buffer radii.

Table 2-Buffer radii scenarios

buffer distance (km)	Farm count	# cows
7	83	79,551
10	116	104,156
15	157	129,540
40	317	210,684
60	371	240,843
90	407	260,754
150	440	275,128

This study will consider the 15 and 90 km buffer distances to illustrate the economies of scale in terms of the technoeconomic analysis. The spatial distribution of farms and digesters (for both the 15 and 90 km buffer cases) is shown in figure 2 below. The farm 'belt' extending from Buffalo to Albany in southwestern NY, comprises most of NY's digesters. The cluster spatial distribution for the 90 km buffer scenario is shown in figure 3. Each color represents the FID of a centralized digester, around which the farms are clustered. Each color therefore represents a cluster.

The results of the spatial analysis, showing farms, cow count, nearest digester and distance to nearest digester are shown in Table A1 in the Appendix.

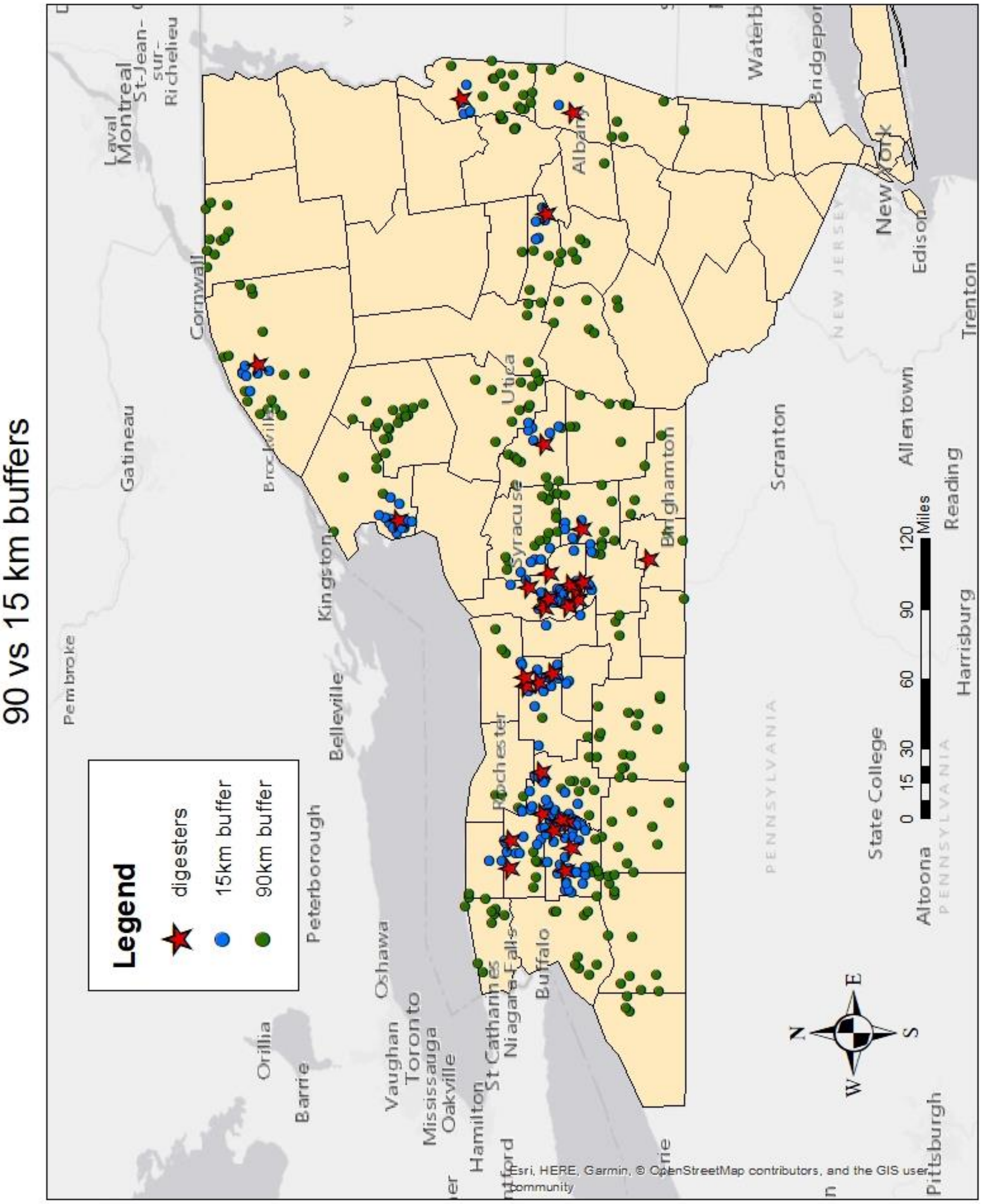

Figure 2-90 vs 15 km buffer scenarios

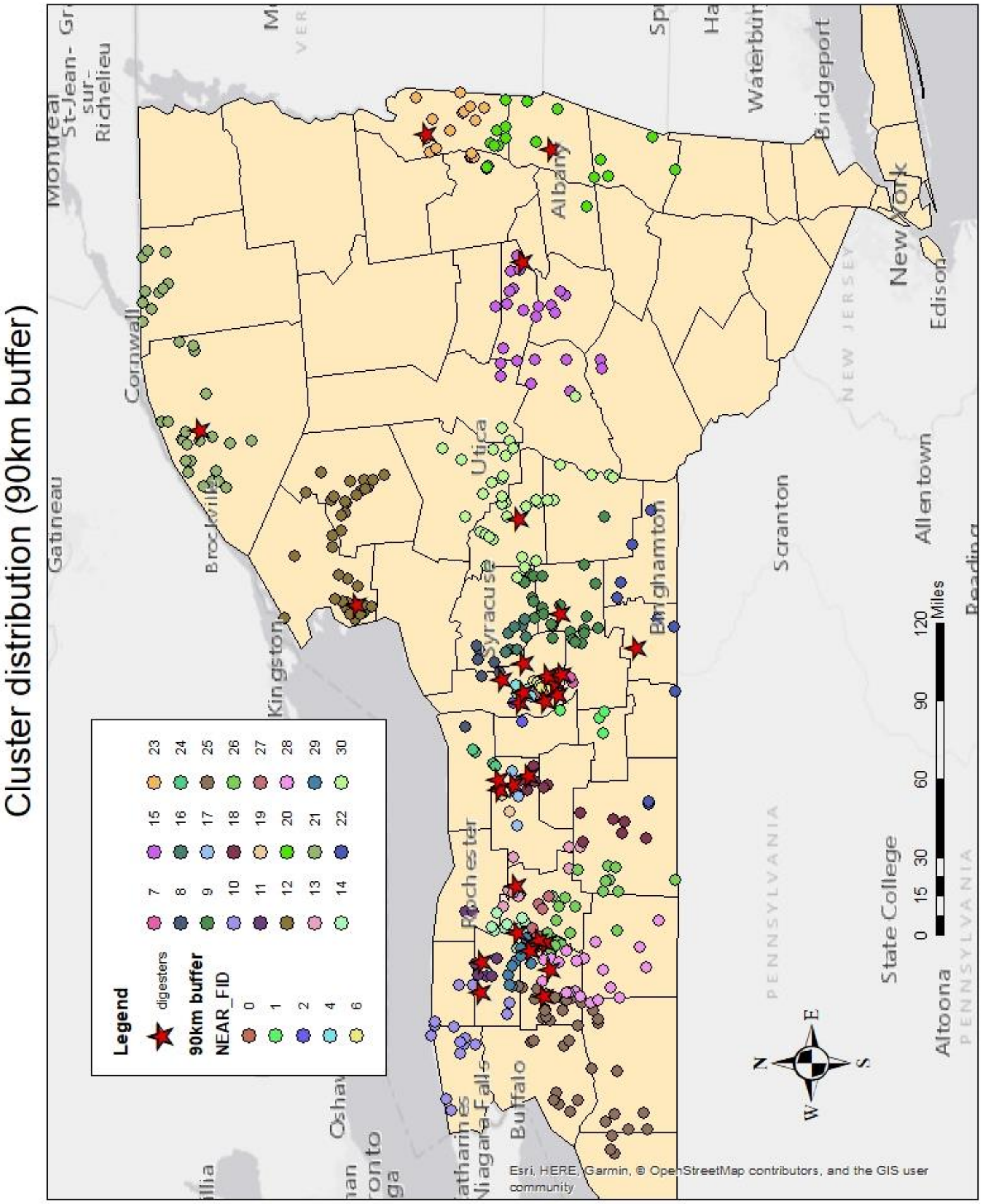

Figure 3-Cluster Distribution (90 km buffer)

3. Anaerobic Digestion of dairy manure

3.1. Methanogenesis

Methanogenesis is an anaerobic process in which organic matter is converted to methane (CH_4), the most reduced form of carbon. In the process, electrons equivalents (eeq) in BOD are directed to CH_4. Each mole of methane contains 8 eeqs, or 64 g BOD. At standard temperature and pressure, each mole of methane has a volume of 22.4 L. So, each gram of BOD generates 0.35 L of methane at STP conditions (Rittman & McCarthy, 2001).

Methanogenesis is an anaerobic process in which organic matter is converted to methane (CH_4), the most reduced form of carbon. The methanogenesis process relies on a complex community of microorganisms that convert complex organics into simple monomers, organic acids (VFAs) and finally methane via a series of hydrolysis and fermentation reactions. The process involves three group of microorganisms: hydrolytic bacteria, acetogens and methanogens. Particularly important are the *methanogens* (or methane producing organisms), which convert acetate (acetate fermenters) or hydrogen (hydrogen oxidizers) into methane. Table 3 shows acetate fermenter methanogens kinetic parameters' empirical values (at 35ºC) (Rittman & McCarthy, Environmental Biotechnology, 2001):

Table 3-Biokinetic parameters for acetate fermenters methanogens

Biokinetic parameter	
Y (g VSS/ g Acetate)	0.04
$\hat{q}$ (g Acetate/ g VSS/ d)	8.1
k (mg Acetate/L)	154
b (d^{-1})	0.019
$f^o s$	0.05
$\hat{\mu}$ (d^{-1})	0.32

Methanogens have a very low f_s (fraction of electrons in electron donor going to cell synthesis) compared to anaerobes: the fraction of electron equivalents in BOD going to biomass synthesis is very low, resulting in little sludge production. Furthermore, anaerobic treatment requires low nutrient input and generates energy (methane) as by-product. However, *methanogens* are slow-growing organisms and require long solids retention time.

3.2. Methane generation: calculations and methods

For centralized digestion systems, manure is the stable, continuously produced feedstock. A typical US dairy lactating cow produces around 68 kg of manure per day ("manure production and characteristics", ASABE, 2014, table 1.b). With a moisture content of 87%, the density of manure can be approximated to that of water. Characteristics of dairy manure excreted daily by a typical US dairy cow are summarized in the table 4 below (ASABE, 2014):

Table 4-Typical manure characteristics (ASABE, 2014)

Total solids (TS) (kg)	8.9
Volatile solids (VS) (kg)	7.5
COD (kg)	8.1
BOD (kg)	1.3
Total manure (kg, L)	68
Moisture content (%)	87

Manure consists of the total solids and the moisture content. Anaerobic digestion consists of two rate-limiting steps: hydrolysis of complex substrate into soluble fatty acids and (2) conversion of VFAs into methane by methanogenesis. Hydrolytic bacteria use extracellular enzymes to convert organic insoluble fibrous material (complex particulate organics) into soluble material (Gooch et al.). Methanogens convert volatile fatty acids into methane gas. The rate limiting step depends on the type of organics in the waste stream. Manure has many complex organics (cellulose (slowly degradable) and hemicellulose (readily degradable) (Myint et al., 2006) that need to be hydrolyzed before being converted into methane. The hydrolysis products (soluble simple organics) are converted by acetogens into volatile fatty acids such as acetate, butyrate and propionate (McCarty and Rittman, 2001). The kinetic parameters for anaerobic treatment of the three VFAs are given in table 2 below. Total organic matter in manure that would be consumed during anaerobic digestion consists of the soluble BOD (i.e. soluble VFAs, 1.3kg) and the particulate organics (VS-BOD= 7.5-1.3=6.2 kg). The relationship between TS, VS BOD and COD is shown in figure 4 below.

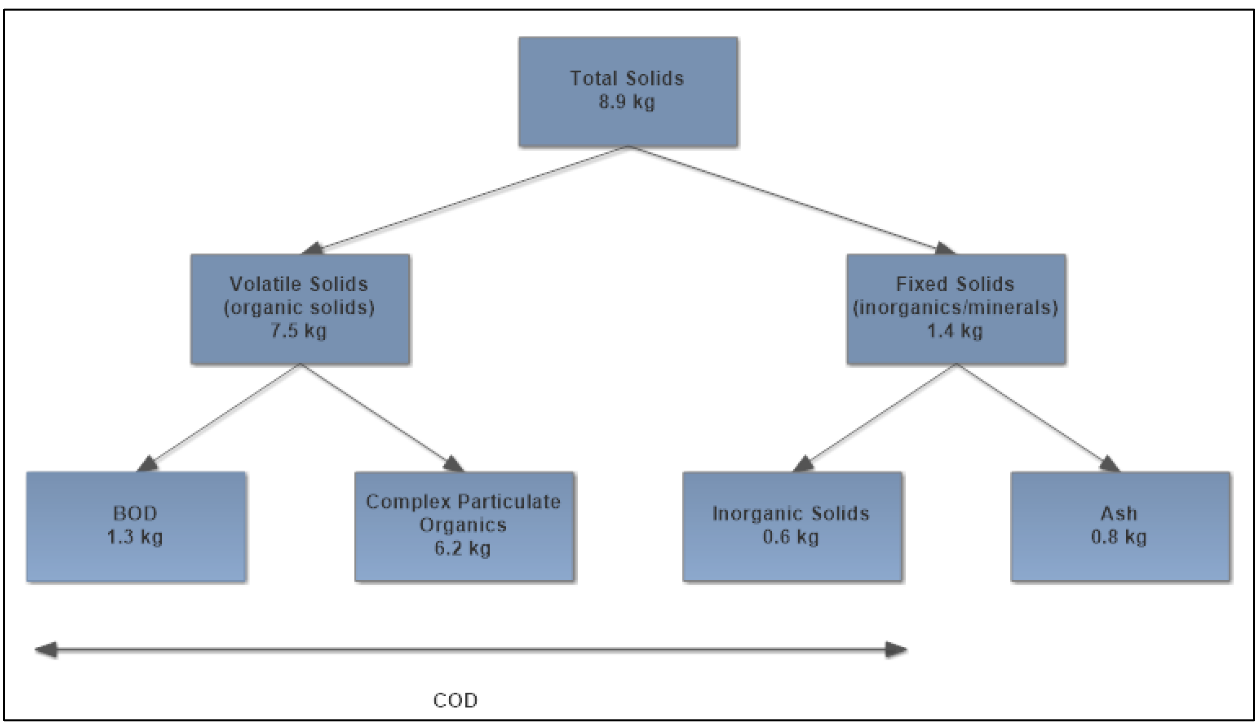

Figure 4-Manure Composition

The AD influent soluble BOD (S_o) and particulate BOD (P_o) concentrations are given by:

$$S_o = \frac{1.3kg}{68L} \times 10^6 \frac{mg}{kg} = 19{,}117 \frac{mg}{L}$$
$$P_o = \frac{6.2kg}{68L} \times 10^6 \frac{mg}{kg} = 91{,}176 \frac{mg}{L}$$

A steady state mass balance on soluble BOD (assuming CSTR kinetics) yields the following:

$$S = K \frac{(1 + b\theta_x)}{Y\hat{q}\theta_x - (1 + b\theta_x)}$$

where S is the effluent soluble BOD concentration. The hydrolysis of complex particulate organics into soluble VFAs can be modeled by first order kinetics (McCarthy?):

$$\left(\frac{dP}{dt}\right)_{hydrolysis} = K_h P$$

where K_h is the hydrolysis rate constant (=0.15 d^{-1}) and P the effluent particulate organics concentration. A steady state mass balance on P yields the following:

$$P = \frac{P_o}{1 + K_h\theta_x}$$

Where P_o is the influent particulate BOD (or VS). The amount of particulate BOD that has been converted into soluble fatty acids is then given by:

$$P_o - P = P_o \left[\frac{K_h\theta_x}{1 + K_h\theta_x}\right]$$

The total amount of BOD consumed during anaerobic digestion is given by:

$$\Delta BOD = S_o + P_o \left[\frac{K_h\theta_x}{1 + K_h\theta_x}\right] - S$$

Table 5-Kinetic parameters for anaerobic treatment of volatile fatty acids (at 35°C)

Substrate (S)	**Chemical Formula**	**Y (mg X/mg S)**	**K (mg/l)**	**$\hat{q}$(mg S/mg X.d)**	**b (d^{-1})**
Acetate	$C_2H_3O_2$	0.04	154	8.1	0.019
Propionate	$C_3H_5O_2$	0.042	32	9.6	0.010
Butyrate	$C_4H_7O_2$	0.042	5	15.6	0.010
Composite	$C_3H_5O_2$	0.041	64	11.1	0.013

Source: Environmental Biotechnology, McCarthy, 2001

To model effluent VFAs as BOD, we use composite kinetic parameter values. The composite kinetic constants were calculated by taking the average of the three values, assuming equal distribution of acetate, propionate and butyrate in the digester. So, effluent S concentration is modified to:

$$S = K_c \frac{(1 + b_c\theta_x)}{Y_c\hat{q}_c\theta_x - (1 + b_c\theta_x)}$$

where the c denotes composite values. Methane generation can be calculated using the following equation:

$$CH_4\left(\frac{L}{d}\right) = 0.35 \times Q \times \left[\Delta BOD_{digestion} - 1.42 \times X_v\right]$$

where Q is the flow rate, 0.35 is given in in L CH_4/g BOD and 1.42 in g BOD/g biomass. X_v denotes the biomass concentration in the reactor/effluent, and is given by:

$$X_v = Y_n \times \Delta BOD$$

where Y_n, the net yield is given by $Y_n = \frac{1+(1-f_d)b\theta_x}{1+b\theta_x}$. The net yield accounts for cell decay. f_d represents the biodegradable fraction of biomass. The biomass term in the methane equation represents the effect of biomass BOD consumption for biosynthesis and growth, so that only a fraction of the BOD consumed is being converted into methane. θ_x denotes the solids retention time and for an AD is typically equal to 20 d.

Knowing the number of cows per farm and the number of farms per cluster, the amount of methane generated per AD can be determined. The results (for the 90km buffer case) are tabulated below:

Table 6-Methane Generation (90 km buffer)

FID	AD	Methane (L/d)
0	AURORA RIDGE DAIRY, LLC	4,605,862
1	FESSENDEN DAIRY, LLC	8,391,584
2	PATTERSON FARMS	7,646,722
4	SPRUCE HAVEN FARM LP	8,595,629
6	THE ROACH FARM	7,567,482
7	WILLET DAIRY LLC	6,832,525
8	CAYUGA REGUONAL BIOENERGY ENTEPRISE	8,972,022
9	NEW HOPE VIEW FARM LLC	30,670,091
10	LAMB FARMS, INC. (FARM #1)	19,497,161
11	ZUBER FARMS	13,470,910
12	SHELAND FARMS	47,368,076
13	COYNE FARMS, INC.	9,082,959
14	NOBLEHURST FARMS INC.	14,629,804
15	CREEK ACRES FARM	21,949,658
16	TWIN BIRCH DAIRY, LLC	11,244,247
17	HALF DUTCH FARM	8,583,743
18	LAWNHURST FARMS	14,150,398
19	WILL-O-CREST FARMS	9,806,030
20	WAGNER FARMS	22,252,754
21	GREENWOOD DAIRY FARM LLC	44,624,369
22	AA DAIRY	11,571,115
23	WALKER FARMS LLC	17,078,340
24	EL-VI FARMS	4,427,571
25	BOXLER DAIRY FARM	40,812,894
26	EMERLING FARMS LLC	36,403,152
27	SUNNY KNOLL FARMS	11,301,697
28	SWISS VALLEY FARMS LLC	33,239,469
29	SYNERGY, LLC	13,041,029
30	MORRISVILLE STATE COLLEGE (EQUINE FACILITY)	28,740,582
	Total	**516,557,874**

Finally, the non-biodegradable inorganic chemicals well as the inert suspended solids (ash content) do not undergo any biological transformation during anaerobic digestion, and thus have the same influent and effluent concentration. Their concentrations are given by:

$$nonbiodegradable\ inorganic\ chemicals = \frac{0.6\ kg}{68\ L} \times 10^6 \frac{mg}{kg} = 8{,}824 \frac{mg}{L}$$

$$inert\ suspended\ solids = \frac{0.8\ kg}{68\ L} \times 10^6 \frac{mg}{kg} = 11{,}765 \frac{mg}{L}$$

The two main AD output streams are the digestate and methane gas. The digestate consists of the cell biomass, the effluent BOD and particulate organic matter, as well as the non-biodegradable inorganic chemicals and inorganic suspended solids. A mass balance around the digester, along with all inputs and outputs is shown in figure 5. The digestate, which still contains organic carbon and other chemically oxidizable material is sent to a hydrothermal liquefaction reactor for further processing.

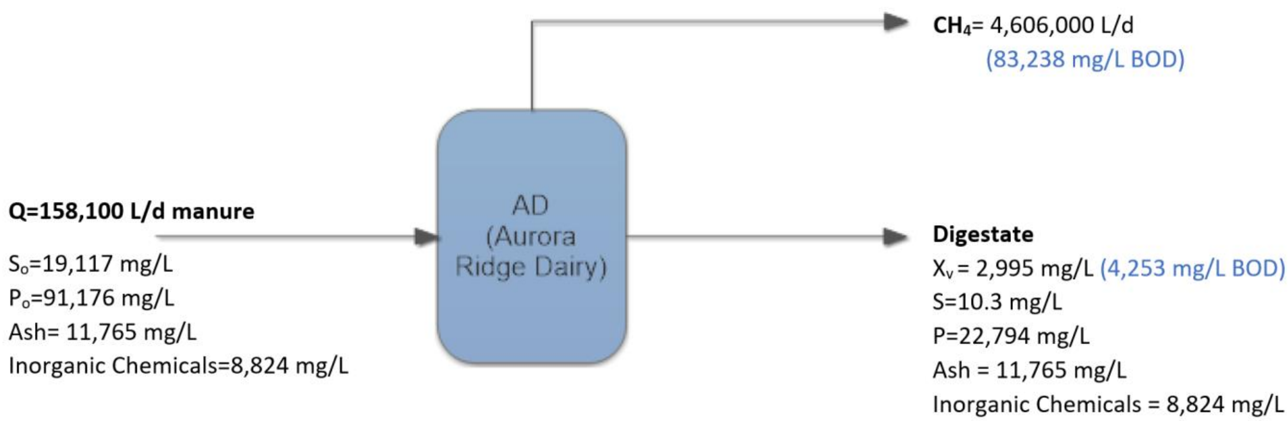

Figure 5-AD Mass Balance

4. Hydrothermal Liquefaction of manure digestate

Hydrothermal liquefaction of organic wastes is a thermochemical based on fast hydrolysis reactions followed by dehydration and condensation of sugars, lipids proteins and their degradation products using supercritical water (Peterson et al., 2008). Hydrothermal liquefaction converts biomass into three main products: bio-oil, bio-char and a carbon rich aqueous phase. The relative amount of the different products depends on time and temperature of the reaction (Toor et al, 2011). In this analysis, HTL will be performed at 300 ºC for 60 minutes.

To conduct a mass balance around the HTL, effluent and influent compositions must be determined. The influent concentrations were determined in the previous section above. The manure digestate consists of an aqueous mixture of carbohydrates, protein, lipids, minerals and nutrients (Deniel et al., 2016 & Pham et al., 2015). Manure is a lignocellulosic rich biomass, so many of the carbohydrates in the digestate are cellulose, hemicellulose or lignin, representing the complex particulate organic matter that were not consumed during anaerobic digestion. The effluent consists of the three products mentioned earlier, in addition to a gas stream (mainly CO_2). Posmanik et al. conducted a study on HTL of dairy manure digestate and calculated the conversion yields of the different products on a carbon basis. The conversion yields, measured in grams carbon in product per g carbon in feed were as follows: 38%, 24% and 19% for biocrude, biochar and the aqueous phase respectively. The bio-crude oil is rich in carbon and hydrogen and has little amount of hydrogen and nitrogen (Posmanik et al., 2018). According to the same study, the C, H, O and N composition of the biocrude oil fraction is 73, 8, 15.8, and 3.3 wt% respectively. The bio crude empirical formula was then calculated to be $C_{28}H_{34}O_4N$. The dominant dissolved organic carbon in the aqueous phase are lactic ($C_3O_3H_5$) and acetic acid ($C_2O_2H_4$), with a 40/60 percentage distribution respectively (Posmanik et al. 2017). According to a study from Celia et al. (Acid and alkali paper, table 3), the FITR spectra signature of hydro-char generated from manure under non-modified hydrothermal liquefaction (without additives) shows major absorbance bands at 1637, 1258, 1028, 970 and 868 cm^{-1}. According to the literature, the 1637, 1259 and 868 cm^{-1} wavenumbers detected correspond to the Carbonyl, Guaiacyl and Guaiacylpropane functional groups respectively (Abidi et al., 2014, Magalhaes et al., 2012, Xu et al., 2013, liu et al., 2014), suggesting a lignin hydro-char composition. The lignin molecular formula can be taken as $C_{81}H_{92}O_{28}$ (PubChem CID 73555271).

To calculate the amount of carbon that got diverted into each product fraction, we will first compute the total amount of carbon in the digestate using the concentrations computed earlier and the chemical formulas of the digestate compounds. Knowing the total amount of carbon in the feed, we can then use the conversion yields obtained from Posmanik et al. to calculate the mass of carbon diverted into each product stream.

4.1. Determining total carbon in digestate feed

The following assumptions will be made regarding the manure digestate composition. The volatile fatty acid will be represented by a composite chemical formula by taking the average amounts of carbon, oxygen and hydrogen in each of acetate, butyrate and propionate. The particulate organic matter consisting of lignocellulosic material such as cellulose, hemicellulose and lignin will be represented by cellulose only $(C_6H_{10}O_5)_n$. The following assumptions will be made regarding ash and hydro-char: The Ash content (has no carbon) will be completely diverted into the hydro-char fraction, while the inorganic chemicals (no carbon) will be diverted into the aqueous phase. Decayed cells in the digestate have the following formula $C_5H_7O_2N$. The carbon fraction in each of the digestate compounds will be calculated then multiplied by the compound concentration to get the mass of carbon concentration in the digestate (mg Carbon /L). The results are shown in table 7 below.

Table 7-Digestate Compounds characteristics & total digestate carbon concentration

Digestate Compounds	Chemical Formula	g Carbon/ g compound	Compound concentration (mg/L)	Carbon concentration (mg Carbon /L)
Volatile Fatty acids	$C_3H_5O_2$	0.49	10.3	5.05
Cellulose	$C_6H_{10}O_5$	0.44	22,794	10,029
Biomass	$C_5H_7O_2N$	0.53	2,995	1,587

4.2. HTL products

The total carbon concentration in the digestate feed is therefore 11,621 mg/L (5.05+10,029+1,587 mg/L). Now we can use the HTL conversion yields to calculate the amount of carbon in the digestate that is diverted into each of the HTL products. Per liter of digestate entering the hydrothermal liquefaction plant, we have the following:

Table 8-HTL products characteristics & concentration yields

HTL products	Chemical Formula	g C/ g product	Conversion yield (g C product/ g C feed)	mg C in product/L	HTL product concentration (mg/L)[1]
Bio crude	$C_{28}H_{34}O_4N$	0.73[2]	0.38	4,416[3]	6,049
Hydro Char	$C_{81}H_{92}O_{28}$	0.64	0.24	2,789	4,459
Aqueous phase **Acetic acid (60%)** **Lactic Acid (40%)**	 $C_2O_2H_4$ $C_3O_3H_5$	 0.40 0.40	0.19	2,208	 3,312[4] 2,208
Gas	CO_2	0.27	0.19	2,208	8,178

[1] = carbon concentration in product/fraction of carbon in product

[2] From Posmanik et al. study elemental composition ratios

[3] =0.38*11,621 mg C /L

[4] (0.60x2,208)/0.4

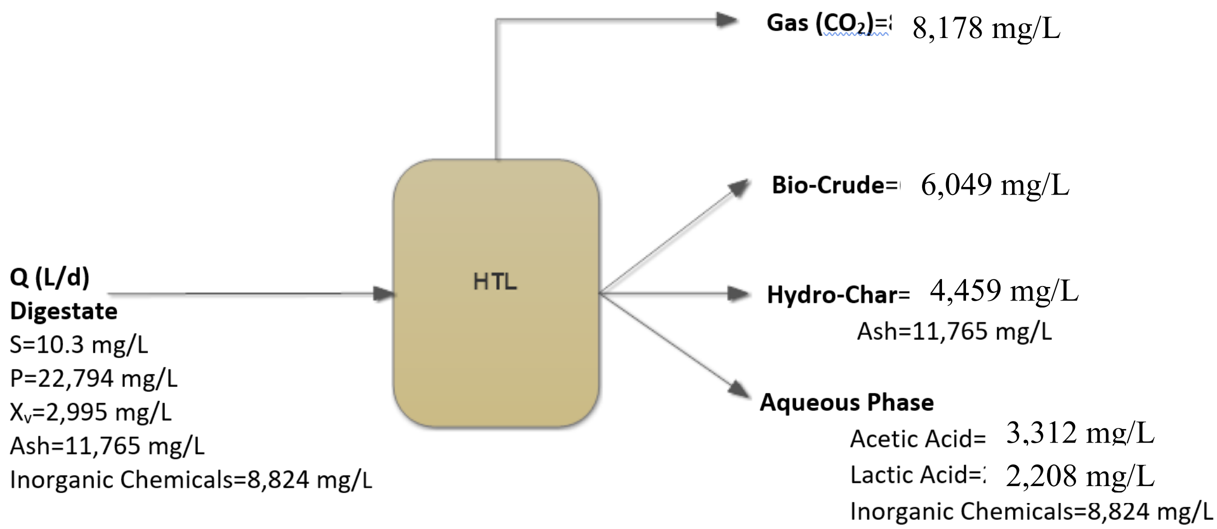

Figure 6-HTL mass balance

The mass rates of biocrude, biochar and aqueous phase are computed by multiplying the concentration of each product by the HTL influent flow rate. The daily HTL products generated by each farm are shown in table 9 (90 km buffer case).

Table 9-HTL products yields

		HTL products (kg/d)			
FID	AD Facility	CO2	biocrude	hydro char	aq phase
0	AURORA RIDGE DAIRY, LLC	1,184	876	645	2,076
1	FESSENDEN DAIRY, LLC	2,157	1,595	1,176	3,783
2	PATTERSON FARMS	1,965	1,454	1,072	3,447
4	SPRUCE HAVEN FARM LP	2,209	1,634	1,204	3,875
6	THE ROACH FARM	1,945	1,439	1,060	3,411
7	WILLET DAIRY LLC	1,756	1,299	957	3,080
8	CAYUGA REGUONAL BIOENERGY ENTEPRISE	2,306	1,706	1,257	4,044
9	NEW HOPE VIEW FARM LLC	7,882	5,830	4,298	13,825
10	LAMB FARMS, INC. (FARM #1)	5,011	3,706	2,732	8,789
11	ZUBER FARMS	3,462	2,561	1,888	6,072
12	SHELAND FARMS	12,174	9,004	6,638	21,352
13	COYNE FARMS, INC.	2,334	1,727	1,273	4,094
14	NOBLEHURST FARMS INC.	3,760	2,781	2,050	6,595
15	CREEK ACRES FARM	5,641	4,173	3,076	9,894
16	TWIN BIRCH DAIRY, LLC	2,890	2,137	1,576	5,069
17	HALF DUTCH FARM	2,206	1,632	1,203	3,869
18	LAWNHURST FARMS	3,637	2,690	1,983	6,379
19	WILL-O-CREST FARMS	2,520	1,864	1,374	4,420
20	WAGNER FARMS	5,719	4,230	3,118	10,031
21	GREENWOOD DAIRY FARM LLC	11,468	8,483	6,253	20,115
22	AA DAIRY	2,974	2,200	1,621	5,216
23	WALKER FARMS LLC	4,389	3,246	2,393	7,698
24	EL-VI FARMS	1,138	842	620	1,996
25	BOXLER DAIRY FARM	10,489	7,758	5,719	18,397
26	EMERLING FARMS LLC	9,356	6,920	5,101	16,409
27	SUNNY KNOLL FARMS	2,905	2,148	1,584	5,094
28	SWISS VALLEY FARMS LLC	8,543	6,319	4,658	14,983
29	SYNERGY, LLC	3,352	2,479	1,827	5,879
30	MORRISVILLE STATE COLLEGE(EQUINE FACILITY)	7,386	5,463	4,027	12,955
	total	**132,755**	**98,195**	**72,384**	**232,849**

5. Secondary anaerobic treatment system

5.1. Aqueous phase characteristics

The waste stream entering the secondary anaerobic reactor consists of the aqueous phase effluent from the hydrothermal liquefaction of digested manure. The dominant dissolved organic carbon in the aqueous phase after HTL of digested manure are lactic acid ($C_3H_6O_3$) and acetic acid ($C_2H_4O_2$) with recoveries of 26 and 38 $\frac{mg\ C\ in\ product}{g\ C\ in\ feed}$ respectively (Posmanik et al. 2018). Acetate is readily consumed by methanogens to produce methane. Lactate, on the other hand, needs to be fermented to acetate before it can be converted to methane. The two organisms involved in the anaerobic processes are lactate fermenters and acetoclastic methanogens.

The high heating value (HHV) of acetate is calculated using Dulong's formula:

$$HHV = 0.338 \times C + 1.428 \times \left(H - \frac{O}{8}\right)$$

Where HHV is in MJ/kg and C, H and O are the mass percentages of carbon hydrogen and oxygen in the compound respectively. For acetic acid, we get a value of 13.6 MJ/kg.

5.2. Bioenergetics

In this section, we will explore the thermodynamics of the two reactions: acetate-utilizing methanogenesis and lactate fermentation.

5.2.1. lactate/acetate

In lactate fermentation, lactate (electron donor & acceptor) is converted to acetate. The energy reaction is given by:

$$\frac{1}{12}CH_3CHOHCOO^- + \frac{1}{3}H_2O \longrightarrow \frac{1}{6}CO_2 + \frac{1}{12}HCO_3^- + H^+ + e^- \qquad \Delta G^{o\prime} = -32.29\frac{KJ}{eeq}$$

$$\frac{1}{8}CO_2 + \frac{1}{8}HCO^{-3} + H^+ + e^- \longrightarrow \frac{1}{8}CH3COO^- + \frac{3}{8}H_2O \qquad \Delta G^{o\prime} = 27.4\frac{KJ}{eeq}$$

$$(R_e): \frac{1}{12}CH_3CHOHCOO^- + \frac{1}{24}HCO_3^- \longrightarrow \frac{1}{24}H_2O + \frac{1}{24}CO_2 + \frac{1}{8}CH3COO^- \ \Delta G_r = -4.89\frac{KJ}{eeq}$$

Since manure has high ammonia content (Posmanik et al., 2017), we will assume ammonia will be the nitrogen source in the aqueous phase for cell synthesis and that ammonia will not be limiting. The cell synthesis reaction is given by:

$$\frac{1}{12}CH_3CHOHCOO^- + \frac{1}{3}H_2O \longrightarrow \frac{1}{6}CO_2 + \frac{1}{12}HCO_3^- + H^+ + e^-$$
$$\frac{1}{5}CO_2 + \frac{1}{20}HCO_3^- + \frac{1}{20}NH_4^+ + H^+ + e^- \longrightarrow \frac{1}{20}C_5H_7O_2N + \frac{9}{20}H_2O$$

$$(R_c): \frac{1}{12}CH_3CHOHCOO^- + \frac{1}{30}CO_2 + \frac{1}{20}NH_4^+ \longrightarrow \frac{7}{60}H_2O + \frac{1}{30}HCO_3^- + \frac{1}{20}C_5H_7O_2N$$

The amount of energy needed to convert the lactate into pyruvate, an intermediate carbon product, is given to be $\Delta G_p = \Delta G^{o\prime}{}_{pyruvate} - \Delta G^{o\prime}{}_{lactate} = 35.09 - 32.29 = 2.8\frac{KJ}{eeq}$. The amount of energy needed to convert pyruvate to cell carbon is empirical and given to be $\Delta G_c = 18.8\frac{KJ}{eeq}$.

Now we can calculate A, the number of electrons going to energy production per eeq going to cell synthesis.

$$A = \frac{-\left(\frac{\Delta G_p}{\varepsilon^n} + \frac{\Delta G_c}{\varepsilon}\right)}{\varepsilon \Delta G_r} = \frac{\left(\frac{2.8}{0.6} + \frac{18.8}{0.6}\right)}{-0.6 \times 4.89} = 12.3\frac{eeq\ energy}{eeq\ synthesis}$$

The fraction of electron donor going to energy and cell synthesis respectively are given by:

$$f_e^o = \frac{A}{1+A} = 0.925\,, \quad f_s^o = \frac{1}{1+A} = 0.075$$

The overall reaction can then be calculated by $R = f_e^o R_e + f_s^o R_c$ and is given to be:

$$0.083\ Lactate + 0.036\ HCO_3^- + 0.00375\ NH_4^+ \longrightarrow 0.036\ CO_2 + 0.116\ acetate + 0.0473\ H_2O + 0.00375\ C_5H_7O_2N$$

The yield is then calculated by: $Y = \frac{0.00375\ mol \times 113\frac{g}{mol}}{0.083\ mol \times 89\frac{g}{mol}} = 0.057\frac{g\ VSS}{g\ Lactate}$

For the cell's primary growth substrates, the maximum specific substrate utilization rate is mainly controlled by electron flow to the electron acceptor (McCarthy, 2001). For 20ºC, the maximum flow of electron to the electron acceptor $\hat{q}_e$ (in the energy reaction) is about 1 eeq/gVSS-d (McCarthy, 2001). The maximum specific substrate utilization rate $\hat{q}$ can then be calculated by:

$$\hat{q} = \frac{\hat{q}_e}{f_e^o} = \frac{1\frac{eeq\ energy}{gVSS.d}}{0.925\frac{eeq\ energy}{eeq\ lactate}} = 1.08\frac{eeq\ lactate}{g\ VSS.d}$$

From the lactate half reaction, we get that that 1 eeq is equivalent to $\frac{1}{12}mol \times 89\frac{g}{mol} = 7.4\ g\ lactate$.

$$\hat{q} = 1.08\ \frac{eeq\ lactate}{g\ VSS.d} \times 7.4 \frac{g\ lactate}{eeq\ lactate} = 7.992 \frac{g\ lactate}{gVSS.d}$$

The maximum specific growth rate can then be computed from:

$$\hat{\mu} = Y\hat{q} = 0.057 \times 7.992 = 0.456\ d^{-1}$$

5.2.2. Acetate/methane

Doing the same set of calculations, using the acetate and methane half reactions, the following net reaction is obtained (kinetic parameters computed are listed in table 10):

$$0.125\ Acetate + 0.234\ H_2O + 0.00375\ CO_2 + 0.0025\ NH_4^+ \longrightarrow 0.119\ CH_4 + 0.123\ HCO_3^- + 0.0025\ C_5H_7O_2N$$

5.2.3. Comparison of the two microbial kinetics

In this section, the effect of the microbial kinetics of both the lactate fermenters and acetoclastic methanogens on solids residence time will be discussed. The design SRT will be chosen so both organisms can grow and survive.

Table 10-Biokinetic parameters as computed by thermodynamics

Kinetic parameter	Lactate fermenters (X_1)	Acetate fermenters (X_2)
Y (gVSS/g substrate)	0.057	0.038
$\hat{q}$ (g S/g VSS.d)	7.992	7.74
$\hat{\mu}$ (d^{-1})	0.456	0.294
f_e^o	0.925	0.95
f_s^o	0.075	0.05

From table 3, we can see that the empirical values for Y, $\hat{\mu}$ and $\hat{q}$ are 0.04, 0.32 and 8.1 respectively. The empirical values are consistent with the theoretical values calculated. Furthermore, the f_S^o value calculated for acetoclastic methanogens matches the empirical value given by McCarthy.

Lactate fermenters have a higher maximum specific growth rate, meaning they grow faster than acetate fermenters. Assuming that both lactate and acetate are in excess in the aqueous phase such that S>>K for both organisms, the growth rates at steady state will be equal to $\hat{\mu}$ (zero order reaction). The solids residence time can then be estimated by $\theta_x = 1/\hat{\mu}$. The minimum SRT for both organisms are then computed to be:

$$\theta_{x,1} = 2.2\ d,\ \ \theta_{x,2} = 3.4\ d$$

The design SRT should accommodate both organisms without any being washed out. If the design SRT is $\theta_{x,1}$, then X2 will be washed out of the reactor as soon as it enters, without having enough time to grow and feed on acetate. If design SRT $\geq \theta_{x,2}$, then both organisms can grow and survive without being washed out. The slowest-growing organism will therefore control the SRT of the system, and methanogenesis is the rate-limiting reaction. This has implications on CSTR design; in a CSTR without recycle, SRT is equivalent to the Hydraulic Residence Time, so that a higher design SRT would need a bigger reactor volume (given a fixed flow rate).

Furthermore, since lactate fermenters grow faster, the acetate substrate will always be in excess for the methanogens as long as the acetogens are growing. When lactate is completely consumed, lactate fermenters will stop growing, and only methanogenesis will occur. It is important to note that X2 growth do not depend on X1 growth, since both acetate and lactate are available in the inflow stream.

5.3. Mathematical modeling of substrate concentrations in secondary anaerobic system

The microbial ecology within an anaerobic digester is very complex and includes a variety of fermenters and methanogens. Metagenomic studies and gene sequencing of anaerobic digester microbiomes revealed two dominant methanogens: *methanosarcina* and *methanothermobacter* (Kouzuma et al. 2017). In another study, Yang & Tang (1990) evaluated the kinetics of a co-culture of *Clostridium formicoaceticum* and *Methanosarcina mazei* in the conversion of lactate to methane in a two-step process: conversion of lactate to acetate, then conversion of acetate into methane. It has been shown that *C. formicoaceticum* can convert lactate to acetate in anaerobic digestion when PH is near neutral (Yang et al. 1987). It is known that *C. formicoaceticum* has an optimum pH at 7.6 (Tang et al. 1989), while that of M. mazei is at around 7.0 (Yang & Okos, 1987). An accumulation of acetate increases the acidity of the medium and inhibits both organisms. Neutral pH conditions are however maintained due to the commensalism relationship between the two organisms: at first the medium pH decreases as acetic acid is produced, and then increases again as methanogens consume acetic acid to grow. Thus, the methanogens keep the medium pH from decreasing, creating optimal growth environment. However, as has been shown from bioenergetics, methanogenesis is the rate-limiting step, acetogens have a higher growth rate and the influent already contains acetic acid. So, in order to maintain balanced growth (i.e no acetate accumulation) it is necessary for the methanogenic population to be higher than that of the lactate fermenters. To treat the HTL effluent, it is therefore essential to inoculate the anaerobic CSTR with a higher methanogens concentration.

Half saturation constants for methanogen and acetogen species were collected from the literature. K_s values collected are summarized in the table below.

Table 11-Half saturation constants for acetogens and methanogens species

	organism	Ks	Ks (mg/L)	source
Acetogens	Clostridium homopropionicum	560 µM	50	Seeliger et al. (2002)
Methanogens	Methanosarcina mazei	0.017 M	1020	Yang & Tang (1990)
	Methanosarcina barkeri	5.7 mM	342	Fukuzaki et al. (1990)

5.3.1. Reactor configurations

In this section, different reactor configurations will be discussed (anaerobic CSTR, fluidized bed reactor (upflow anaerobic sludge blanket – UASB) and anaerobic filter), and their advantages and disadvantages will be compared to determine what is the 'best' anaerobic system for the treatment of the aqueous phase in the context of carbon recovery and energy generation.

The CSTR is a basic anaerobic treatment system that is commonly used to treat highly concentrated organic mixtures (Rittman & McCarthy, 2001). The CSTR is characterized by continuous inflows and outflows of liquid stream. Here, microorganisms that grow (suspended growth) within the reactor continuously replace those that are removed by the effluent. The biomass and substrates concentration are the same everywhere within the reactor, and the concentrations leaving the reactor in the effluent are the same as those in the reactor. Solids retention times in a typical anaerobic CSTR is around 15-25 days. One disadvantage of anaerobic CSTRs is that high loading per unit volume can only be achieved with highly concentrated waste streams, such as municipal sludges (BOD of 8,000 to 50,000 mg/L). However, the aqueous phase resulting after hydrothermal liquefaction is much more dilute. So, treating the much dilute aqueous phase with a same SRT of 15-25 days would eliminate the cost advantage of using anaerobic treatment since the BOD loading per unit volume would be very low. One way to counter that problem is to decouple HRT and SRT to have greater biomass solids retention time (i.e: $\frac{\theta_x}{\theta} > 1$). Such systems including biofilm reactors and CSTR with recycle are discussed below. Biofilm reactors are reactors in which biomass is not suspended, but rather attached to a solid surface, forming a 'biofilm'.

One type of biofilm reactor is the anaerobic filter. In this system, the medium to which the microorganisms are attached is stationary. The growth media - consisting of plastic or rock – is completely submerged and the reactor is operated at an upflow configuration. One advantage of anaerobic filters is the high SRT that could be achieved by having a stationary growth media. SRT ranges from 4 to 36 hours. One main concern with this system is clogging by the biosolids. As the biofilm develops and grow, it starts clogging the pore spaces in the solid support matrix.
Another type of biofilm reactor is the fluidized bed reactor. In this system, the microorganisms are attached to suspended particles that are maintained in suspension by a high upward flow rate. The particles consist of sand grains, granular activated carbon or diatomaceous earth. To maintain a high upward velocity, the effluent is sometimes recycled back to the influent. The effect of effluent recycle on fluid regime flow and its implication on kinetic modeling in the reactor will be

discussed in the next section. Bed expansion creates relatively large pore spaces, meaning the flow through the reactor is less likely to clog the system compared to the anaerobic filter. The high flow rate around the particle creates good mass transfer of dissolved organic matter from the bulk liquid to the particle surface. In fact, a high bulk velocity decreases the diffuse layer thickness, increasing the diffusion of substrate into the biofilm. Furthermore, the small size of the suspended particles results in a very high specific surface area for biofilm attachment, meaning that fluidized beds can treat higher loads per unit volume of reactor. This is significant especially when one considers the bigger size needed for a CSTR to treat the same load. One problem with fluidized beds however, is biofilm detachment due to the high bulk velocity. A very high velocity might also result in washout of the granules. So, operation of a fluidized bed system requires careful control of bulk velocity. Furthermore, high bed fluidization requires a high recycle flow which can increase the overall cost of the system due to excessive pumping energy requirements.

A variant of this reactor type is the UASB, in which the microorganisms accumulate to form granules, or 'flocs', serving as the suspended biological support media. The UASB's performance improves with time as the granules 'mature'. It has been found that acetate methanogens dominate in the granules. This is advantageous since acetate is the main organic compound in the aqueous phase. The gas bubbles generated by methanogenesis help fluidize the granules, eliminating the need for mechanical mixing. UASB are characterized with high biofilm contact area and SRT.

5.3.2. CSTR kinetics

For a CSTR, the effluent substrate is modeled as follows:

$$S_i = K_i \frac{(1 + b\theta_x)}{Y_i \hat{q}_i \theta_x - (1 + b\theta_x)}$$

Where i denotes lactate or acetate. This equation computes substrate concentration resulting from microorganism consumption. We will assume a minimum SRT of 5 days $(> \theta_{x,2})$ and a decay rate of 0.02 d^{-1} for both acetate and lactate fermenters. Y and $\hat{q}$ values obtained from bioenergetic calculations will be used, and half saturation constants for the different microbial species will be taken from table 3 above.

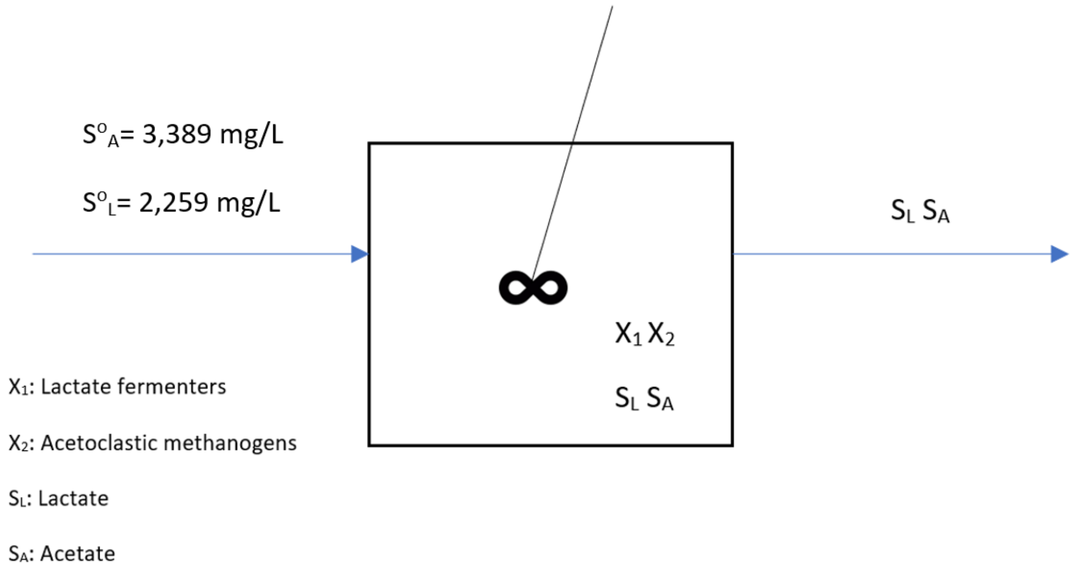

Figure 7-Anaerobic CSTR

As lactate is being consumed, acetate is produced and is being added to the current acetate concentration in the reactor. From the overall lactate fermentation net reaction, we have that $0.038\,mol \times 89\frac{g}{mol} = 3.38\,g\ lactate \rightarrow 0.116\,mol \times 59\frac{g}{mol} = 6.84\,g\ acetate$. So, for each gram of lactate consumed, 2.02 g of acetate are produced. So, for any $\theta_x \geq 5$ d, the amount of acetate produced form lactate fermentation is given by:

$$Acetate\ production_{\theta_x} = 2.02\frac{g\ acetate}{g\ lactate} \times \Delta S_L\,, \qquad \Delta S_L = S_L^o - S_{L,\theta_x}$$

The acetate and lactate effluent concentrations were plotted against the solids residence time (SRT) for the anaerobic CSTR (90 km buffer case) (figures 8 & 9). Acetate production from lactate fermentation is also plotted in figure 8.

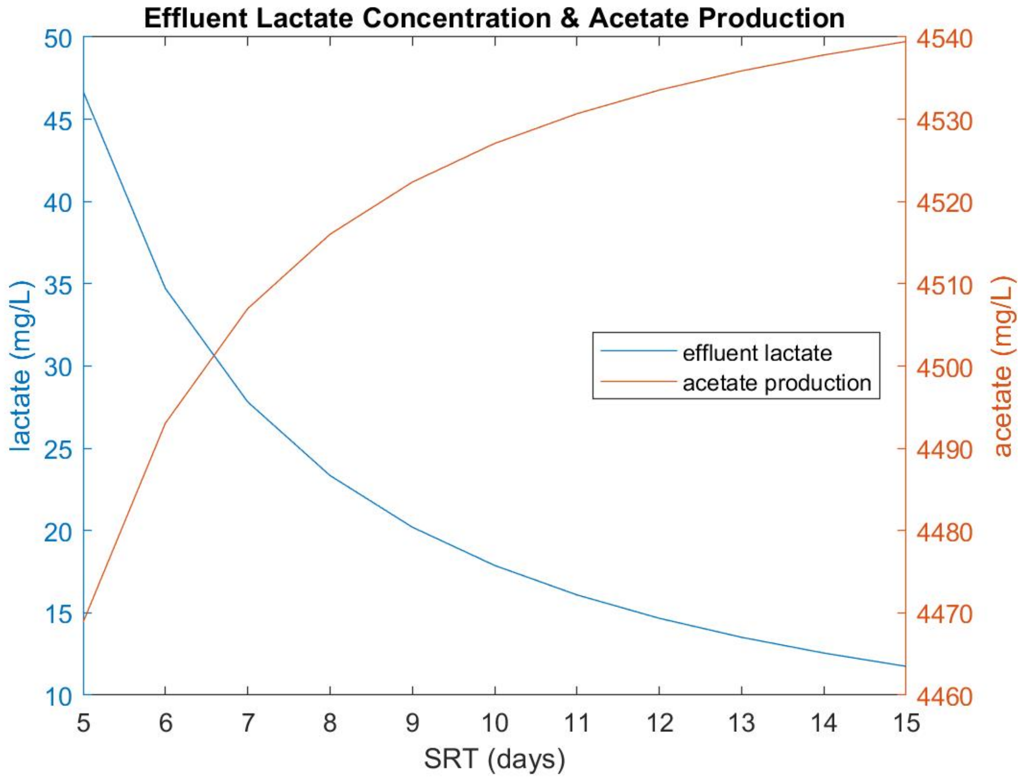

Figure 8- Effluent Lactate Concentration & Acetate Production (CSTR)

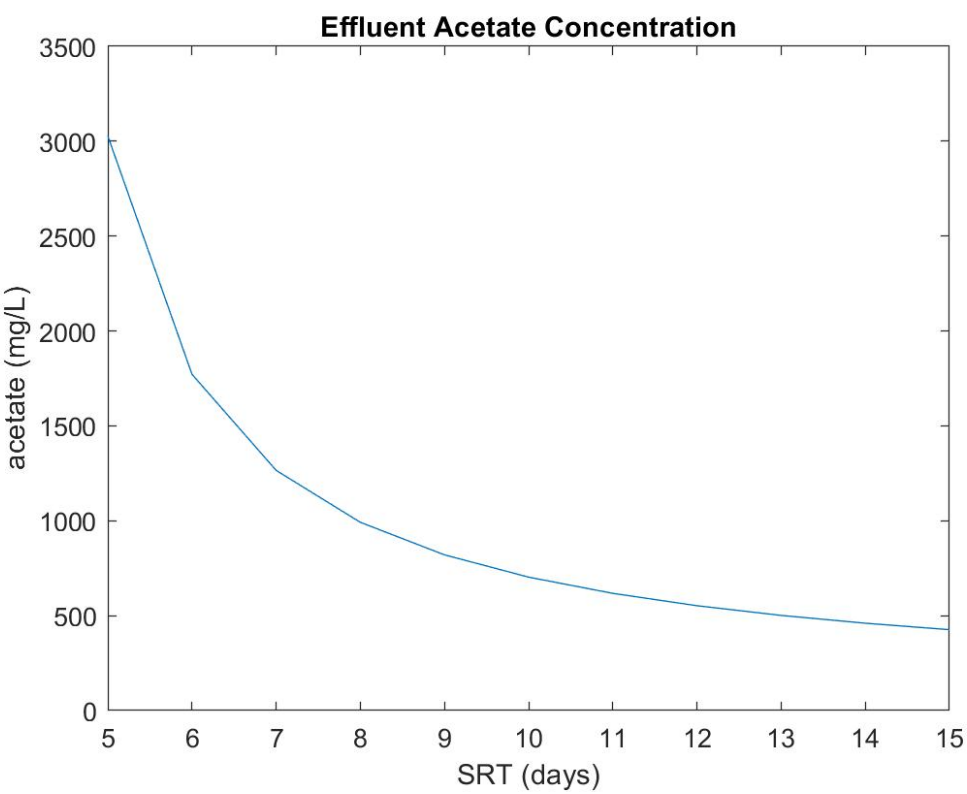

Figure 9-Effluent Acetate Concentration (CSTR)

The total amount of BOD consumed is then given by:

$$\Delta BOD = \Delta S_A + 2.02 \times \Delta S_L = (S_A^o - S_A) + 2.02 \times (S_L^o - S_L)$$

The amount of digested BOD with solids residence time is plotted in the figure below.

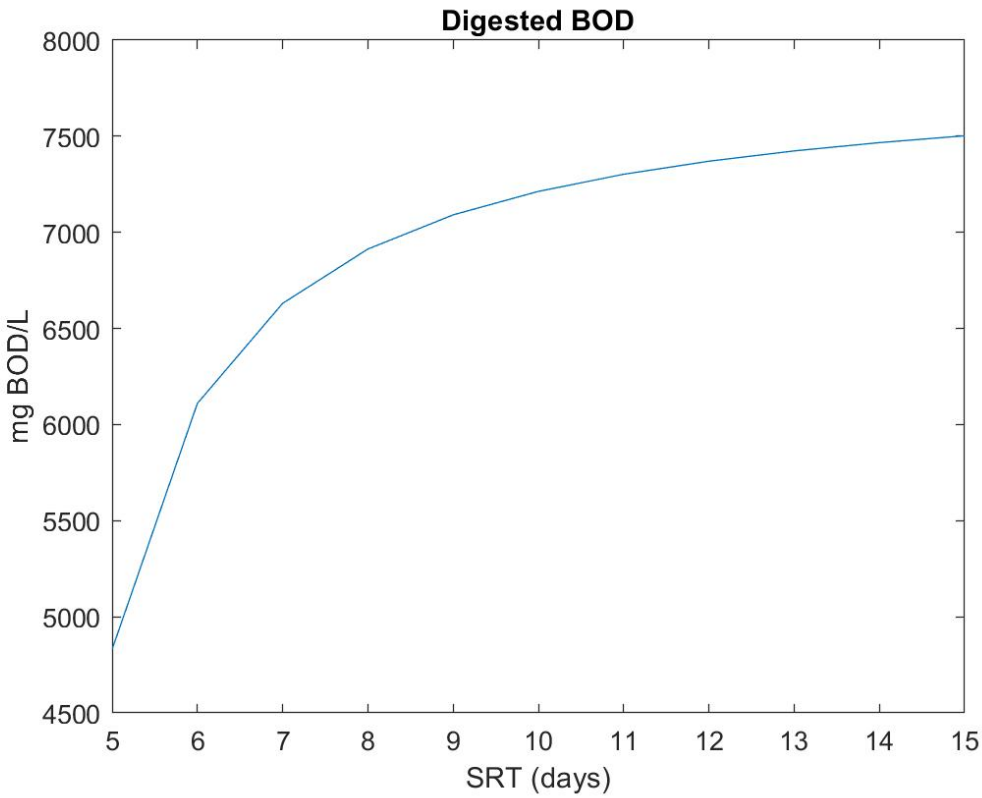

Figure 10-Digested BOD vs SRT (CSTR)

The methane generation is then computed for each SRT (table 12).

Table 12-Secondary Methane generation vs SRT for each digester (CSTR)

FID\SRT (days)	5	6	7	8	9	10	11	12	13	14	15
0	224,138	283,733	308,115	321,474	329,958	335,856	340,216	**343,585**	346,277	348,486	350,338
1	408,365	516,943	561,366	585,705	601,163	611,909	619,851	**625,989**	630,894	634,919	638,293
2	372,117	471,058	511,537	533,716	547,802	557,594	564,832	**570,424**	574,894	578,562	581,636
4	418,295	529,513	575,016	599,946	615,780	626,787	634,923	**641,210**	646,234	650,357	653,813
6	368,261	466,177	506,236	528,185	542,125	551,816	558,978	**564,513**	568,936	572,566	575,609
7	332,495	420,901	457,070	476,887	489,474	498,223	504,690	**509,687**	513,681	516,958	519,705
8	436,611	552,700	600,195	626,217	642,744	654,234	662,726	**669,288**	674,532	678,836	682,443
9	1,492,518	1,889,358	2,051,715	2,140,670	2,197,167	2,236,442	2,265,472	**2,287,903**	2,305,830	2,320,541	2,332,873
10	948,803	1,201,076	1,304,288	1,360,837	1,396,752	1,421,720	1,440,174	**1,454,434**	1,465,830	1,475,182	1,483,021
11	655,543	829,843	901,154	940,225	965,039	982,290	995,040	**1,004,892**	1,012,766	1,019,228	1,024,644
12	2,305,103	2,917,997	3,168,748	3,306,134	3,393,390	3,454,048	3,498,883	**3,533,527**	3,561,214	3,583,934	3,602,979
13	442,010	559,534	607,616	633,960	650,692	662,323	670,920	**677,563**	682,873	687,229	690,881
14	711,939	901,234	978,679	1,021,112	1,048,061	1,066,795	1,080,643	**1,091,343**	1,099,894	1,106,911	1,112,793
15	1,068,150	1,352,156	1,468,351	1,532,013	1,572,446	1,600,554	1,621,330	**1,637,383**	1,650,213	1,660,741	1,669,567
16	547,186	692,675	752,198	784,811	805,524	819,923	830,566	**838,790**	845,362	850,755	855,276
17	417,716	528,781	574,220	599,117	614,929	625,921	634,045	**640,323**	645,341	649,458	652,909
18	688,610	871,701	946,609	987,651	1,013,717	1,031,838	1,045,231	**1,055,580**	1,063,851	1,070,639	1,076,328
19	477,197	604,077	655,987	684,428	702,492	715,049	724,331	**731,503**	737,234	741,938	745,880
20	1,082,900	1,370,828	1,488,627	1,553,168	1,594,159	1,622,656	1,643,718	**1,659,993**	1,673,000	1,683,674	1,692,621
21	2,171,584	2,748,977	2,985,204	3,114,632	3,196,834	3,253,979	3,296,217	**3,328,854**	3,354,937	3,376,341	3,394,284
22	563,093	712,811	774,065	807,625	828,940	843,758	854,710	**863,173**	869,936	875,486	880,139
23	831,094	1,052,070	1,142,477	1,192,011	1,223,471	1,245,341	1,261,506	**1,273,997**	1,283,979	1,292,171	1,299,038
24	215,462	272,750	296,188	309,030	317,186	322,856	327,046	**330,284**	332,872	334,996	336,776
25	1,986,104	2,514,181	2,730,231	2,848,604	2,923,785	2,976,049	3,014,679	**3,044,528**	3,068,384	3,087,960	3,104,370
26	1,771,510	2,242,529	2,435,236	2,540,819	2,607,876	2,654,493	2,688,949	**2,715,574**	2,736,852	2,754,313	2,768,949
27	549,982	696,214	756,042	788,821	809,639	824,112	834,809	**843,075**	849,681	855,102	859,646
28	1,617,553	2,047,638	2,223,597	2,320,004	2,381,234	2,423,800	2,455,261	**2,479,572**	2,499,001	2,514,944	2,528,309
29	634,624	803,361	872,396	910,220	934,243	950,943	963,287	**972,824**	980,447	986,702	991,946
30	1,398,621	1,770,495	1,922,638	2,005,997	2,058,939	2,095,744	2,122,947	**2,143,967**	2,160,766	2,174,552	2,186,108
total	**25,137,583**	**31,821,312**	**34,555,801**	**36,054,018**	**37,005,561**	**37,667,054**	**38,155,982**	**38,533,779**	**38,835,712**	**39,083,480**	**39,291,176**

The bolded column represents the SRT at which the amount of methane generated reaches 95%[5] of its maximum asymptotic value.

[5] =(95,533,779-25,137,583)/(39,291,176-25,137,583)=0.95

5.3.3. UASB kinetics

Kinetic modeling of the UASB depends on its mode of operation. When the system is operated without recycling, the fluid regime has strong plug flow character: concentrations of microorganisms and substrate vary throughout the length of the reactor, with higher substrate concentration at the entrance, resulting in higher rates there. However, the liquid regime of a UASB with effluent recycle resemble that of a CSTR. In fact, effluent recycle (higher bulk velocity) increases mixing throughout the reactor, and results in a more uniform distribution of the concentrations across the cross section and length of the reactor, resembling more the conditions in a CSTR. So, for a UASB without recycle, the substrate concentration is modelled as follows:

$$\frac{1}{\theta_x} = \frac{Y\hat{q}(S_o - S)}{(S_o - S) + eK} - b$$

Where $e = (1 + r)\ln\left(\frac{r \times S + S_o}{(1+r) \times S}\right)$

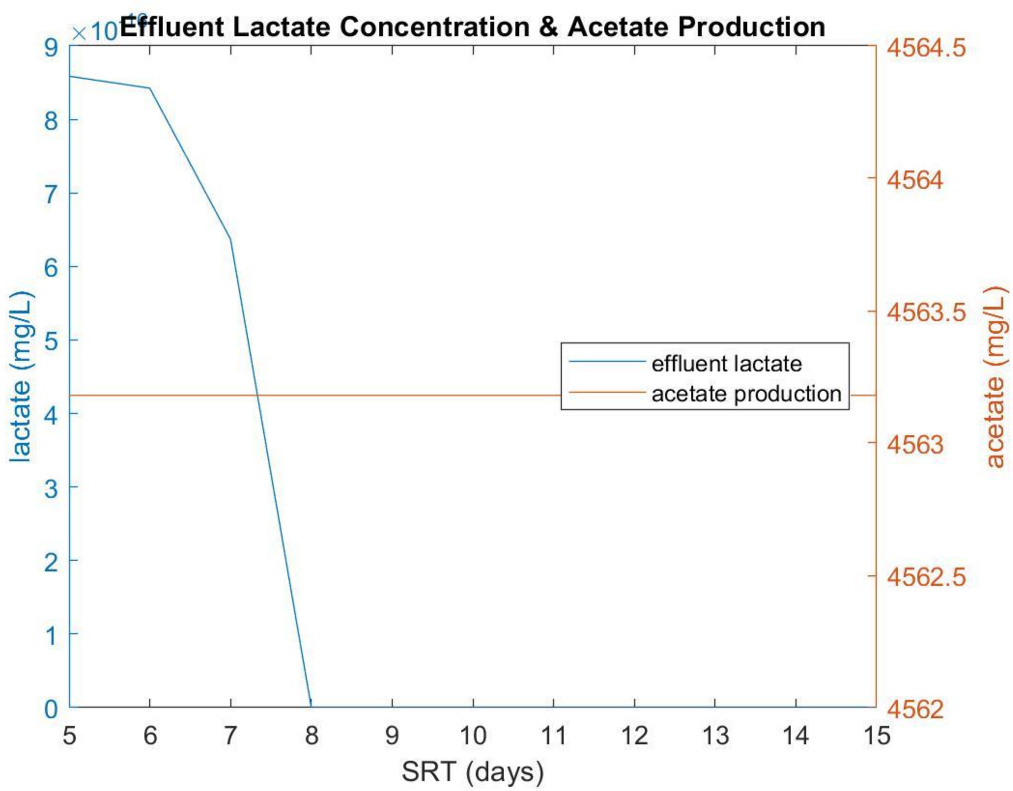

Figure 11- Effluent Lactate Concentration & Acetate Production (UASB)

Note how acetate production is constant for every SRT. Since the UASB is a high rate reactor, as soon as lactate enters the reactor, it is all consumed and converted into acetate. The scale on the y axis (left) shows that for every SRT, the effluent lactate concentration (and therein the concentration inside the reactor) is almost equal to zero[6], meaning all lactate has been consumed. Since the influent lactate is constant, then, acetate production will be constant.

[6] The numbers on the left y axis scale are multiple of 10^{-16}

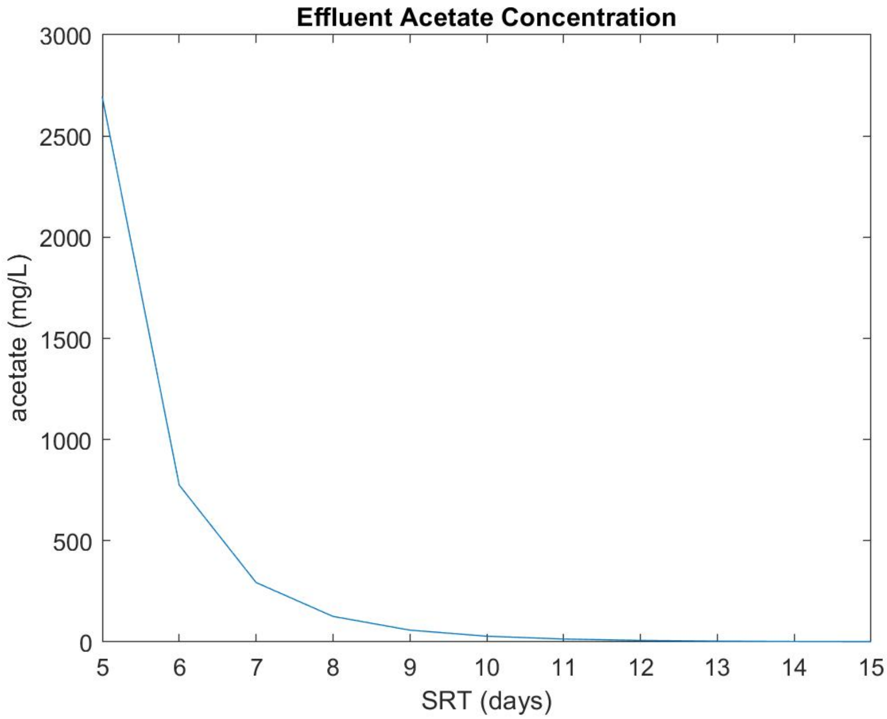

Figure 12-Effluent Acetate Concentration (UASB)

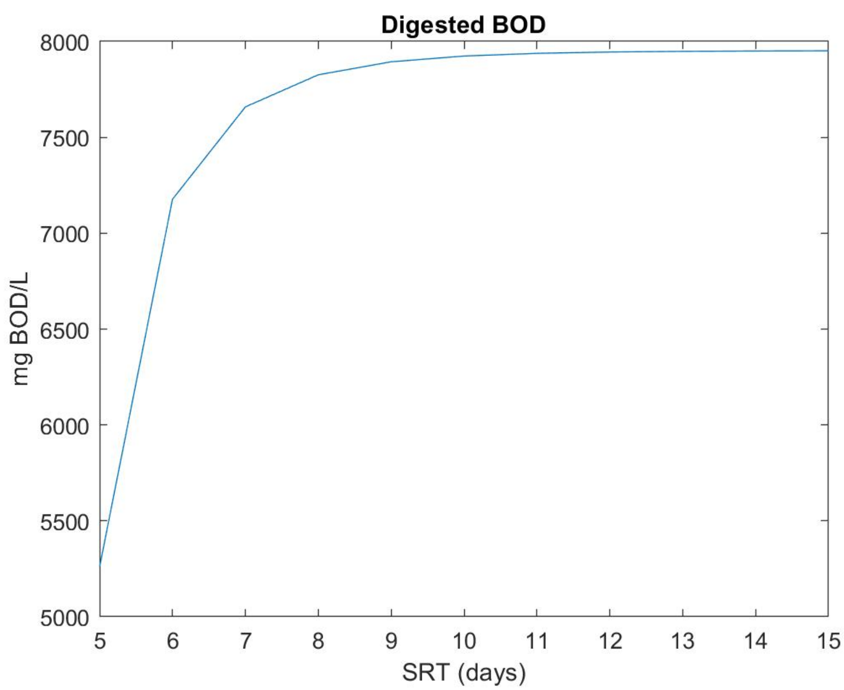

Figure 13-Digested BOD vs SRT (UASB)

Figures 12 and 13 show the effluent acetate and digested BOD concentration as a function of SRT. The methane generated from the UASB at different given SRTs is given in the table 13 below (90km buffer case):

Table 13-Secondary Methane generation vs SRT for each digester (UASB)

FID\SRT (days)	5	6	7	8	9	10	11	12	13	14	15
0	244,051	333,270	355,889	**363,915**	367,312	368,946	369,831	370,373	370,750	371,042	371,289
1	444,646	607,197	648,407	**663,029**	669,218	672,195	673,808	674,796	675,483	676,015	676,464
2	405,178	553,300	590,852	**604,176**	609,816	612,529	613,998	614,900	615,525	616,010	616,419
4	455,458	621,961	664,173	**679,151**	685,490	688,540	690,191	691,204	691,908	692,453	692,913
6	400,979	547,567	584,729	**597,916**	603,497	606,181	607,636	608,528	609,147	609,627	610,031
7	362,036	494,387	527,940	**539,846**	544,885	547,309	548,622	549,427	549,986	550,420	550,785
8	475,402	649,196	693,256	**708,890**	715,507	718,690	720,414	721,471	722,206	722,775	723,254
9	1,625,120	2,219,222	2,369,838	**2,423,280**	2,445,900	2,456,780	2,462,674	2,466,289	2,468,799	2,470,744	2,472,384
10	1,033,098	1,410,773	1,506,520	**1,540,493**	1,554,873	1,561,790	1,565,537	1,567,834	1,569,430	1,570,667	1,571,709
11	713,785	974,726	1,040,880	**1,064,352**	1,074,288	1,079,066	1,081,655	1,083,243	1,084,345	1,085,199	1,085,920
12	2,509,898	3,427,453	3,660,070	**3,742,607**	3,777,543	3,794,347	3,803,450	3,809,032	3,812,908	3,815,913	3,818,445
13	481,280	657,224	701,828	**717,655**	724,354	727,576	729,322	730,392	731,136	731,712	732,197
14	775,191	1,058,581	1,130,426	**1,155,918**	1,166,708	1,171,898	1,174,709	1,176,433	1,177,631	1,178,559	1,179,341
15	1,163,049	1,588,230	1,696,022	**1,734,268**	1,750,457	1,758,244	1,762,462	1,765,048	1,766,845	1,768,237	1,769,410
16	595,800	813,610	868,828	**888,421**	896,714	900,703	902,864	904,189	905,109	905,822	906,424
17	454,828	621,101	663,255	**678,212**	684,542	687,587	689,237	690,249	690,951	691,495	691,954
18	749,789	1,023,893	1,093,383	**1,118,039**	1,128,476	1,133,496	1,136,215	1,137,883	1,139,041	1,139,938	1,140,695
19	519,593	709,543	757,699	**774,786**	782,018	785,497	787,381	788,537	789,339	789,961	790,486
20	1,179,109	1,610,162	1,719,441	**1,758,216**	1,774,628	1,782,523	1,786,799	1,789,421	1,791,242	1,792,654	1,793,844
21	2,364,517	3,228,924	3,448,067	**3,525,823**	3,558,736	3,574,566	3,583,142	3,588,401	3,592,052	3,594,883	3,597,269
22	613,120	837,261	894,085	**914,247**	922,782	926,886	929,110	930,474	931,421	932,154	932,773
23	904,932	1,235,752	1,319,621	**1,349,380**	1,361,976	1,368,034	1,371,316	1,373,329	1,374,726	1,375,810	1,376,723
24	234,604	320,370	342,113	**349,828**	353,093	354,664	355,515	356,036	356,399	356,680	356,916
25	2,162,557	2,953,134	3,153,559	**3,224,674**	3,254,776	3,269,254	3,277,097	3,281,907	3,285,247	3,287,835	3,290,017
26	1,928,898	2,634,054	2,812,824	**2,876,256**	2,903,105	2,916,018	2,923,014	2,927,304	2,930,283	2,932,592	2,934,538
27	598,844	817,767	873,267	**892,960**	901,296	905,305	907,477	908,809	909,734	910,450	911,055
28	1,761,264	2,405,137	2,568,371	**2,626,289**	2,650,805	2,662,596	2,668,984	2,672,901	2,675,621	2,677,730	2,679,507
29	691,006	943,621	1,007,663	**1,030,387**	1,040,005	1,044,632	1,047,138	1,048,675	1,049,742	1,050,569	1,051,266
30	1,522,880	2,079,607	2,220,747	**2,270,827**	2,292,024	2,302,220	2,307,743	2,311,130	2,313,482	2,315,305	2,316,842
Total	**27,370,911**	**37,377,025**	**39,913,754**	**40,813,840**	**41,194,826**	**41,378,073**	**41,477,342**	**41,538,215**	**41,580,487**	**41,613,251**	**41,640,869**

Again, the bolded column represents the SRT at which methane generation reaches around 95% of its asymptotic value. Note that for the same SRT, a UASB generates more methane compared to a CSTR. As such the UASB is more efficient at producing methane at much quicker times. Therefore, the UASB is the optimal anaerobic system.

6. Energy potential

Table 14 below is a summary of the different bioproducts generated in the bioenergy system.

Table 14-Summary of the different bioproducts generated for each centralized cluster

		Methane AD1 (L/d)	**HTL Products (kg/d)**			**Methane AD2 (L/d)**	
FID	Bioplant	CSTR (SRT= 20 days)	CO2 (kg/d)	biocrude (kg/d)	hydro char (kg/d)	UASB (SRT=8 days)	CSTR (SRT=12 days)
0	AURORA RIDGE DAIRY, LLC	4,605,862	1,184	876	645	363,915	343,585
1	FESSENDEN DAIRY, LLC	8,391,584	2,157	1,595	1,176	663,029	625,989
2	PATTERSON FARMS	7,646,722	1,965	1,454	1,072	604,176	570,424
4	SPRUCE HAVEN FARM LP	8,595,629	2,209	1,634	1,204	679,151	641,210
6	THE ROACH FARM	7,567,482	1,945	1,439	1,060	597,916	564,513
7	WILLET DAIRY LLC	6,832,525	1,756	1,299	957	539,846	509,687
8	CAYUGA REGUONAL BIOENERGY ENTEPRISE	8,972,022	2,306	1,706	1,257	708,890	669,288
9	NEW HOPE VIEW FARM LLC	30,670,091	7,882	5,830	4,298	2,423,280	2,287,903
10	LAMB FARMS, INC. (FARM #1)	19,497,161	5,011	3,706	2,732	1,540,493	1,454,434
11	ZUBER FARMS	13,470,910	3,462	2,561	1,888	1,064,352	1,004,892
12	SHELAND FARMS	47,368,076	12,174	9,004	6,638	3,742,607	3,533,527
13	COYNE FARMS, INC.	9,082,959	2,334	1,727	1,273	717,655	677,563
14	NOBLEHURST FARMS INC.	14,629,804	3,760	2,781	2,050	1,155,918	1,091,343
15	CREEK ACRES FARM	21,949,658	5,641	4,173	3,076	1,734,268	1,637,383
16	TWIN BIRCH DAIRY, LLC	11,244,247	2,890	2,137	1,576	888,421	838,790
17	HALF DUTCH FARM	8,583,743	2,206	1,632	1,203	678,212	640,323
18	LAWNHURST FARMS	14,150,398	3,637	2,690	1,983	1,118,039	1,055,580
19	WILL-O-CREST FARMS	9,806,030	2,520	1,864	1,374	774,786	731,503
20	WAGNER FARMS	22,252,754	5,719	4,230	3,118	1,758,216	1,659,993
21	GREENWOOD DAIRY FARM LLC	44,624,369	11,468	8,483	6,253	3,525,823	3,328,854
22	AA DAIRY	11,571,115	2,974	2,200	1,621	914,247	863,173
23	WALKER FARMS LLC	17,078,340	4,389	3,246	2,393	1,349,380	1,273,997
24	EL-VI FARMS	4,427,571	1,138	842	620	349,828	330,284
25	BOXLER DAIRY FARM	40,812,894	10,489	7,758	5,719	3,224,674	3,044,528
26	EMERLING FARMS LLC	36,403,152	9,356	6,920	5,101	2,876,256	2,715,574
27	SUNNY KNOLL FARMS	11,301,697	2,905	2,148	1,584	892,960	843,075
28	SWISS VALLEY FARMS LLC	33,239,469	8,543	6,319	4,658	2,626,289	2,479,572
29	SYNERGY, LLC	13,041,029	3,352	2,479	1,827	1,030,387	972,824
30	MORRISVILLE STATE COLLEGE(EQUINE FACILITY)	28,740,582	7,386	5,463	4,027	2,270,827	2,143,967
	total	**516,557,874**	**132,755**	**98,195**	**72,384**	**40,813,840**	**38,533,779**

The entire centralized bioenergy system can potentially generate 560 million liters of methane per day (AD1 and AD2-UASB). Methane has an energy density of **36.4 KJ/L**[7] **(55.5 MJ/Kg)**. This is equivalent to 20 trillion Joules of primary energy source, or 6.9 trillion Btu per year. This primary source of energy can be used to generate electricity. 130 tons of carbon dioxide are emitted daily by the HTL process.

Using the elemental composition of bio-crude (Posmanik et al.), the high heating value of bio-crude was calculated to be **33.3 MJ/kg** (Dulong formula). As a comparison, the HHV of manure is **13.3 MJ/kg** (Posmanik et al.), meaning the biogas and bio crude portion are much more carbon/energy dense than manure. The integrated AD/HTL process directs much of the carbon in manure into the biocrude and biogas fractions, which are more carbon dense products.

Using the HHV of biocrude, **3.3 million MJ** of energy can be generated daily from the total bio-crude produced. Biocrude oil can be sold to refineries for further processing into useful fuels such as diesel or gasoline.

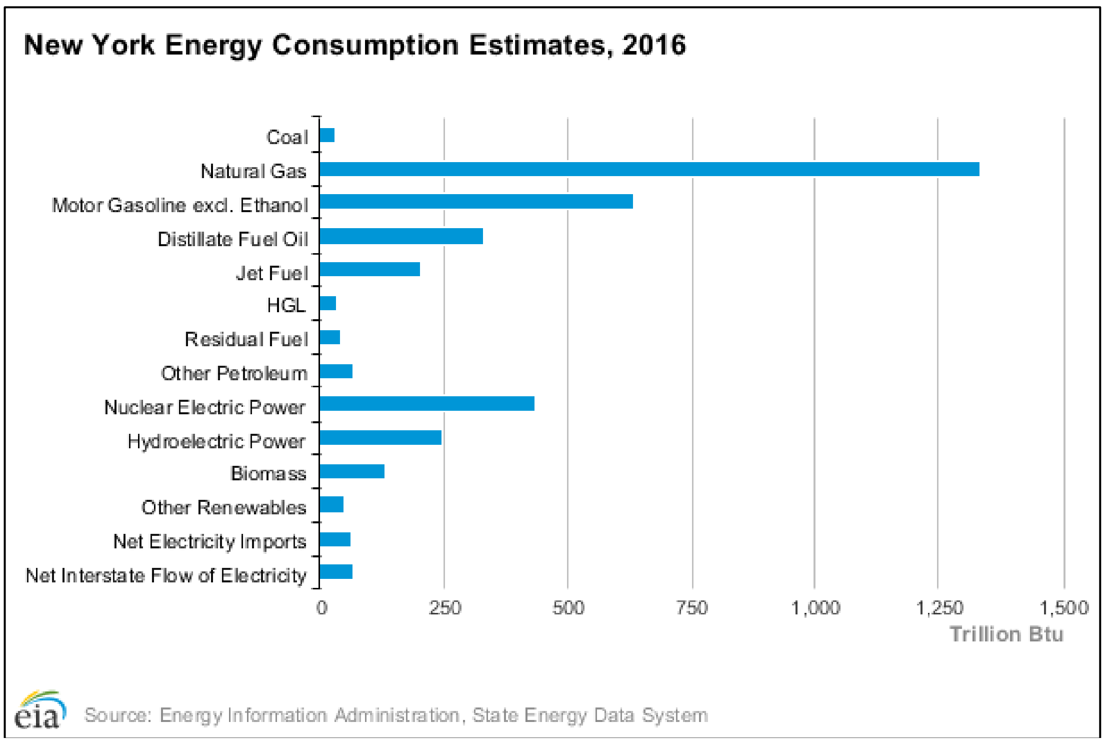

Figure 14- New York Energy Consumption Estimates, 2016 (Source: EIA, state energy data system)

To put things into perspective, the amount of energy consumed in New York state from biomass resources in 2016 is estimated at 170 trillion Btu (figure 14), which is significantly greater than the 7 trillion Btu/year embedded in the methane generated.

[7] Methane volumetric density 0.656 kg/m^3. Methane energy density 55.5 MJ/kg. Volumetric density*energy density =0.656*55.5=36.4 MJ/m^3. To convert to KJ/L we multiply by 10^3 MJ/KJ and by 10^{-3} m^3/L.

Around 18 million liters/d (or kg) of manure are generated by the 407 farms in the 90km analysis. Using HHV of manure, **235 million MJ** of energy is embedded in the manure.

Overall, the energy recovery in the different energy products is

$$ER = \frac{HHV_{energy\ products}}{HHV_{feed}} = \frac{20\text{ million MJ} + 3.3\text{ million MJ}}{235\ million\ MJ} \approx \mathbf{10}\%$$

So, 10% of the energy in manure is recovered in the methane and biocrude fractions produced. The methane produced from the digesters can be used produce electricity or heat, resulting in significant reductions in greenhouse gas emissions (Gooch et al.). In fact, using methane as an energy source to fuel on-site engine-generator sets is the most common use of biogas today (Gooch et al.). Heat can be used to maintain digester temperature at optimal levels, thus reducing electric heating needs. Electricity can be either used to power biorefinery operations or can be transmitted into the grid. Hydrogen sulfide gas (H_2S) is an important component of AD biogas and is very corrosive. In this report, we will assume that H_2S is negligible, and thus its effect on engine performance will not be discussed. Hydro-char, a nutrient rich product, can be used as a soil amendment, and can be given back to farmers at no cost, eliminating their need to purchase synthetic fertilizers.

7. Economic analysis

An economic analysis will be performed in order to evaluate the feasibility of the bioenergy project. Project-related costs and revenues streams will be determined and a discounted cash flow analysis will ensue to determine the overall profitability of the project. The DCF analysis will be performed under two cases: 15 and 90 km buffer radius.

7.1. Transportation costs

7.1.1. Project owned fleet

An analysis of a project-owned truck fleet (not shown in this paper) showed very high transportation costs. It was determined that a contracted manure trucking fleet might be more appropriate given our scenario.

7.1.2. Contracted fleet scenario

Method #1 (cost per gallon based)

Cost data from local septic companies were provided for manure transport cost estimation. Mark Thomas septic services charge $270 per 1,000 gal, serving the Tompkins county area. The Drain brain, based in Ithaca, charges $243 per 1,000 gal. Their fleet comprises of 3,500 and 5,000 gal tanker trucks and do on average 4 pick-ups per day. Clean Earth septic services LLC charge $250 per 1,000 gal, and travel on average 6 to 7 miles (~10-11 km) per trip. These rates comprise the fuel, labor and truck maintenance costs.

Taking the average of the three, we get around $255 per 1,000 gal. This rate applies to a driving distance of 10.5 km. Adjusting this rate by the individual distance between each farm and the digester, we can calculate the transportation costs. Again, the annual costs proved to be too prohibitive (not shown).

Method#2 (cost per hour based)

Based on an hourly rate of $82/hr (Shue Trucking), we calculate the number of truck trips per year as well as the number of hours spent per trip. The number of annual truck trips is calculated by dividing the yearly volume of wet manure by the truck volume (6,000 gal truck).

$$\#\frac{trips}{year} = \frac{Annual\ manure\ volume}{truck\ size}$$

The hours spent per trip is determined by the loading/unloading time and trucking time. The loading unloading time is assumed to be 2h. Trucking time is calculated by dividing the distance travelled by the truck average speed (assumed at 40 mph). The trucking time is significantly less than that, so that the total time spent per trip is actually skewed to the loading/unloading time.

$$\#\frac{hrs}{trip} = (load/unload\ time) + \frac{distance\ traveled}{speed}$$

The total annual cost is then given by:

$$Annual\ costs = \frac{\$82}{hr} \times \frac{hrs}{trip} \times \frac{trip}{yr}$$

The total annual transportation cost for the 90 km buffer case is determined to be **$48 million**.

Another way to determine the loading/unloading time is by using the pump flow rate. Using a 500 mpg truck mounted pump, the loading time may be estimated by:

$$\frac{6000\ gal}{500\ gpm} = 12\ min$$

Accounting for loading and unloading, and a 40 min leeway time (20 min each trip), the loading/unloading time is given to be 12+12+40=64 minutes. The total time spent per trip is calculated by adding the loading/unloading time and the trucking time. The new total transportation cost is then determined to be **$29 million.** To be more conservative, the highest cost will be used in our financial analysis.

7.2. Reactors capital and operational costs:

All centralized facilities have two anaerobic digesters and a HTL reactor; a primary AD to treat the raw manure, an HTL reactor to treat the manure digestate effluent from the primary digester and a secondary, high-rate AD to treat the HTL aqueous phase effluent. The primary ADs are already in place, so that only costs associated with HTL reactors and the secondary ADs will be considered in the financial analysis.

7.2.1. Anaerobic Digesters

To estimate the capital and operational costs associated with the anaerobic digester, we started by using AD costs data from the Cornell Manure Management database. Data on annual and operational costs, along with data on digester capacity and loading rates were collected for each anaerobic digester. Capital and operational costs were then plotted against digester loading rate and capacity. Using Excel's regression tools, a trendline that best fits the data was added. The capital and operational cost data were best modeled using exponential and second-degree polynomial functions respectively. The plots along with their trendlines are displayed in figures 15, 16 and 17.

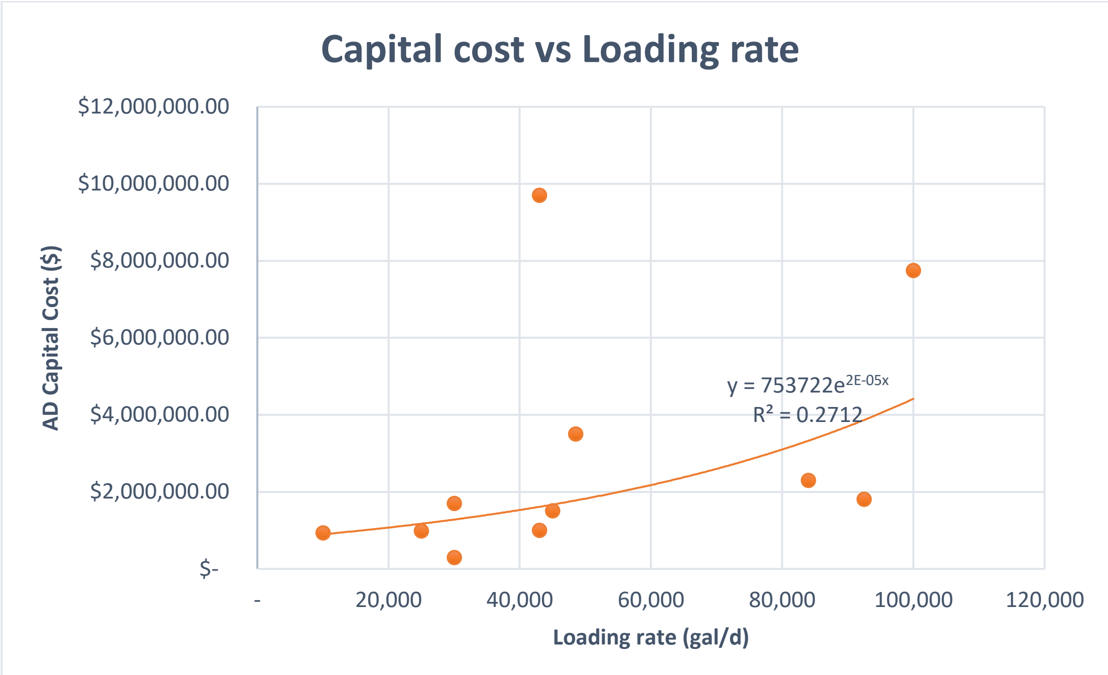

Figure 15-AD Capital Cost vs Loading Rate

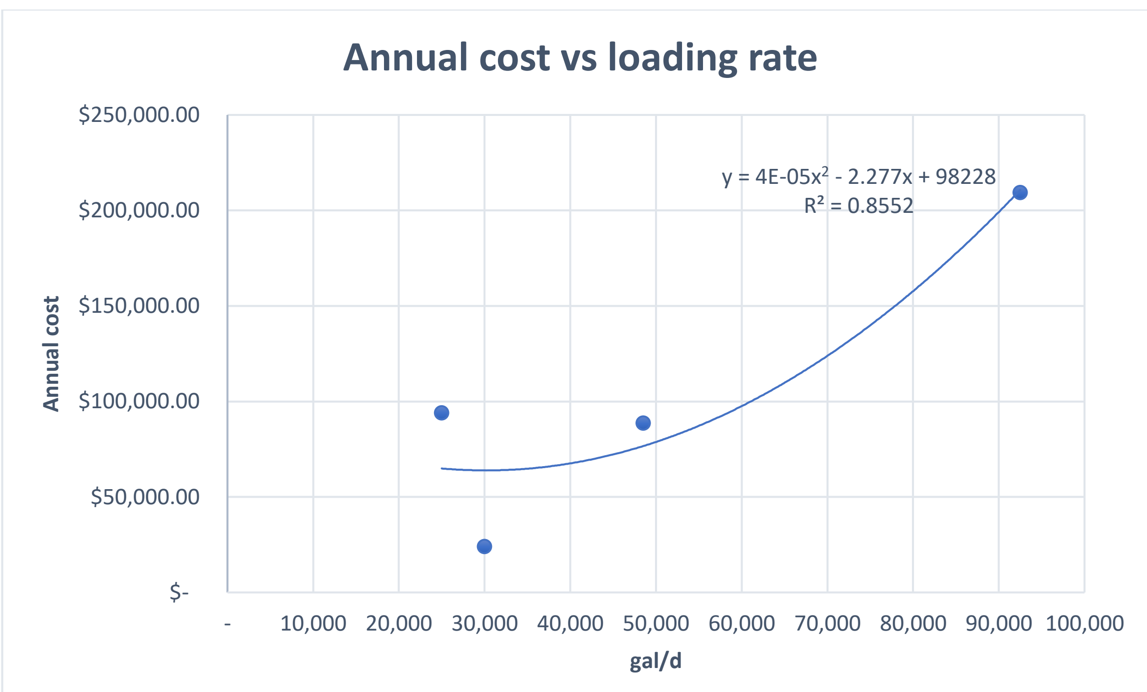

Figure 16-AD Annual Cost vs Loading rate

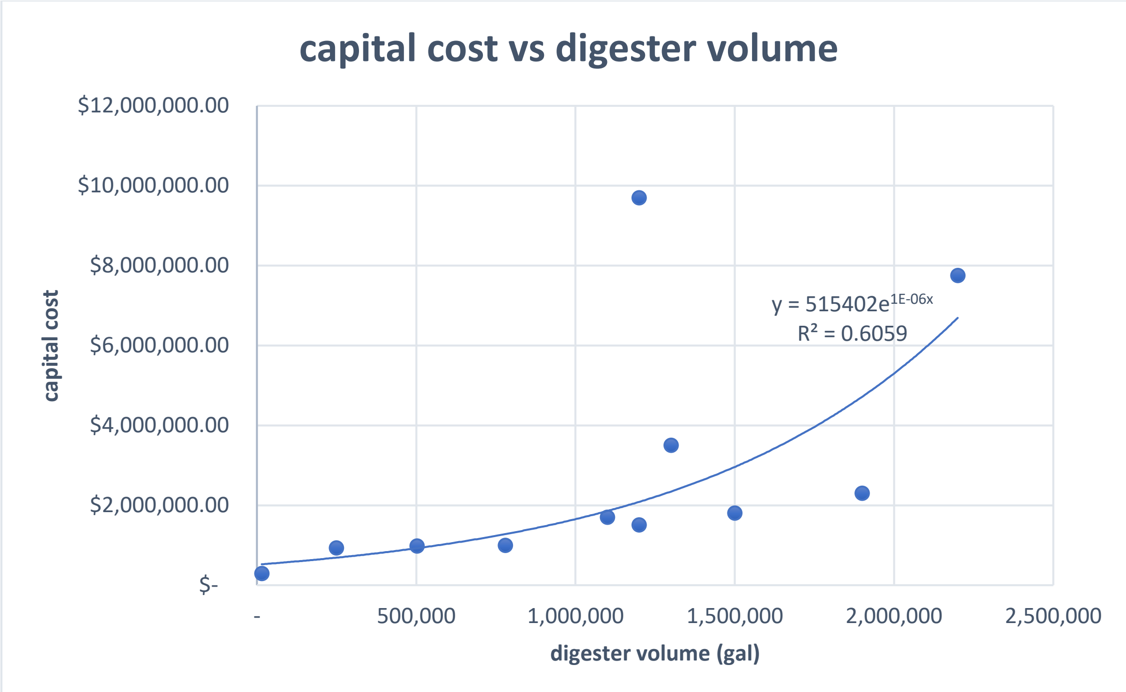

Figure 17-Capital cost vs digester Volume

Knowing the digester loading rates and capacities[8], and using the trendline equations, the annual operating and capital costs associated with each digester can be determined. However, the incomplete availability of capital costs, annual costs, loading rates and capacity data for all digesters in the database (some digesters have missing information) undermines the accuracy of the above curves, resulting in different CC and O&M estimates.

The Cornell manure management database will be used to illustrate the economies of scale (EOS) associated with increased system sizes/scales, an important concept that is vital to the economic success of this bioenergy development project. Using the same database, we calculate the cost per unit AD capacity ($/gal). We then take the log of that value and plot it against the log of the AD capacity and get the following (figure 18).

[8] AD size is calculated by multiplying the loading rate by the SRT (=HRT (no recycling)). SRT for the UASB is given to be 8 days (see earlier sections).

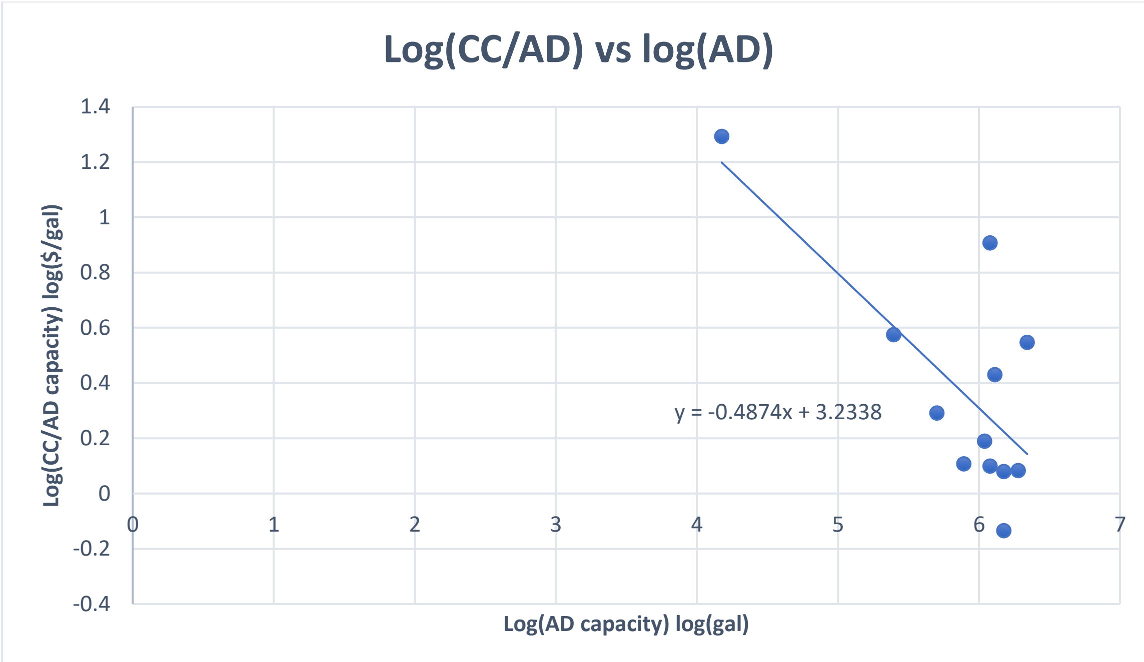

Figure 18-AD economies of scale: capital cost per unit size vs AD size

The negative slope indicates that the price per unit AD capacity (AD size) decreases with increasing AD capacity. This relationship illustrates the economies of scale that come into play with increasing production scales. This concept of EOS is also true for every type of system that could be scaled up, including HTL systems.

The AD capital and O&M costs will then be estimated using literature data on European digesters (reference: J. Usack's survey of the literature for AD costs). Sanscrantier et al. and Yirdoe et al. have reported AD capital cost curves for AD processing dairy wastes and other mixed feedstocks that give similar cost ranges. The capital cost curve for AD facilities based on a survey of the literature for centralized AD facilities processing mixed feedstock (manure, food wastes, etc…) including the cost of CHP engine and connection to the grid, but not the cost of land is (Sanscartier et al., 2012):

$$CC(AD) = 706{,}000 \times V(waste)^{0.6}$$

where $CC(AD)$ is the capital cost of the facility ($) and $V(waste)$ the volume of degradable waste treated per day (m^3/d). The secondary digester is processing the aqueous phase produced from the HTL process, and thus, the degradable waste consists of acetic and lactic acid. Knowing their relative amount in the aqueous phase as well as their density, $V(waste)$ can be calculated by:

$$V(waste) = V_{lactic} + V_{acetic} = \frac{m_{lactic}}{\rho_{lactic}} + \frac{m_{acetic}}{\rho_{acetic}}$$

where V_{acetic}, V_{lactic}, m_{acetic}, m_{lactic}, ρ_{acetic} and ρ_{lactic} represent the volumes (L/d), mass (kg/d) and densities (kg/L) of acetic and lactic acid in the aqueous phase stream respectively.

The maintenance costs of the AD facility, including disposal of the residues, digestate, full time staff and utilities on-site is 3% of the capital cost (Sanscartier et al., 2012) while the operational costs are around 10-12% of the capital costs, with a range of 4-15% (Smyth et al., 2010). The secondary AD capital and annual O&M costs for each centralized facility (FID) are shown in table 15.

Table 15-AD capital, operational & maintenance costs

	AD2 influent				**Sanscartier et al., 2012**		**Smyth et al., 2010**
FID	Total (L/d or kg/d)	m_{acetic} (kg)	m_{lactic} (kg)	$V(waste)$ (m3/d)	AD facility capital cost	maintenance cost	operational cost
0	139,561	455	303	0.685407631	$ 562,826	$ 16,885	$ 61,911
1	254,271	829	553	1.248768485	$ 806,666	$ 24,200	$ 88,733
2	231,701	756	504	1.137924068	$ 762,909	$ 22,887	$ 83,920
4	260,454	849	566	1.27913278	$ 818,378	$ 24,551	$ 90,022
6	229,300	748	498	1.126132108	$ 758,156	$ 22,745	$ 83,397
7	207,030	675	450	1.016761686	$ 713,077	$ 21,392	$ 78,438
8	271,859	887	591	1.335144586	$ 839,695	$ 25,191	$ 92,366
9	929,326	3030	2020	4.564077828	$ 1,755,563	$ 52,667	$ 193,112
10	590,778	1926	1284	2.901411574	$ 1,337,736	$ 40,132	$ 147,151
11	408,178	1331	887	2.004633073	$ 1,071,583	$ 32,147	$ 117,874
12	1,435,287	4680	3120	7.048938441	$ 2,278,657	$ 68,360	$ 250,652
13	275,220	897	598	1.351653329	$ 845,909	$ 25,377	$ 93,050
14	443,294	1446	964	2.177090477	$ 1,125,980	$ 33,779	$ 123,858
15	665,091	2169	1446	3.266372712	$ 1,436,297	$ 43,089	$ 157,993
16	340,709	1111	741	1.673279018	$ 961,492	$ 28,845	$ 105,764
17	260,094	848	565	1.277363986	$ 817,699	$ 24,531	$ 89,947
18	428,767	1398	932	2.105749123	$ 1,103,694	$ 33,111	$ 121,406
19	297,130	969	646	1.459254957	$ 885,693	$ 26,571	$ 97,426
20	674,275	2199	1466	3.311476957	$ 1,448,164	$ 43,445	$ 159,298
21	1,352,151	4409	2939	6.640641852	$ 2,198,522	$ 65,956	$241,837
22	350,613	1143	762	1.72192085	$ 978,166	$ 29,345	$ 107,598
23	517,486	1687	1125	2.541462017	$ 1,235,534	$ 37,066	$ 135,909
24	134,159	437	292	0.658875723	$ 549,651	$16,490	$ 60,462
25	1,236,660	4033	2688	6.073448612	$ 2,083,847	$ 62,515	$ 229,223
26	1,103,042	3597	2398	5.41722608	$ 1,945,678	$ 58,370	$ 214,025
27	342,450	1117	744	1.681828188	$ 964,437	$ 28,933	$ 106,088
28	1,007,180	3284	2190	4.946432107	$ 1,842,383	$ 55,271	$ 202,662
29	395,153	1289	859	1.940661694	$ 1,050,932	$ 31,528	$ 115,603
30	870,861	2840	1893	4.27694362	$ 1,688,437	$ 50,653	$185,728
				Total CC	**$ 34,867,760**	$ 1,046,033	$3,835,454
						Total O/M	**$4,881,486**

The total capital and annual O&M costs are therefore \$35 million and \$ 5 million respectively. Note that only costs associated with the secondary digester will be computed since the primary digesters are already in place (those will only be upgraded to have increased capacity).

7.2.2. HTL reactors

The HTL system capital costs consist of the HTL reactor, heat exchangers, product separation and pumping systems. According to Van Doren et al. (2017), the capital cost associated with each of the system components are estimated to be \$956,000, \$1,530,000, \$215,000 and \$991,000 respectively, amounting to a total of \$3,692,000. Note that these figures are based on a 200 kg/hr dry biomass feedstock flow rate. The capital costs associated with each system component were calculated using cost correlations that account for the economies of scale and the sizing of the reactor (Ulrich, 1996; Turton, 1998). The HTL capital costs for the different farms will be estimated using each farm's HTL influent dry flowrate. In order to get more accurate cost estimations, rather than using a linear simple linear scale-up based on the 200 kg/hr flow rate, a non-linear cost function will be used with a scaling factor to account for the economies of scale. Knowing the HTL influent dry flow rates, we can then estimate the capital costs. The capital cost curve for the HTL plant is given to be:

$$\frac{CC(HTL)_x}{CC(HTL)_{200}} = \left(\frac{x}{200}\right)^{0.6}$$

$$CC(HTL)_x = \$3{,}692{,}000 \times \left(\frac{x}{200\ kg/hr}\right)^{0.6}$$

where x is the dry flow rate in kg/hr.

To determine the dry mass flow rate entering the HTL reactor, we first conduct a mass balance around the primary digester (refer to 'Actual methane generation section' and Appendix). We get that anaerobic digestion results in an 8.75% mass/volume reduction. Note that manure and digestate are mainly composed of water so that their densities are assumed to be equal to that of water (1kg=1L).

From mass balances calculations, it is determined that the digestate is around 95% moist. Accounting for the moisture content, the dry digestate inflow (kg/hr) can be computed, and the HTL capital costs can be estimated. The HTL capital cost for FID 0 would be \$5.6 million using the linear cost function (scaling factor =1), and \$4.8 million using a 0.6 power scaling (Tsagkari et al., 2016, US EPA, *Technical Economic Analysis Guide*, 2015, Bauman & Lopatnikov, 2017). This illustrates again the economies of scales that come into play with increased system size, and are better representative of actual costs. In fact, the more mature the technology, the lower the scaling factor. HTL is a relatively new technology, it is complex and has not been widely deployed at commercial scales yet and therefore has high uncertainties when it comes to scaling up. That explains the HTL cost function's high scaling factor (0.6).

According to Doren et al. (2017), the annual operational and maintenance costs for the HTL-AD system consist of electricity and external heat (natural gas) import, labor costs as well as equipment maintenance. The cost of heat and electricity, however, are negligible for an anaerobic digester compared to an HTL system, and most equipment maintenance cost are associated with HTL. We will then assume that the total annual costs as provided by Doren et al. represent only that of HTL. The yearly costs are \$8070, \$5480, \$199,000 and \$399,000 for electricity, heat, equipment maintenance and labor costs respectively, amounting to \$611,550. Again, these numbers are based on a 200 kg/hr of dry biomass, and similarly to the capital costs, a non-linear 0.6 power scale-up cost function will be used to compute the annual O&M costs.

$$\frac{OM(HTL)_x}{OM(HTL)_{200}} = \left(\frac{x}{200}\right)^{0.6}$$

$$OM(HTL)_x = \$611.550 \times \left(\frac{x}{200\ kg/hr}\right)^{0.6}$$

where x is the dry flow rate in kg/hr.

The HTL capital and O&M costs for the entire bioenergy system are shown in table 16:

Table 16-HTL Capital and O&M costs

FID	HTL capital costs (1000's \$)	HTL annual costs (1000's \$)
0	4,762	789
1	6,825	1,130
2	6,455	1,069
4	6,924	1,147
6	6,414	1,062
7	6,033	999
8	7,104	1,177
9	14,853	2,460
10	11,318	1,875
11	9,066	1,502
12	19,278	3,193
13	7,157	1,185
14	9,526	1,578
15	12,152	2,013
16	8,135	1,347
17	6,918	1,146
18	9,338	1,547
19	7,493	1,241
20	12,252	2,029
21	18,600	3,081
22	8,276	1,371
23	10,453	1,731
24	4,650	770

25	17,630	2,920
26	16,461	2,727
27	8,160	1,352
28	15,587	2,582
29	8,891	1,473
30	14,285	2,366
Total	**294,997**	**48,864**

7.3. Revenues

The revenue streams consist of (1) selling biocrude oil to refineries for further processing, (2) selling electricity from methane combustion, and (3) selling hydrochar as a soil amendment. Waste heat from CHP would be used to supply the heating requirements of nearby towns and/or industrial facilities. The annual revenues associated with each of the bioproducts will be determined for each farm, and subsequently the total revenue across the entire bioenergy system. Details about revenue estimation for each bioproduct are shown in the sections below.

7.3.1. Methane electricity and heating generation

To calculate the revenue generated from selling electricity, we first need to determine the amount of energy that is embedded in the methane feedstock. Knowing the heating value and the amount of methane produced, we can calculate the total potential energy embodied in methane. CHP electric and heat efficiencies of 28% and 47% were used to convert methane's heat energy into electricity and heat respectively (U.S. EPA, 2015). Note that the amount of methane produced on each farm consist of methane generated by the primary and secondary digesters. A sample calculation for methane electricity generation (for FID 0) is shown below (1 kwh_e=3.6 MJ_e):

$$\begin{aligned} electrical\ output &= 0.28\frac{J_{electricity}}{J_{heat}} \times 36.4\frac{KJ_{heat}}{L_{methane}} \times 10^{-3}\frac{MJ}{KJ} \times 4{,}969{,}777\ L_{methane} \times \frac{1kWh_e}{3.6MJ_e} \\ &= 14{,}070\ kWh\ per\ day \end{aligned}$$

$$\begin{aligned} thermal\ output &= 0.47\frac{J_{heat\ recovered}}{J_{heat}} 36.4\frac{KJ_{heat}}{L_{methane}} \times 10^{-3}\frac{MJ}{KJ} \times 4{,}969{,}777\ L_{methane} \\ &= 85{,}023\ MJ\ per\ day \end{aligned}$$

The revenues generated by each farm will be computed using an electricity wholesale price of \$0.06/kWh (NYSERDA, 2017) The entire bioenergy system would generate 576 million kWh per

day, amounting to a total of **$35 million** in annual electricity revenues (90 km buffer case). Table A2 in the appendix shows methane electricity generation and revenues for each farm.
In a later section, the levelized cost of electricity (LCOE) is calculated to benchmark the bioenergy system against other types of energy projects.

7.3.2. Hydro-char sales

Since hydro-char has a relatively low energy density compared to methane and biocrude oil, hydro-char produced will not be used as an energy source, but rather as a soil amendment product. In fact, hydro-char is very rich in carbon and nutrients, making it perfect for use as a soil fertilizer.

To estimate the price per unit mass of hydro-char, we gathered price data from three biochar manufacturers (New England Biochar, Biochar Supreme and Vermont Organics Reclamation) and calculated an average price of $2.87/kg. With that, the hydro-char annual revenues were estimated at **$76 million.** Table A3 in the appendix shows the individual Hydro-char revenues for each farm.

7.3.3. Biocrude oil sales

To estimate bio-crude oil revenues, we used a biocrude oil price of $0.55/L (U.S. EPA, 2016). We assumed a bio-oil density similar to that of Brent crude (835kg/m^3). Sample calculations for FID 0:

$$bio\ crude\ revnue = 876\frac{kg}{d} \times \frac{1}{835}\frac{m^3}{kg} \times 10^3\,\frac{L}{m^3} \times \frac{\$0.55}{L} = \$577\ per\ day$$

Summing up all biocrude oil revenues across all farms we obtain an annual revenue of **$24 million** for the entire energy system. Table A4 in the appendix shows the individual Bio-oil revenues for each farm.

7.4. Financial analysis

The following table summarizes all the capital and annual costs and revenues associated with the bioenergy system.

Table 17-Summary of AD & HTL costs and revenues

	Transportation	**HTL**	**AD**	**Total**
Capital Cost	N/A	$ 294,996,609	$ 34,867,760	**$ 329,864,369**
Annual Cost	$ 47,612,676	$ 48,863,807	$ 4,881,486	**$ 101,357,969**
	Electricity	Bio-crude	Hydro-char	
Revenues	$ 34,557,789	$ 23,607,913	$ 75,825,830	**$ 133,991,532**
Annual Tax				**$ 6,526,713**

The amount of taxes paid is computed by applying the tax rate to the annual profits (Annual revenues – annual costs). For simplicity, the tax rate as well as the O&M costs were assumed to be constant over the lifetime of the project. Although such assumptions might not hold in real systems, the purpose of this financial analysis is just to give an estimate of the overall feasibility of the bioenergy system. The cash flow diagram for the bioenergy system is shown in figure 19.

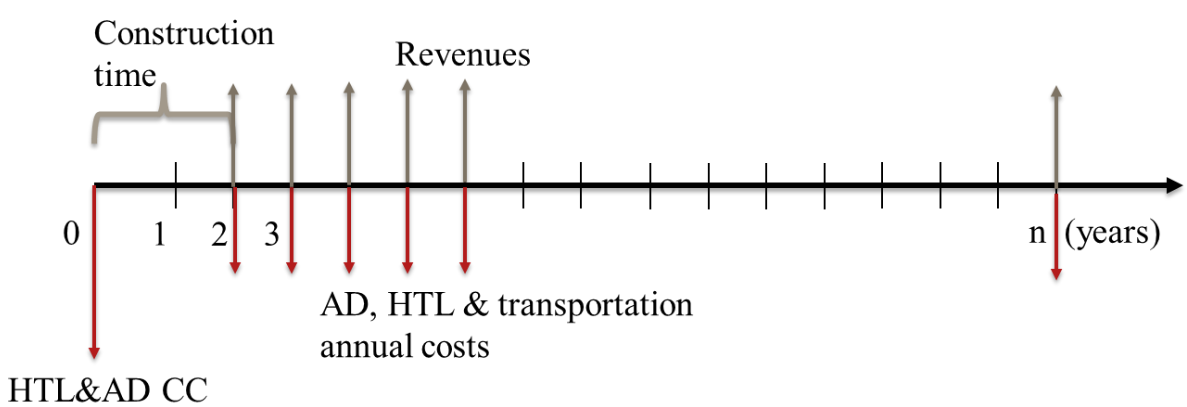

Figure 19- Project Cash Flow diagram

For the financial evaluation of the project, a present worth analysis will be conducted to determine the net present value (NPV) of the cash flow. All elements of the financial analysis of the project are discounted back to their present worth. A positive NPV at the end of the project lifetime indicates a financially attractive project. The economic parameters used for the cash flow analysis are shown in table 18.

Table 18-Financial parameters used in the cash flow analysis

Discount rate	4%
Lifetime (years)	40
Tax rate	20%

The capital costs represent a one-time upfront payment occurring at the beginning of the project. The net cash flow for every year is computed by subtracting the O&M costs and taxes from the revenues each year, starting at year 2, when the project becomes operational after accounting for two years of construction.

$$Net\ cash\ flow_n = Revenues_n - O\&M_n - Tax_n$$

where $n \geq 2$ represents the year number. The present value (PV) of each net cash flow is computed by:

$$P = F(P/F\ , i, n) = F \times (1 + i)^{-n}$$

where P is the present value, F the future value, i, the discount rate and n the year number. The sum of each year's PV (including the upfront capital costs at year 0) gives the net present value (NPV).

$$NPV = \sum_{n=2}^{40} PV_n + C_0$$

where C_0 is the initial capital cost at year 0. Table A7 in the appendix shows the detailed cash flows' PV and NPV calculated. The NPV vs time graph is plotted in figure 20.

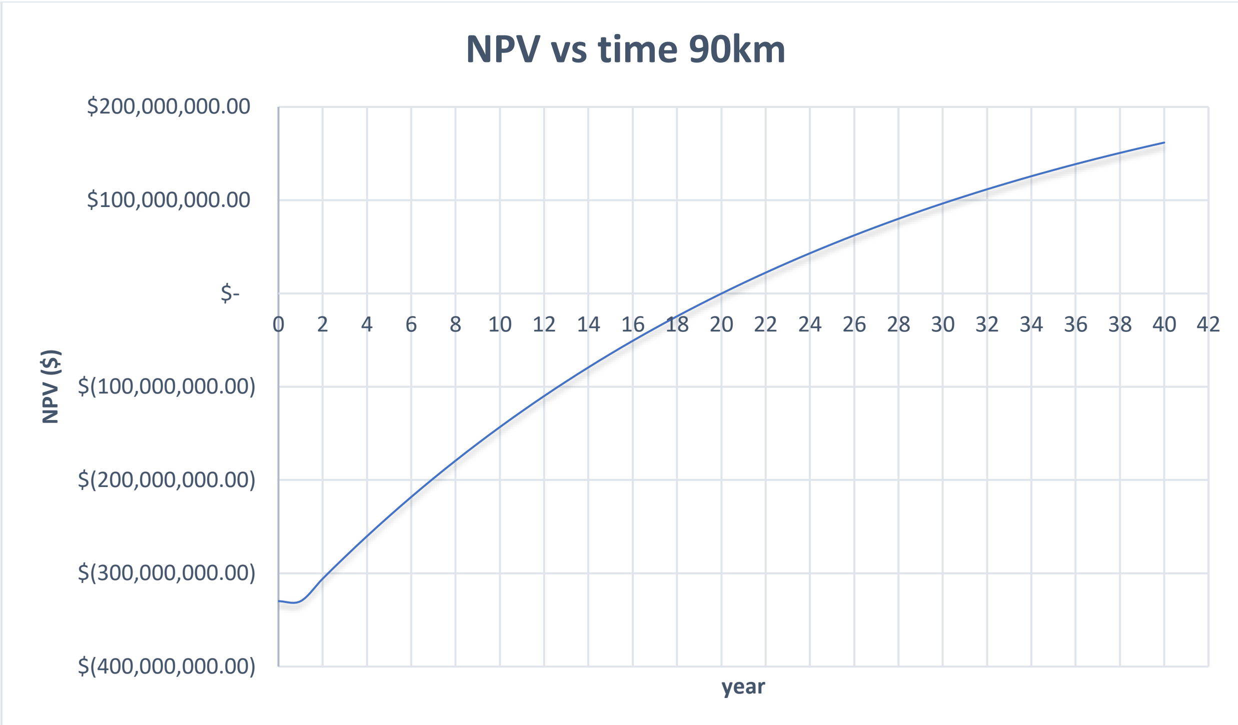

Figure 20-NPV vs time (90 km buffer)

The graph shows that payout occurs at year 20. The net present value at the end of the 40-year lifetime of the project is around $162 million. The project is therefore financially attractive. The project will breakeven and start making profits at the onset of the 20th year.

The internal rate of return (IRR) is the interest rate at which a project breakeven at exactly the end of its lifetime (i.e. NPV=0 at year 40). Using Excel solver and setting NPV=0 at end of project lifetime (year 40), we get an IRR=6.8% (see figure 21). Again, the IRR is greater than the discount rate, meaning the project is financially attractive.

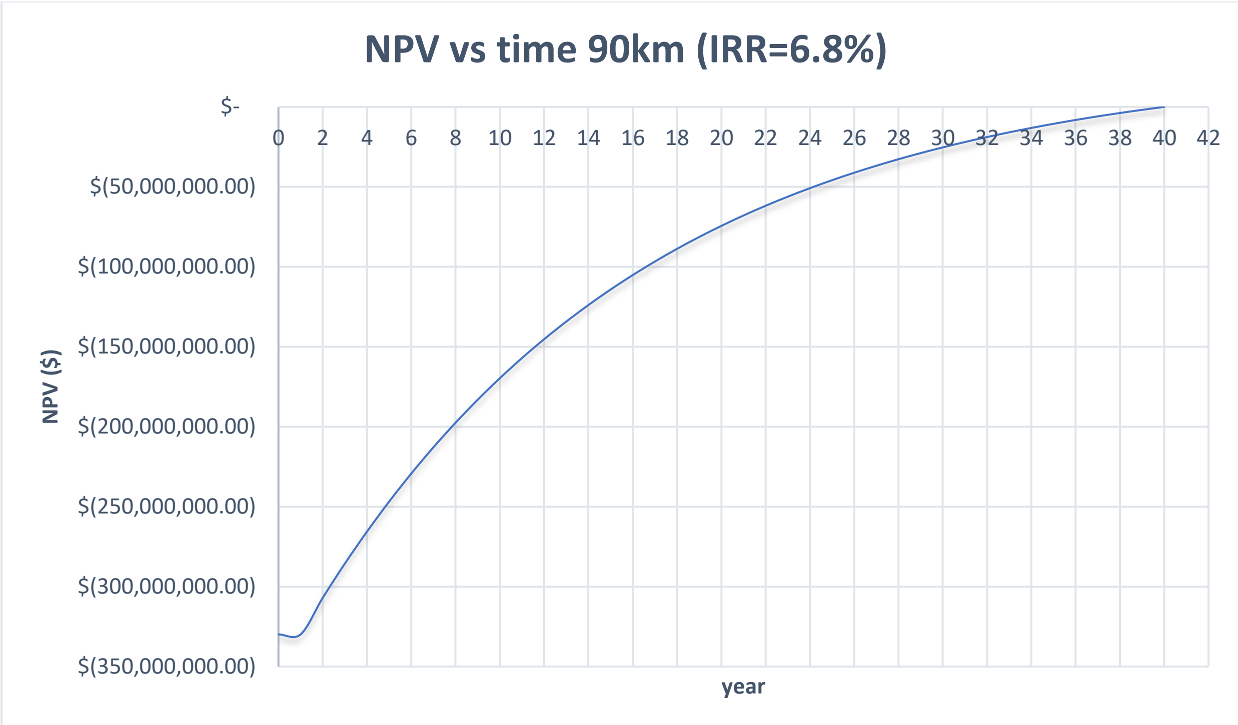

Figure 21-NPV vs time (90 km and IRR=6.8%)

The levelized cost of electricity (LCOE) combines all cost factors into a cost-per-unit (i.e. $/kwh) that is comparable between technologies. The LCOE is obtained by summing up all annual costs and dividing by the annual electricity output:

$$LCOE = \frac{total\ annual\ costs\ (\$)}{Annual\ electric\ output\ (kWh)}$$

The total annual costs consist of the O&M costs, the annualized capital cost and taxes:

$$total\ annual\ costs = Annualized\ CC + O\&M + tax$$

The annualized capital cost is given by:

$$Annualized\ CC = C_0 \times \left({}^{A}/_{P}, i, n \right) = C_0 \times \frac{i(1+i)^n}{(1+i)^n - 1}$$

where i is the discount rate, n the lifetime of the project, C_0 the initial capital cost. The total annual cost is then determined to be $125 million.

With an annual electricity output of 576 million kwh (for the entire bioenergy system at 90km buffer) the levelized cost of electricity was calculated to be $0.22/kWh. It can be seen that the LCOE is higher than the wholesale price of electricity ($0.06/kWh), suggesting electricity is sold at a loss. However, the financial profitability of the project is not solely measured by selling electricity, but by also selling bio-crude oil and hydro-char, which explains the positive NPV of the project.

Doing the same analysis for the 15 km buffer case, using the same financial parameters, we get the following:

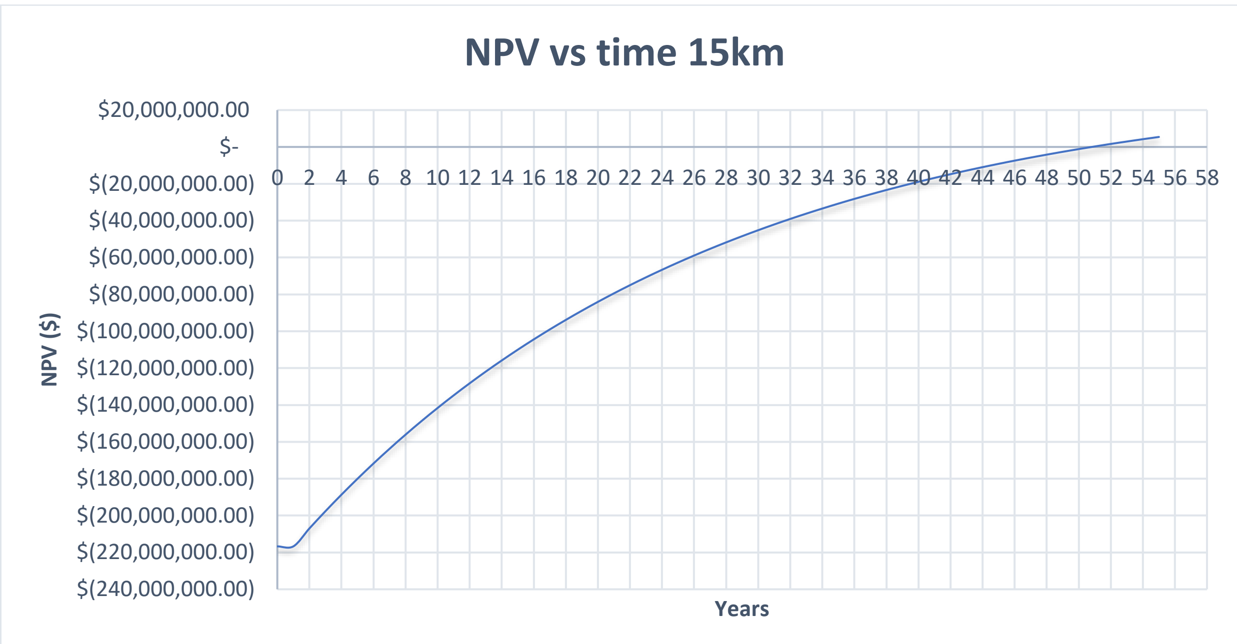

Figure 22-NPV vs time (15 km buffer)

The graph shows that at 15 km buffer, the project does not breakeven before the end of its lifetime (negative NPV of $19 million at year 40). The breakeven point (BP) for this project in that case is 50 years. The project is therefore not economically feasible (for a lifetime of 40 years). Furthermore, the LCOE for the 15 km buffer case was calculated to be $0.23/kWh. Table 19 shows a comparison between the 15 and 90km cases.

Table 19- 15 and 90 km cases comparison

Buffer Distance	15 km	90km
# farms	157	407
Methane (L/d)	276,896,738	557,371,715
Biocrude (L/d)	58,422	117,599
Hydro-char (kg/d)	35,960	72,384
CO2 (kg/d)	65,952	132,755
Annual Transportation costs ($)	18,123,805	47,612,676
HTL CC ($)	193,814,449	294,996,609
HTL O/M ($)	32,103,799	48,863,807
AD CC ($)	22,908,317	34,867,760
AD O/M ($)	3,207,164	4,881,486
Biocrude sales ($)	11,728,177	23,607,913
electricity sales ($)	17,167,967	34,557,789
hydrochar sales ($)	37,669,520	75,825,830
LCOE ($/kWh)	0.23	0.22
NPV(40 years) ($)	-18,905,976	161,759879
Years to breakeven	50	20

As can be seen, the LCOE for the entire bioenergy system decreases with increasing system size: from $0.23/kWh for the 15 km buffer case down to $0.22/kWh for the 90 km case. Clearly, project economics improve by scaling up from a 15 to a 90km buffer radius. This can be explained by higher revenues and electricity generation and minor increases in reactors capital and operating costs with increased scale: central AD's are already in place and increasing farms will just increase influent feedstock flowrate (more waste resource) and transportation costs.

7.4.1. Sensitivity Analysis

In this section, a sensitivity analysis will be performed in order to quantify the effect of various variables (discount rates, buffer radius, electricity selling price, project lifetime and biomass energy tax credits) on financial parameters such as the NPV, breakeven point (BP), Internal rate of return (IRR) and the LCOE. The baseline case against which the changes in parameters are being evaluated is shown in table 20.

Table 20- Baseline case for sensitivity analysis

Baseline Parameters		Baseline Variables	
Baseline NPV	$162M	**baseline discount rate**	4%
Baseline IRR	6.80%	**baseline buffer radius**	90km
Baseline BP	20 years	**baseline electricity selling price**	0.06$/kWh
Baseline LCOE	0.22 $/kWh	**baseline project lifetime**	40 years
		baseline subsidies	no subsidies

The sensitivity analysis is performed by changing the value of the baseline variable while keeping other variables constant and measuring the resultant change in the different parameter values. This is repeated for every variable. The different cases that were considered along with the sensitivity results are shown in table 21.

Table 21- Sensitivity Analysis Results

Discount rate	**NPV ($)**	**BP (*years*)**	**IRR (*%*)**	**LCOE *($/kWh)***
0%	$688M[9]	13	6.80%	0.19
2%	$360M	16	6.80%	0.21
4% (baseline)	$162M	20	6.80%	0.22
6%	$38M	28	6.80%	0.23
12%	($138M) [10]	N/A	6.80%	0.26
Buffer radius				
low (15 km)	($19M)	50	3.40%	0.23
baseline (90km)	$162M	20	6.80%	0.22
Electricity selling price				
baseline (W - 0.06 $/kWh)	$162M	20	6.80%	0.22
W/S (0.10 $/kWh)	$509M	10	12%	0.22
R (0.18 $/kWh)	$1.2B[11]	5	20.50%	0.24
R/S (0.22$/kWh)	$1.6B	4	24.30%	0.25
Tax credit				
baseline (without)	$162M	20	6.80%	0.22
25% BETC	$174M	19	7%	0.22
25% BITC	$240M	16	8.08%	0.21
Lifetime				
low (20 years)	($166K[12])	20	4%	0.23
baseline (40 years)	$162M	20	6.80%	0.22
high (60 years)	$236M	20	7.30%	0.21

[9] M: Million
[10] Parenthesis indicate negative numbers
[11] B: Billion
[12] K: Thousand

The different electricity prices considered are (1) Wholesale - W, (2) Wholesale with subsidy - W/S, (3) Retail - R and (4) Retail with subsidy - R/S. The subsidy was assumed to be part of a NY state public authority's renewable energy development funding plan or policy initiatives (i.e. NYSERDA, REV[13]). It was assumed to amount to $0.04/kWh. Retail and wholesale prices were obtained from NYSERDA's monthly average electricity prices for the year 2017.

Two types of tax credits were evaluated. The first is the Biomass Energy Tax Credit (BETC) currently applied in South Carolina. It allows a 25% income tax credit for industrial customers engaged in energy projects involving biomass, anaerobic digestion and other forms of bioenergy (Database of State Incentives for Renewables & Efficiency (DSIRE)). Total credits claimed cannot however exceed $650,000 per year or 50% of the tax liability, whichever is lower. Since 25% of the bioenergy project's tax amount exceeded the $650,000 limit, a $650,000 yearly tax rebate was therefore considered.

For the second tax credit incentive, we assumed a biomass investment tax credit (BITC) similar to the solar ITC incentive, where customers are eligible for a certain deduction in their investment costs used to purchase and install equipment and reactors used to create energy from biomass sources. It was assumed that the BITC would amount to 25% of initial capital costs. The annual tax rebate was calculated by taking 25% of the CC and annualizing that amount over the lifetime of the project. Doing so, we get a $4.2 million/year tax deduction. A better visualization of the sensitivity analysis is shown in figures 23 through 26.

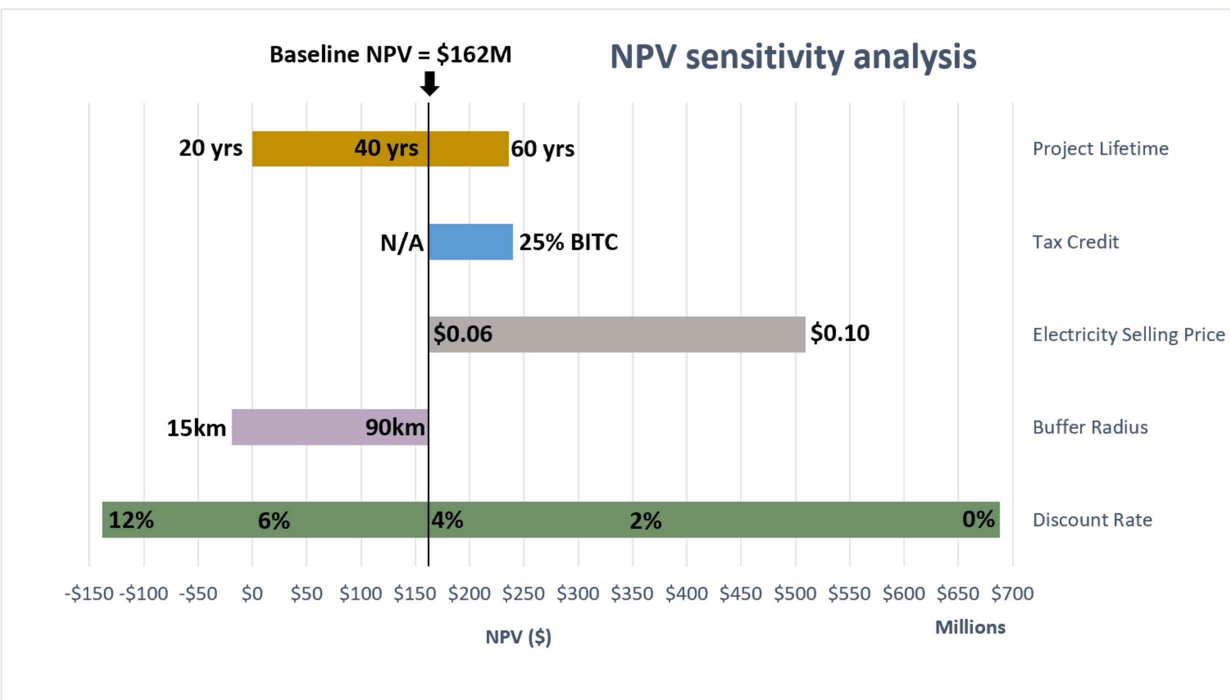

Figure 23-NPV Sensitivity chart

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[13] Governor Cuomo's energy strategy for New York

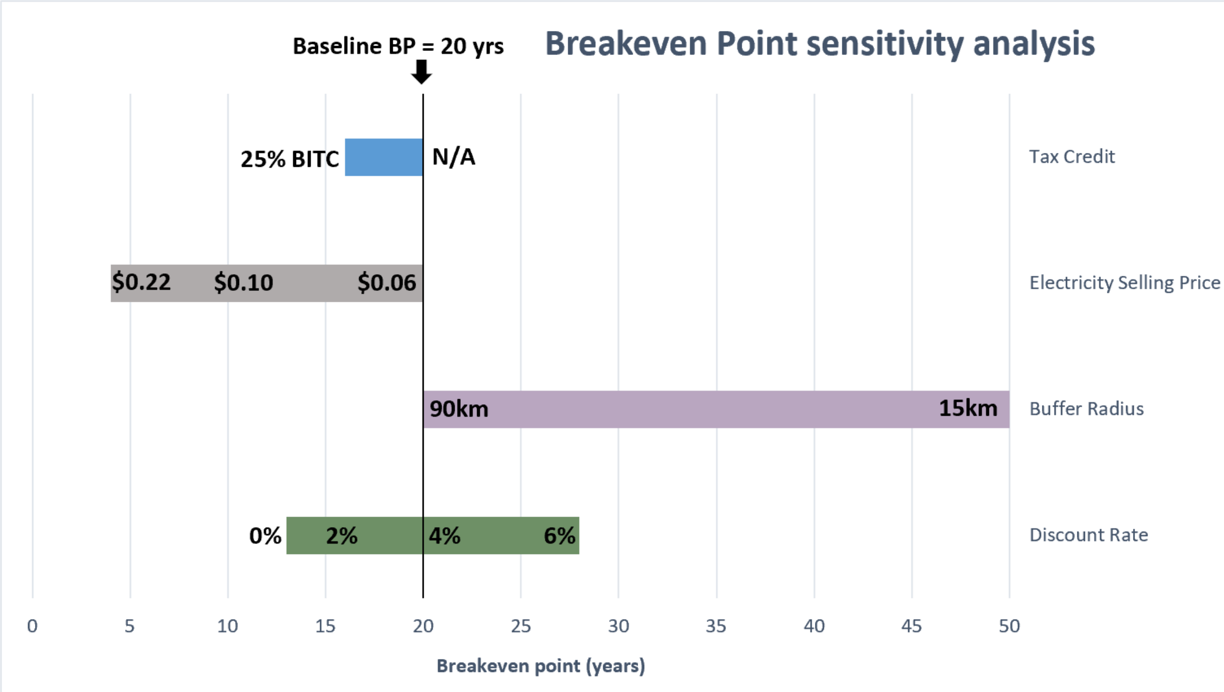

Figure 24-Breakeven Point Sensitivity Chart

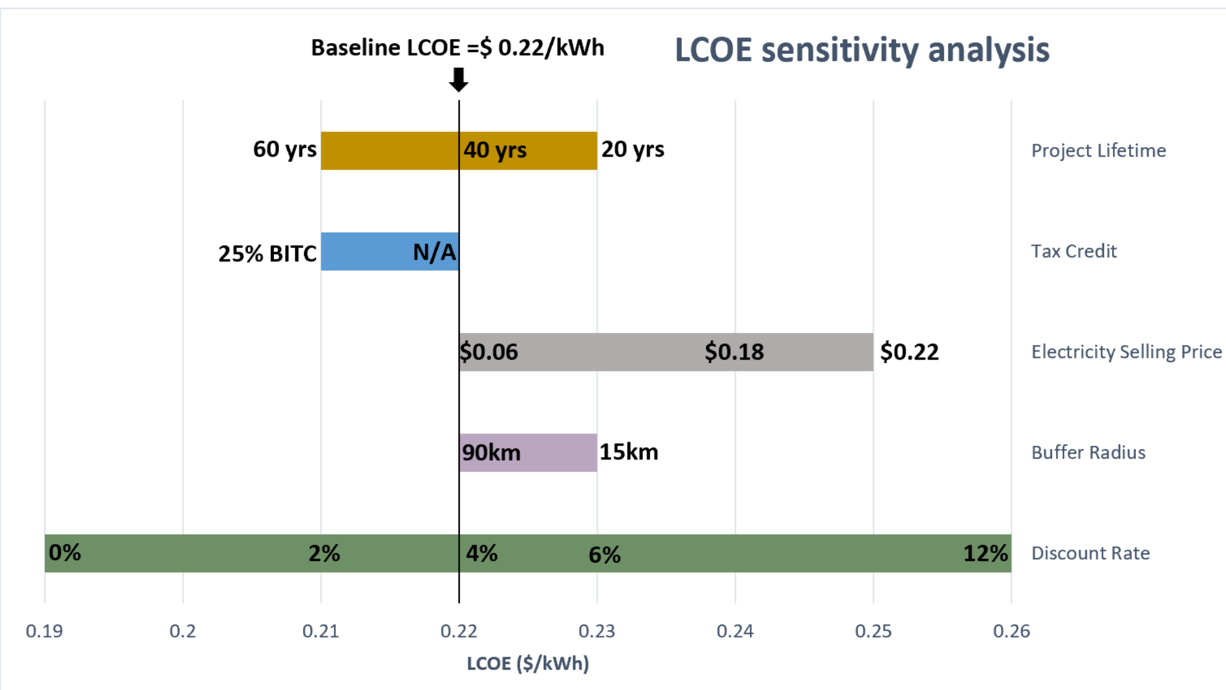

Figure 25-LCOE Sensitivity Chart

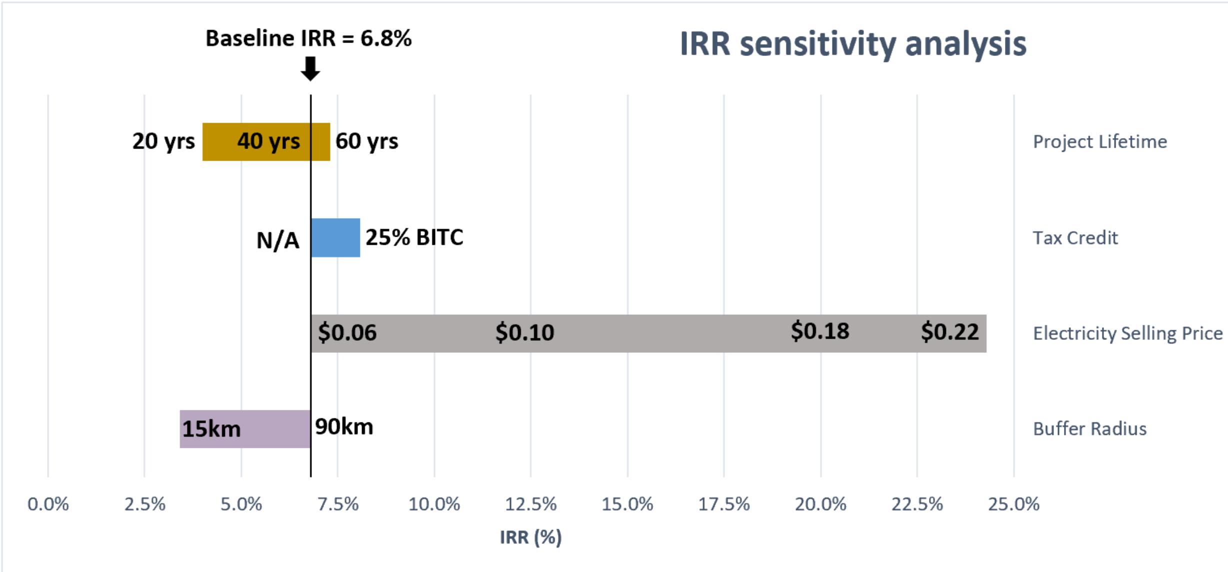

Figure 26-IRR Sensitivity Chart

Higher electrify selling prices greatly benefit the project, resulting in higher NPVs, lower breakeven points and higher IRRs. However, as can be seen in figure 25, the LCOE increases with increasing electricity selling price: higher electricity revenues imply higher taxes, leading to higher annual costs. System scale up and tax credits always benefit the project, improving all the financial parameters. Higher discount rates lead to lower NPVs, higher LCOEs and longer breakeven points, to the detriment of the project.

8. Conclusion

In this report, the economic feasibility of implementing a centralized bioenergy system in New York state was investigated. It has been shown that the feasibility of the project depends on many factors, with system scale being the most determinant factor. Increasing the system size from 157 farms and 130,000 cows to 407 farms and 260,000 cows increases the NPV from a negative $19 million to $162 million (considering a 40-year project lifetime). Other variables such as electricity selling price and government support in forms of tax incentives and subsidies greatly improve the economics of the project. In fact, for smaller centralized systems, a project can never be viable without such programs. Furthermore, for a state-scale energy system, centralization is key to reduce transportation costs and benefit from the economies of scale. The spatial analysis showed how farms could be grouped in such a way to optimize transportation logistics. This study demonstrated the benefits of having an integrated AD/HTL system to recover energy from waste products. Hydrothermal liquefaction allows the recovery of carbon from an otherwise wasted material (digestate) and produce a variety of useful by-products such as biocrude oil and hydro-char, which helps to expand the revenue streams of the project.

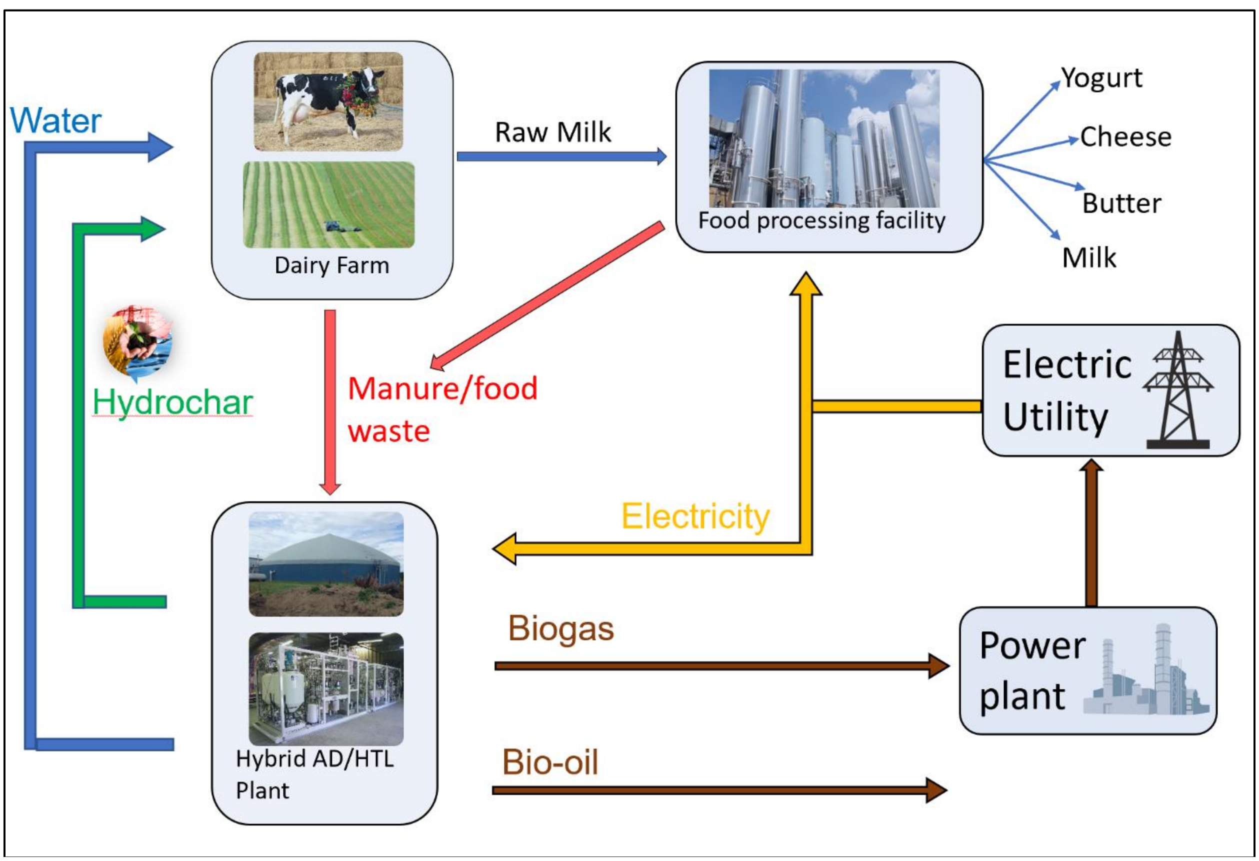

Figure 27- Dairy industry life cycle

This study has focused on the prospects of energy and has not considered nutrient recovery from the aqueous phase nor the environmental impacts such a system would have in its life cycle. These considerations are essential for a full life cycle assessment (LCA) of the project, which might give a more balanced and comprehensive view of the overall benefits of the centralized system. A techno-economic analysis alone is not enough to convince policy makers and energy developers to implement the bioenergy system. More work should be done in terms of quantifying the environmental impacts the system would have in terms of greenhouse gas emissions resulting from the different processes involved in the dairy industry life cycle. Recovery of nutrients and clean water for fertilizer and irrigation use respectively, the co-digestion of manure waste with food processing wastes for better digestion efficiency and the role of electric utilities should all be evaluated to create a more inclusive and sustainable system. Finally, a policy framework should be developed to manage the different transactions (energy, water, waste, capital…) that happen within the dairy life cycle.

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Appendix

Table A1 - The near_FID represent the ID of the nearest digester. The digesters and their IDs are represented in the table below. Note that the digesters are farms that have an AD on site.

Farm	Cows	NEAR_FID	NEAR_DIST (m)
ASHLAND FARM, LLC	1105	0	3184.771
SPRINGBROOK FARMS	630	0	6245.254
BERGEN FARMS	1700	1	28811.27
GAIGE FARMS,INC.	370	1	30549.65
GEORGE FAMILY FARMS, LLC	300	1	7635.673
SENECA VALLEY FARM	1016	1	33867.65
CANOGA SPRING FARMS	400	2	8867.87
OAKWOOD DAIRY LLC	1220	2	2873.38
GREEN HILL DAIRY INC	1030	4	4297.517
LINCOLN DAIRY	1300	4	3367.368
LITTLEJOHN FARMS	300	4	5388.604
LOCKWOOD FARMS	209	4	5335.717
ALLEN FARMS	750	6	8410.983
HATFIELD FARMS, LLC	195	6	6411.586
VALLEY MOUND FARMS, LLC	410	6	5952.325
VANSRIDGE FARM	940	6	5841.694
BENVUE FARMS	295	7	8081.343
COOK FARMS	275	7	7129.329
ELKENDALE FARMS, LLC	469	7	1293.218
PINE HOLLOW DAIRY	600	7	2795.154
VISION QUEST DAIRY	420	7	8366.034
WALNUT RIDGE DAIRY LLC	710	7	6087.105
AIRY RIDGE FARMS	370	8	18916.54
BLUME AGAIN DAIRY LLC	270	8	17099.78
JOHN HOURIGAN	850	8	9044.819
KA VERN FARMS	319	8	11932.15
MERRELL FARMS, INC.	1050	8	30507.55
PETER'S DAIRY FARM	600	8	3828.642
SCHOLTEN DAIRY FARM	400	8	21549.22
ALPINE DAIRY	400	9	16536.41
BARBLAND FARMS	790	9	25380.7
BECK FARMS, LP	700	9	18915.17
CORNELL HARTFORD TEACHING/RESERC	584	9	24733.08
COVALE HOLSTIENS	288	9	15490.24
CURRIE VALLEY DAIRY LLC	889	9	10729.99

DAIRYLAND, LLC	400	9	26462.13
EAST RIVER DAIRY LLC	1035	9	4254.846
EASTVIEW FARMS LLC	650	9	27229.51
FABIUS GREENWOOD FARM LLC	850	9	25794.35
FOUTS FARM	350	9	10554.03
FULLER FAMILY DAIRY, LLC	500	9	14208.41
JERRY DELL FARM, INC.	415	9	16466.69
LEW-LIN FARM	320	9	17767.08
MAPLEHURST FARM, LLC	391	9	23596.51
MARKHAM HOLLOW FARM	300	9	18544.87
MARSHMAN FARMS	400	9	52945.99
MCMAHON'S E-Z ACRES	635	9	6692.468
MILLBROOK FARM	710	9	16023.23
PREBLE HILL FARM LLC.	800	9	10094.81
RIPLEY FARMS	350	9	11911.79
RIVERSIDE DAIRY, LLC	950	9	27243.2
VENTURE FARMS LLC	850	9	17299.27
WHEY STREET DAIRY	460	9	20346.2
WILLOW BREEZE FARM	245	9	6567.175
ATWATER FARMS	750	10	35379.64
CHAFFEE FARMS	750	10	30862.89
DACODA DAIRY	600	10	21745.27
GASPORT VIEW DAIRY FARMS INC	672	10	25271.53
J J FARMS	485	10	22440.4
JOHN, MARK, MAUREEN J. TORREY PA	760	10	30027.62
LAKESHORE DAIRY, LLC	1500	10	52332.97
MCCOLLUM FARMS	720	10	29860.73
MILLER'S SON SHINE ACRES, INC.	630	10	19684.17
ORLEANS POVERTY HILL FARM	500	10	12861.39
REYNCREST FARMS, INC.	740	10	20120.18
SUN-RICH FARMS	145	10	5270.828
VERRATTI FARMS, LLC	540	10	25167.85
WILLS DAIRY FARM	325	10	55821.11
COLBY HOMESTEAD FARM, INC.	300	11	24770.71
HY-HOPE FARMS	680	11	9965.208
JOHN/MARK/MAUREEN J. TORREY	1050	11	7742.665
LEIBECK FARM, LLC	220	11	23429.03
OAK ORCHARD DAIRY, LLC	1400	11	6053.465
OFFHAUS FARMS INC	950	11	9535.238
POST DAIRY FARMS, LLC	400	11	3527.402
BELLE WOOD FARMS	305	12	1825.952
BELLER FARMS, LLC	270	12	49664.16
BIRCH CREEK FARM LLC.	1050	12	5957.695

BUTLER CREEK DAIRY FARM LLC.	250	12	55612.1
BUTTERVILLE FARMS	600	12	4539.802
CARROLL FARMS, LLC	50	12	34523.9
CONWAY DAIRY FARMS LLC	320	12	61432.47
CTS DAIRY LLC	817	12	5813.796
DEER RUN DAIRY	775	12	5696.687
DEMKO DAIRY LLC.	1480	12	53161.07
DOUBLE E DAIRY	260	12	46207.77
DOUBLEDALE FARM LLC	875	12	5140.481
DOUGLAS E. BROWN FARM	284	12	2469.575
EASTMAN DAIRY FARM LLC	400	12	6073.947
GRIMSHAW DAIRY FARM	235	12	4596.105
HAN COR II	500	12	43297.47
HANCOR HOLSTEINS	170	12	50645.3
HANNO FARMS	240	12	46858.48
HI HOPE FARM REALTY ASSOCIATES,	750	12	5639.334
HILLCREST FARMS LLC	730	12	4860.779
HILLTOP FARMS	445	12	51476.57
HY-LIGHT FARMS, LLC	350	12	7916.552
KENNELL FARMS	400	12	41889.9
LOCUST HILL FARM	1650	12	10360.51
MARKS FARMS	1700	12	56291.58
MILK STREET DAIRY, LLC	780	12	29609.43
MORNING STAR FARMS	440	12	7763.153
MOSERDALE DAIRY LLC	750	12	41494.87
MURCREST FARMS LLC	340	12	34304.44
MURROCK FARMS	380	12	59317.85
NORTH HARBOR FARMS	820	12	12867.98
POMINUILLES DAIRY LLC	505	12	63459.28
PORTERDALE FARMS, INC.	1300	12	12592.98
SILVERY FALLS FARMS	200	12	49289.88
TUG EDGE DAIRY	750	12	8839.318
WINDSONG DAIRY LLC	550	12	16865.94
WOOD FARMS LLC	820	12	44099.07
WOODS HILL FARMS, LLC	720	12	57631.74
ANDERSON FARMS	300	13	5075.581
BONNA TERRA FARMS, LLC	650	13	13488.32
CALLAN FARMS LLC	300	13	11764.79
LEFEBER FARMS	225	13	5216.15
MULLIGAN FARM, INC.	1300	13	3917.798
SCHUM-ACRES & ASSOCIATES	755	13	38188.46
WALKER FARM	775	13	35000.68
COTTONWOOD FARMS	350	14	6840.069

DONNAN FARMS, INC.	1500	14	3376.433
ERNEST/TOM GATES	450	14	4899.757
LAWNEL FARMS 2, LLC.	850	14	7902.556
MOWACRES FARM II, LLC	510	14	7823.288
PAGEN FARM, INC	500	14	13811.47
PAUL STEIN & SONS, LLC	400	14	15437.52
STEIN FAMILY FARMS, LLC	560	14	7199.594
STEIN FARMS LLC	630	14	13407.73
UDDERLY BETTER ACRES	550	14	15942.38
ARGUS ACRES LLC	400	15	26532.81
CDS TILLAPAUGH FARM	220	15	23459.99
COOPERSTOWN HOLSTEIN CORP.	270	15	66735.23
CROSSBROOK FARM	340	15	31800.79
DANUBE DAIRIES	800	15	47331.5
DYKEMAN & SONS, INC.	959	15	12983.55
ENVISION DAIRY LLC	350	15	3280.323
EUREKA FARM INC	270	15	27382.61
GLENVUE FARM	250	15	14522.93
GOTTIER FARMS LLC	290	15	7247.646
HAGER FARMS	340	15	66814.42
INSIGHT DAIRY	790	15	53018.87
MARICK FARM	250	15	70087.7
MILK TRAIN INC	650	15	21744.95
MMT CATTLE INC	200	15	20484.62
SPRAGUES DAIRY FARM	530	15	45236.8
STANTON FAMILY FARM LLC	415	15	27885.52
STITZEL'S WATERPOINT FARMS, INC.	360	15	55790.65
STONCREE FARMS	200	15	25283.88
STONY BROOK, INC.	438	15	3574.51
SUNY COBLESKILL	200	15	31906.27
VEIT FARMS, LLC	678	15	40453.79
WORCESTER FARM	350	15	52814.29
YOUNG DAIRY FARM LLC.	380	15	45343.84
COWLES FARM	266	16	17513.48
D. MICHAEL HOURIGAN	925	16	16582.68
ELMER RICHARDS & SONS, LLC	750	16	10831.65
FESKO FARMS, INC.	300	16	12656.81
LAWRENCE DOODY & SONS	360	16	20328.2
MAPLE LANE PARTNERSHIP	600	16	7726.5
VOLLES DAIRY FARM LLC	1200	16	17456.87
WILLIAM RICHARDS & SONS	675	16	12215.23
FA-BA FARMS	600	17	18477.33
HEMDALE FARMS	720	17	3328.461

HILTON FARMS	400	17	6227.511
J. DEBOOVER FARMS	568	17	6250.505
LANDMARK FARMS	270	17	1036.278
BLUEGILL FARMS	100	18	56867.74
DAMIN FARM LLC	1077	18	36512.71
DAVID K. VAUGHAN & SONS	435	18	13044.79
DUNLEA DAIRY FARM	650	18	79007.66
IVY LAKES DAIRY, LLC	775	18	1684.532
J. MINNS FARMS LLC.	760	18	4433.149
LENT HILL DAIRY	400	18	45424.38
LEO DICKSON & SONS, INC.	520	18	63775.31
LIGHTLAND FARMS	400	18	6688.195
OSWALD FARMS	300	18	11395.02
PHALEN FARMS	456	18	5353.251
VINCE DEBOOVER FARM	330	18	5740.105
WILKINS DAIRY FARM LLC	230	18	64079.74
PURDY FAMILY FARM	290	19	12207.65
REEDLAND FARMS	460	19	655.9232
WILLOW BEND FARM, LLC	3000	19	3232.146
A. OOMS & SONS	450	20	31629.03
ALLENWAITE FARMS, INC.	1010	20	32781.68
BERKSHIRE VALLEY HOLSTEINS	840	20	63493.05
BROTHERHOOD FARM	322	20	36904.94
DUTCH HOLLOW FARM	600	20	30059.58
EVERGREEN FARM	350	20	26375.67
HANEHAN FAMILY DAIRY, LLC	690	20	40549.06
HERRINGTON FARMS INC	680	20	9926.53
HORTON FARM	320	20	34434.67
KOVAL BROS DAIRY	350	20	39500.51
LANDVIEW FARM LLC	840	20	35862.13
LO-NAN FARMS LLC	530	20	77890.6
MAPLEDALE FARM	550	20	18793.96
STANTON FARMS LLC	740	20	34083.8
TIASHOBE FARM	590	20	29223.57
TURNING POINT DAIRY, LLC	651	20	40495.38
WIL-ROC FARMS	700	20	37530.48
WOLFF FARMS	180	20	28548.49
ADON FARMS	780	21	17009.7
BILOW FARMS LLC	980	21	81191.32
BRANDY BROOK HAVEN FARMS, LLC	320	21	10641.6
BRANDY VIEW FARMS	310	21	10327.8
BROCKWAY HILLTOP FARM	312	21	59077.49
C & M DAIRY LLC	575	21	9261.161

CARSADA FARMS	880	21	67938.78
CHAMBERS FARMS LLC	910	21	23669.85
DAN'S DAIRY LLC	330	21	65878
DORI B'S FARM	320	21	25542.99
ELLSWORTH FARMS	250	21	61298.62
FIVE MILE LINE FARM	275	21	14157.31
FLACK FARM	338	21	15346.18
FOBARE LAKE FARM LLC	200	21	23154.02
GEBARTEN ACRES	2200	21	20022.09
GOTHAM FAMILY FARM, LLC	650	21	33146.92
JORDAN FARM	450	21	4456.691
KELLY FARM	699	21	20772.29
MAPLEVIEW DAIRY	1900	21	7877.469
MCKNIGHT'S RIVER-BREEZE FARM LLC	1100	21	19340.29
METCALF FARMS	350	21	69790.4
MONICA FARMS	450	21	65674.36
PAPAS DAIRY, LLC	1800	21	66273.37
ROYAL-J-ACRES LLC	1082	21	24816.88
SHIPMAN FARM LLC	325	21	84151.31
STAUFFER FARMS LLC	1200	21	40832.17
SUNSET LAKE FARM #2 LLC	350	21	85465.55
TERIELE FAMILY DAIRY, LLC	450	21	8872.924
WOODCREST DAIRY LLC	900	21	19444.54
CROOKERCREST DAIRY	465	22	71969.8
DWI - BET FARMS	305	22	71239.12
GLEZEN FARMS, LLC	926	22	25784.56
HOME FARM	1400	22	64155.87
LLOYDS USA DEVELOPMENT, INC.	301	22	32261.18
MEAD FARM, LLC	340	22	25941.1
O'HERN DAIRY	550	22	47941.49
ROBINSON FARM	234	22	19196.22
WHITTAKER FARMS LLC	470	22	31321.18
BARBER BROTHERS	280	23	29883.02
BLACK CREEK VALLEY FARM, INC.	450	23	25195.72
CHAMBERS VALLEY FARMS, INC.	900	23	29044.68
CLEAR ECHO FARM, LLC	275	23	30862.67
FULLERTON FARMS	200	23	15803.51
HERITAGE HILL FARM	210	23	1806.514
HURD DAIRY	400	23	8212.846
IDEAL DAIRY FARMS	900	23	9579.045
KENYON HILL FARM	400	23	38721.77
KINGS-RANSOM FARM, LLC	900	23	32100.5
RED TOP DAIRY	225	23	17285.46

SKELLKILL FARMS	360	23	31658.89
TRINKLE FARMS	400	23	26028.37
TWIN BROOK FARM OF HARTFORD, LLC	125	23	8225.01
WELCOME STOCK FARM, LLC.	300	23	29887.63
WOODY HILL FARMS, INC.	946	23	30768.63
MAPLE LAWN FARMS, INC.	480	24	7732.397
MARTIN'S DAIRY	280	24	17788.48
ROSE VIEW DAIRY	275	24	20564.39
SCHOE ACRES	200	24	6366.586
BAKER BROOK DAIRY, LLC	890	25	12700.63
BEAVERS DAIRY FARM	800	25	89437.64
BLESY FARMS LLC	290	25	45051.89
BLISS DAIRY COMPANY	525	25	31919.38
BREEZY DAIRY LLC	906	25	9590.151
C J DAIRY FARM	740	25	37031.16
CONRAD FARMS,LLC	550	25	11696.96
CO-VISTA LLC	300	25	26126.95
DAN PINGREY FARM	300	25	11867.18
DZIEDZIC FARMS	540	25	19270.27
EDEN VALLEY DAIRY, LLC	1200	25	44965.84
EDEN VALLEY ORGANICS, LLC	437	25	69785.95
FONTAINE FARMS, LLC	290	25	10016.9
FRIENDLY ACRES. LLC	650	25	4388.849
G.C. ACRES	340	25	21955.26
KRAMER FARMS	500	25	26471.93
LUCE DIARY FARMS	400	25	3212.737
MARK R. MANSFIELD LLC	260	25	84970.24
MCCORMICK DAIRY	750	25	15285.35
NOBLES FARM	600	25	77191.45
OUTBACK DAIRY	400	25	6147.563
PALMER FARMS	1250	25	26223.69
PERL FARMS	750	25	6613.971
PHILLIPS FAMILY FARM (FEASLEY)	250	25	50473.48
PHILLIPS FAMILY FARM, INC.	682	25	55469.67
PIMM'S VIEW FARM	291	25	81096.86
PREISCHEL FARMS INC	580	25	48043.08
R & D CROWELL FARM, LLC	698	25	82777.39
R & D JANIGA ENTERPRISES	551	25	82131.06
R & D JANIGA ENTERPRISES	290	25	21081.52
ROBBIEHILL DAIRY FARM LLC	200	25	14121.54
ROLLING MEADOWS FARM, LLC	577	25	52704.94
SCHWAB DAIRY FARM, LLC	680	25	36101.43
SEEWADT BROTHERS	230	25	6415.685

SREGNUOY FARM LLC	325	25	8072.485
TELAAK FARMS	320	25	57896.14
ZIELENIESKI FARMS INC	260	25	24563.88
BAINBRIDGE FAMILY FARM	650	26	46191.34
BURNS FAMILY FARM, LLC	450	26	53149.76
EDGEWOOD FARMS	850	26	22282.56
FITCH FARMS INC	1200	26	5190.104
GARDEAU CREST FARM	1400	26	6801.863
GRACELAND DAIRIES	350	26	24870.33
HALO FARMS	450	26	5174.285
HENDEE HOMESTEAD FARM, INC.	350	26	51874.67
KARR DAIRY FARMS, LLC	600	26	50087.49
L.H. BRIGGS, INC.	400	26	47720.51
LISMORE DAIRY	900	26	44128.33
MT. MORRIS DAIRY FARMS, INC.	1350	26	12916.1
OLD ACRE FARM	787	26	3714.755
PARK VIEW FARM	350	26	5398.406
PINGREY FARM II, LLC	275	26	5612.041
ROLA FARM	400	26	86598.39
ROLL-N-VIEW	640	26	16938.91
SCHREIBERDALE HOLSTEINS, LLC	790	26	8383.957
SMITH'S STOCK FARM, INC.	600	26	56738.52
SOUTHVIEW FARMS INC	1350	26	11062.19
SPARTA FARMS LP	1450	26	19015.12
T. JOSEPH SWYERS	750	26	26083.8
TABLE ROCK FARM INC	964	26	7357.552
TRUE FARMS, INC.	700	26	926.7169
ARMSON FARMS, LLC	450	27	4806.736
DAIRY KNOLL FARMS	804	27	21157.29
DUEPPENGIESSER DAIRY CO	840	27	2124.432
KINGSTON FARMS	386	27	16544.77
MERRIMAC FARMS, INC.	350	27	14771.48
PEILA BROTHERS, LLC	400	27	2747.966
THORNAPPLE DAIRY, LLC.	900	27	6196.348
WOODVALE FARMS	575	27	2840.321
BEHEN FARM	280	28	33593.31
BENNETT BROTHERS	200	28	31768.29
BRANDES FARMS	600	28	72188.53
BROUGHTON FARM OPERATION LLC	2165	28	7398.941
DAVIS VALLEY FARM	260	28	16229.15
EAGLEVIEW DIARY LLC	400	28	22904.3
EAST HILL FARM LLC	650	28	5835.818
EDELWEISS FARMS, INC.	900	28	29742.1

FLINT'S DAIRY FARM	680	28	6099.581
HILLCREST HOMSTEAD	375	28	39755.84
MALLARDS DAIRY LLC - MAIN	2000	28	45657.01
MCCORMICK FARMS, INC. - DAIRY	2074	28	14758.1
NICHOLS FARM	271	28	33992.06
PANKOW FARM	580	28	14233
VAL DALE FARMS	500	28	60759.32
VAN SLYKE'S DAIRY FARM LLC	844	28	17659.91
BARNIAK FARMS	620	29	8679.92
BLUMER DIARY FARM	400	29	18861
BOWHILL FARMS, INC.	650	29	3352.7
HARKINS DAIRY FARM, LLC	300	29	4665.744
HIGHLAND FARMS	740	29	5634.983
HILDENE FARMS, INC.	873	29	5036.734
LOGWELL ARCES, INC.	350	29	5977.001
LOR-ROB DAIRY FARM	1700	29	12259.63
VALLEY VIEW FARM	300	29	19285.43
ABC FARMS	580	30	23686.38
BRABANT FARM	690	30	32227.53
BRUCE EDWARDS DIARY	305	30	44205.2
CASLER FARM	300	30	35847.42
CEDAR KNOBS, FARMS, LLC	290	30	6043.378
CHAMPION FARMS LLC	190	30	23053.31
COBAR DAIRY LLC	219	30	61016.87
COLLINS KNOLL FARM, LLC	690	30	34803.59
CURTIN DAIRY	1000	30	32198.29
EDWARD GALLAGHER FARM	230	30	20651.1
EFS, LLC.	375	30	15811.64
ENTWISTLE	774	30	42338.16
FINNDALE FARMS	360	30	56499.86
FRAZEE FARMS, LLC	435	30	22332.07
GATEHOUSE FARMS	225	30	22325.04
HANEHAN FAMILY DAIRY LLC	730	30	62817.82
HAPPY VALLEY FARM	250	30	24530.55
HEMLOCK VALLEY FARM	500	30	66848.19
HOLMES ACRE EAST	129	30	10421.41
HOLMES ACRE, LLC	402	30	17614.62
INDIAN CAMP FARM, LLC	380	30	20980.76
JOHNSON FARMS, LLC	260	30	36554.03
KAB FARMS, LLC	199	30	20416.69
MY-BAR-K MEADOWS	310	30	11592.4
PASTURELAND DAIRY	290	30	26621.75
REND-CACH FARMS. LLC	175	30	14698.47

RICHARD WEAVER FARM	270	30	21549.37
SOUTHTOWN DAIRY	270	30	50584.78
SPRINGWATER FARMS	266	30	19078.23
TRUANDVIN DAIRY, LLC	714	30	13845.85
TUSCARORA DAIRY, LLC	370	30	27953.15
VAILL BROS.	400	30	24012.12
WHITE EAGLE FARMS	715	30	8188.896
WORMONT DAIRY	275	30	29838.77

Table A2: Methane electricity generation and revenues – 90 km

FID	Daily methane electrical energy (kWh)	Daily electricity revenues ($/d)
0	14,070	844
1	25,635	1,538
2	23,359	1,402
4	26,258	1,575
6	23,117	1,387
7	20,872	1,252
8	27,408	1,644
9	93,691	5,621
10	59,560	3,574
11	41,151	2,469
12	144,700	8,682
13	27,747	1,665
14	44,691	2,681
15	67,052	4,023
16	34,349	2,061
17	26,222	1,573
18	43,227	2,594
19	29,955	1,797
20	67,978	4,079
21	136,319	8,179
22	35,347	2,121
23	52,171	3,130
24	13,525	812
25	124,675	7,481
26	111,204	6,672
27	34,524	2,071
28	101,540	6,092
29	39,838	2,390
30	87,797	5,268
Daily Total	1,577,981	94,679
Annual Total	575,963,158	34,557,789

Table A3: Hydro-char generation – 90 km

FID	hydro char (kg/d)	Hydro-char sales ($/d)
0	645	1,852
1	1,176	3,375
2	1,072	3,075
4	1,204	3,457
6	1,060	3,043
7	957	2,748
8	1,257	3,608
9	4,298	12,334
10	2,732	7,841
11	1,888	5,418
12	6,638	19,050
13	1,273	3,653
14	2,050	5,884
15	3,076	8,827
16	1,576	4,522
17	1,203	3,452
18	1,983	5,691
19	1,374	3,944
20	3,118	8,949
21	6,253	17,946
22	1,621	4,654
23	2,393	6,868
24	620	1,781
25	5,719	16,414
26	5,101	14,640
27	1,584	4,545
28	4,658	13,368
29	1,827	5,245
30	4,027	11,558
daily total	72,384	207,742
annual total	26,420,150	75,825,830

Table A4: Bio-oil sales – 90 km

FID	biocrude (kg/d)	Biocrude (L/d)	Biocrude revenues ($/d)
0	876	1,049	577
1	1,595	1,910	1,051
2	1,454	1,741	957
4	1,634	1,957	1,076
6	1,439	1,723	948
7	1,299	1,555	856
8	1,706	2,043	1,123
9	5,830	6,982	3,840
10	3,706	4,439	2,441
11	2,561	3,067	1,687
12	9,004	10,784	5,931
13	1,727	2,068	1,137
14	2,781	3,331	1,832
15	4,173	4,997	2,748
16	2,137	2,560	1,408
17	1,632	1,954	1,075
18	2,690	3,221	1,772
19	1,864	2,232	1,228
20	4,230	5,066	2,786
21	8,483	10,159	5,588
22	2,200	2,634	1,449
23	3,246	3,888	2,138
24	842	1,008	554
25	7,758	9,291	5,110
26	6,920	8,287	4,558
27	2,148	2,573	1,415
28	6,319	7,567	4,162
29	2,479	2,969	1,633
30	5,463	6,543	3,599
Daily total	98,195	117,599	64,679
Annual total			**23,607,913**

Table A5: Bioproducts revenues (Daily and annual) – 90 km

FID	Methane electricity revenues ($/d)	Biocrude revenues ($/d)	hydrochar revenues ($/d)
0	844	577	1,852
1	1,538	1,051	3,375
2	1,402	957	3,075
4	1,575	1,076	3,457
6	1,387	948	3,043
7	1,252	856	2,748
8	1,644	1,123	3,608
9	5,621	3,840	12,334
10	3,574	2,441	7,841
11	2,469	1,687	5,418
12	8,682	5,931	19,050
13	1,665	1,137	3,653
14	2,681	1,832	5,884
15	4,023	2,748	8,827
16	2,061	1,408	4,522
17	1,573	1,075	3,452
18	2,594	1,772	5,691
19	1,797	1,228	3,944
20	4,079	2,786	8,949
21	8,179	5,588	17,946
22	2,121	1,449	4,654
23	3,130	2,138	6,868
24	812	554	1,781
25	7,481	5,110	16,414
26	6,672	4,558	14,640
27	2,071	1,415	4,545
28	6,092	4,162	13,368
29	2,390	1,633	5,245
30	5,268	3,599	11,558
daily total	94,679	64,679	207,742
annual total	34,557,789	23,607,913	75,825,830

Table A6: Cash Flow Analysis – 15 km case

year	Revenues	CAPEX	OPEX	TAX	total cash flow	PV	NPV
0	-	(216,722,766)	-		(216,722,766)	(216,722,766)	(216,722,766)
1	-	-	-	-	-	-	(216,722,766)
2	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	9,712,201	(207,010,565)
3	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	9,338,655	(197,671,910)
4	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	8,979,476	(188,692,435)
5	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	8,634,111	(180,058,323)
6	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	8,302,030	(171,756,293)
7	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	7,982,721	(163,773,572)
8	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	7,675,693	(156,097,879)
9	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	7,380,474	(148,717,404)
10	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	7,096,610	(141,620,794)
11	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	6,823,664	(134,797,131)
12	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	6,561,215	(128,235,916)
13	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	6,308,861	(121,927,055)
14	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	6,066,212	(115,860,843)
15	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	5,832,896	(110,027,947)
16	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	5,608,554	(104,419,393)
17	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	5,392,840	(99,026,552)
18	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	5,185,423	(93,841,129)
19	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	4,985,984	(88,855,145)
20	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	4,794,215	(84,060,929)
21	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	4,609,823	(79,451,107)
22	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	4,432,522	(75,018,585)
23	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	4,262,040	(70,756,545)
24	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	4,098,115	(66,658,429)
25	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	3,940,496	(62,717,934)
26	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	3,788,938	(58,928,996)
27	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	3,643,210	(55,285,786)

28	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	3,503,086	(51,782,700)
29	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	3,368,352	(48,414,347)
30	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	3,238,800	(45,175,547)
31	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	3,114,231	(42,061,316)
32	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	2,994,453	(39,066,863)
33	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	2,879,282	(36,187,582)
34	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	2,768,540	(33,419,042)
35	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	2,662,058	(30,756,984)
36	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	2,559,671	(28,197,313)
37	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	2,461,222	(25,736,091)
38	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	2,366,560	(23,369,532)
39	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	2,275,538	(21,093,994)
40	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	2,188,017	(18,905,976)
41	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	2,103,863	(16,802,113)
42	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	2,022,945	(14,779,168)
43	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	1,945,139	(12,834,029)
44	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	1,870,326	(10,963,702)
45	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	1,798,391	(9,165,312)
46	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	1,729,222	(7,436,090)
47	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	1,662,713	(5,773,376)
48	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	1,598,763	(4,174,614)
49	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	1,537,272	(2,637,342)
50	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	1,478,146	(1,159,195)
51	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	1,421,294	262,099
52	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	1,366,629	1,628,728
53	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	1,314,067	2,942,795
54	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	1,263,526	4,206,320
55	66,565,664	-	(53,434,768)	(2,626,179)	10,504,717	1,214,928	5,421,249

Table A7: Cash flow analysis – 90 km case

year	Revenues	CAPEX	OPEX	TAX	Net cash flow	PV	NPV
0	-	(329,864,369)	-		(329,864,369)	(329,864,369)	(329,864,369)
1	-	-	-	-	-	-	(329,864,369)
2	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	24,137,251	(305,727,118)
3	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	23,208,895	(282,518,223)
4	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	22,316,245	(260,201,978)
5	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	21,457,928	(238,744,050)
6	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	20,632,623	(218,111,426)
7	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	19,839,061	(198,272,366)
8	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	19,076,020	(179,196,346)
9	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	18,342,327	(160,854,019)
10	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	17,636,853	(143,217,166)
11	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	16,958,512	(126,258,654)
12	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	16,306,262	(109,952,392)
13	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	15,679,098	(94,273,294)
14	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	15,076,056	(79,197,238)
15	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	14,496,207	(64,701,031)
16	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	13,938,661	(50,762,370)
17	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	13,402,559	(37,359,812)
18	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	12,887,076	(24,472,736)
19	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	12,391,419	(12,081,317)
20	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	11,914,826	(166,491)
21	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	11,456,563	11,290,072
22	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	11,015,926	22,305,998
23	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	10,592,237	32,898,235
24	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	10,184,843	43,083,078
25	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	9,793,118	52,876,196
26	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	9,416,460	62,292,656
27	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	9,054,288	71,346,944
28	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	8,706,046	80,052,991
29	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	8,371,199	88,424,189
30	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	8,049,229	96,473,419
31	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	7,739,644	104,213,062
32	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	7,441,965	111,655,027
33	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	7,155,736	118,810,763
34	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	6,880,515	125,691,278
35	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	6,615,880	132,307,158
36	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	6,361,423	138,668,581
37	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	6,116,753	144,785,333
38	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	5,881,493	150,666,826

39	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	5,655,282	156,322,108
40	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	5,437,771	161,759,879
41	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	5,228,626	166,988,505
42	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	5,027,525	172,016,030
43	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	4,834,159	176,850,188
44	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	4,648,229	181,498,418
45	133,991,532	-	(101,357,969)	(6,526,713)	26,106,850	4,469,451	185,967,869

MATLAB Scripts

A8 - MethaneGenerationAD1

```
%composite kinetic parameters:
Y=0.041;
q=11.1;
K=64;
b=0.013;

fd=0.8;
SRT=20;

%hydrolysis rate constant (d^-1)
Kh=0.15;

%influent S and P (mg/L)
So=19117;
Po=91176;


%AD outputs: Methane, biomass(cells), effluent S & P
digested_BOD=So+(Po*((Kh*SRT)/(1+Kh*SRT)))-((K*(1+b*SRT))/((Y*q*SRT)-
(1+b*SRT))); %BOD consumed for methane generation
Yn=Y*((1+(1-fd)*b*SRT)/(1+b*SRT)); %net yield
Xv=Yn*digested_BOD; % effluent biomass (mg/L)
S=((K*(1+b*SRT))/((Y*q*SRT)-(1+b*SRT))); % effluent S (mg/L)
P=Po/(1+(Kh*SRT)); % effluent P (mg/L)

methane=ones(1,28);
i=1;
for cows_per_AD=[ 2325  1150    3860    4339    3820    3449    2439    6024
1370    6280    12781   3055    6435    3437    2925    3733    4166    4950
1520    6120    2985    1680    6891    9986    4515    10149   5883    3273
]
    methane(i)=0.35*(cows_per_AD*68)*(digested_BOD-
1.42*Yn*digested_BOD)*(10^-3); %*10^-3 to convert mgBOD/L to gBOD/L cuz 0.35
is in L/g
    i=i+1;

end

disp(methane); % L/day CH4
disp(Xv);
disp(S);
disp(P);

%export data to excel

filename='MATLAB_Uploads_90km.xlsx';
xlswrite(filename,methane,'methane1 90km')
```

A9 – HTL products

```
%computing flow rates
%cows_per_AD=[2325 3460 4339 3070 2459 1270 3135 870 3600 7471 2105 3385 1938
3733 3431 4660 2290 1560 1200 3430 5532 4165 5330 3563 1230];
%Q=cows_per_AD*68; %in L/d
Q=[144742.782   263712.0106 240304.1456 270124.2714 237813.9472 214717.357
281952.7138 963831.2907 612713.3163 423333.728  1488578.349 285438.9916
459752.8796 689784.9568 353359.153  269750.7417 444687.1793 308162.052
699309.9657 1402355.229 363631.2214 536700.0102 139139.8356 1282576.686
1143997.145 355164.5468 1044575.974 409824.4017 903194.9597
];

%carbon dioxide generation
CO2=8178*(10^-6)*Q; %kg/d

%Bio-crude
bioCrude=6049*(10^-6)*Q; %kg/d

%Hydro-char
hydroChar=4459*(10^-6)*Q; %kg/d

%Aqueous phase (acetate and lactate)
aceticAcid=3312*(10^-6)*Q; %kg/d
lacticAcid=2208*(10^-6)*Q; %kg/d

%Total Aqueous phase (lactate, acetate and inorganic chemicals)
aqPhase=14344*(10^-6)*Q; %kg/d



disp(CO2);
disp(bioCrude);
disp(hydroChar);
disp(aceticAcid);
disp(lacticAcid);
disp(aqPhase);

%export data to excel

filename='MATLAB_Uploads_15km_updated.xlsx';
xlswrite(filename,CO2,'CO2')
xlswrite(filename,bioCrude,'bioCrude')
xlswrite(filename,hydroChar,'hydroChar')
xlswrite(filename,aceticAcid,'aceticAcid')
xlswrite(filename,lacticAcid,'lacticAcid')
xlswrite(filename,aqPhase,'aqPhase')
```

A10 – Kinetic Reactor ModelingAD2

```
%kinetic parameters
K_Clostridium=50;
K_mazei=1020;
b=0.02;
Y_Clostridium=0.057;
Y_mazei=0.038;
qmax_clostridium=7.992;
qmax_mazei=7.74;
fd=0.8;

%influent substrate concentrations:
So_A=3389;
So_L=2259;



SA=ones(1,11);
SL=ones(1,11);
SA_L=ones(1,11); %Acetate production from lactate
SA_total=ones(1,11);
delta_BOD=ones(1,11);
Yn=ones(1,11);

%CSTR=1
%UASB=2
%Anaerobic filter=3
reactor=2;

if reactor==1

i=1;
for SRT=[5 6 7 8 9 10 11 12 13 14 15]
    SL(i)=K_Clostridium*((1+b*SRT)/((Y_Clostridium*qmax_clostridium*SRT)-
(1+b*SRT)));
    SA(i)=K_mazei*((1+b*SRT)/((Y_mazei*qmax_mazei*SRT)-(1+b*SRT)));
    SA_L(i)=(So_L-SL(i))*2.02; % acetate produced from lactate
    delta_BOD(i)=(So_A-SA(i))+2.02*(So_L-SL(i));
    Yn(i)=Y_mazei*((1+(1-fd)*b*SRT)/(1+b*SRT)); %net yield
    i=i+1;
end

elseif reactor==2
        i=1;
        for SRT=[5 6 7 8 9 10 11 12 13 14 15]
            fun1=@(SA) 1/SRT + b - ( (Y_mazei*qmax_mazei*(So_A-SA))/( (So_A-
SA) + (log(So_A/SA))*K_mazei  ) );
            xo=[0.000000001 60000000];
            SA(i)=fzero(fun1,xo);
            fun2=@(SL) 1/SRT + b - ( (Y_Clostridium*qmax_clostridium*(So_L-
SL))/( (So_L-SL) + (log(So_L/SL))*K_Clostridium  ) );

x1=[0.00000000000000000000000000000000000000000000000000000000000000000000
0000000001 999];
            SL(i)=fzero(fun2,x1);
```

```
            SA_L(i)=(So_L-SL(i))*2.02; % acetate produced from lactate
            delta_BOD(i)=(So_A-SA(i))+2.02*(So_L-SL(i));
            Yn(i)=Y_mazei*((1+(1-fd)*b*SRT)/(1+b*SRT)); %net yield
            i=i+1;
        end

else
    disp('hello')
end

disp(SA)
disp(SL)
disp(Yn(3))
disp(delta_BOD(3));

methane=ones(11,25);
%Q=68.*[2325 3460 4339 3070 2459 1270 3135 870 3600 7471 2105 3385 1938 3733
3431 4660 2290 1560 1200 3430 5532 4165 5330 3563 1230];
%need to have flow entering the AD2, and not the manure flow rate into AD1
%(above is incorrect)
Q=[139560.9894  69030.1668  231701.2555 260453.8206 229300.2062 207030.4742
146403.9798 361598.0216 82235.93784 376964.737  767195.2712 183380.1388
386268.8029 206310.1594 175576.7286 224077.9241 250069.2825 297129.8484
91239.87264 367360.5398 179178.3025 100844.0698 413640.7647 599421.9528
271018.4375 609206.2286 353134.3229 196465.8573
]; %flow rates entering AD2

for k=1:11
    for j=1:28
        methane(k,j)=0.35*Q(j)*(delta_BOD(k)-1.42*Yn(k)*delta_BOD(k))*(10^-
3);
    end
end

disp(methane);

SRT=[5 6 7 8 9 10 11 12 13 14 15];


figure
yyaxis left
plot(SRT,SL)
xlabel('SRT (days)')
xticks([5 6 7 8 9 10 11 12 13 14 15])
ylabel('lactate (mg/L)')

yyaxis right
plot(SRT,SA_L)
ylabel('acetate (mg/L)')
legend('effluent lactate','acetate production','Location','east')
title('Effluent Lactate Concentration & Acetate Production')

figure
plot(SRT,SA)
ylabel('acetate (mg/L)');
xlabel('SRT (days)');
xticks([5 6 7 8 9 10 11 12 13 14 15])
```

```
title('Effluent Acetate Concentration')

figure
plot(SRT,delta_BOD)
xlabel('SRT (days)')
ylabel('mg BOD/L')
xticks([5 6 7 8 9 10 11 12 13 14 15])
title('Digested BOD')


%export to excel

filename='MATLAB_Uploads_15km_updated.xlsx';
xlswrite(filename,methane,'methane2_UASB')
```

All Excel files used for computations and modeling are available upon request.