UNIVERSITY OF CALGARY

Algae Cultivation System as Wastewater Treatment Solution in Wheatland County

By

Adeyinka Adelodun

A RESEARCH PROJECT SUBMITTED

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

GRADUATE PROGRAM IN SUSTAINABLE ENERGY DEVELOPMENT

CALGARY, ALBERTA

AUGUST, 2019

© Adeyinka Adelodun 2019

Abstract

An integrated approach to manage the water, food and energy nexus is essential as impacts of climate change emerge and the complexities of wastewater increases. This project evaluates the energy, environmental and economical implications of using microalgae to treat wastewater in Wheatland County, Alberta. Results demonstrate that wastewater effluent that meets discharge regulatory requirements can be produced using an Algae Cultivation System (ACS) with significant Green House Gas emissions reduction when combined with Hydrothermal Liquefaction (HTL) System for microalgae biomass to biocrude conversion. However, my analysis finds that the volume of biocrude produced is not enough to operate the HTL at full capacity and it would require aggregating other sources of biomass to operate at full capacity. Lastly, I also conclude that externalities must be considered in wastewater treatment cost, and the capital expenditure of deploying ACS and HTL must be lower for economical viability of this solution.

Acknowledgement

I would like to acknowledge and thank Dr Lee Jackson for accepting to supervise this capstone project, I will miss our enriching Tuesday weekly meetings. I would like to thank Art Deane for introducing me the to world of algae and his steadfast support as I worked to complete the project. I would also like to thank Dr Irene Herremans for her keen interest, support and guidance throughout this project. Special thanks to all SEDV lecturers that reminded me that "Knowledge is Power". Lastly, I would like to express my sincere gratitude to my wife Toyin and my children (Tobi, Olumide and Ebun) for supporting and inspiring me throughout my MSc program.

I dedicate this work to my brother, Aremo Adekunle Adeniyi Adelodun (Jan-1971 to Mar-2018), who never stopped telling me he was proud of me. I miss you (RIP).

Table of Contents

Approval Page i

Abstract ii

Acknowledgement iii

Dedication iv

Table of Contents v

List of Tables viii

List of Figures ix

List of Acronyms and Symbols x

Chapter 1: Introduction 1

1.1 The Research Question 3

Chapter 2: Literature Review 5

2.1 Microalgae as a Source of Biofuel 5

2.2 Microalgae Biomass conversion to Biofuel methods 10

2.3 Wastewater facultative ponds and microalgae cultivation 13

Chapter 3: Methodology 17

Chapter 4: Wheatland County 18

4.1 Background 18

4.2 Energy 20

4.3 Environment 21

4.4 Economics 22

Chapter 5: Symbiotic Envirotek 23

5.1 Background 23

5.2 Energy 27

5.3 Environment 30

5.4 Economics 39

Chapter 6: Steeper Energy 40

6.1 Background 40

6.2 Energy 42

6.3 Environment 42

6.4 Economics 44

Chapter 7: Analyses, Discussion and Limitations of Findings 46

7.1 Energy 46

7.2 Environment 47

7.3 Economics 48

Chapter 8: Conclusion and Future Research 51

References 54

Appendix A: Chapter 4 Calculations 60

Appendix B: Chapter 5 Calculations 62

Appendix C: Chapter 6 Calculations 63

Appendix D: Chapter 7 Calculations 64

List of Tables

Table 1 Light irradiance and light:dark ratios effect on nitrogen and phosphorus removal rates .. 8

Table 2 Pilot Project Operating Parameters. 30

Table 3 Effluent Organic Content Regulatory requirements. 32

Table 4 Water Toxicity Test Result 39

Table 5 Hydrofaction system Vs fossil fuel GHG emissions comparison..... 43

List of Figures

Figure 1 ACS and HTL workflow 4

Figure 2 Irradiance and light:dark ratios on growth rate and biomass productivities 7

Figure 3 Effect of light irradiance and light:dark ratios on carbon dioxide update rates 7

Figure 4 Energy Conversion Processes from Algae biomass 11

Figure 5 A potential Workflow for ACS & HTL system 13

Figure 6 Wheatland County 20

Figure 7 Algae Cultivation System Workflow 26

Figure 8 Rosebud Wastewater Algae Growth 29

Figure 9 Gleichen Wastewater Algae Growth. 29

Figure 10 Rosebud wastewater effluent COD measurements. 33

Figure 11 Total Nitrogen & Total Ammonia Nitrogen Plot 34

Figure 12 Phosphorus and Phosphate plot 35

Figure 13 pH and Alkalinity Plot 36

Figure 14 Electrical Conductivity Plot 37

Figure 15 Sodium and SAR Plot 38

Figure 16 Hydrofaction process workflow 41

Figure 17 Hydrofaction GHG Emissions reduction scenarios 44

List of Acronyms and Symbols

ACS - Algae Cultivation System

AD - Anaerobic Digestion

AEP - Alberta Environment and Parks

BOD5 - Biochemical Oxygen Demand 5

bpd - Barrels per Day

CBC - Canadian Broadcasting Corporation

CBOD - Carbonaceous Biological Oxygen Demand

CCME - Canadian Council of Ministers of the Environment

CEC - Contaminant of Emerging Concern

CH4 - Methane

cm - Centimeters

CO2 - Carbon Dioxide

COD - Chemical Oxygen Demand

EC - Electrical Conductivity

EPA - US Environmental Protection Agency

g - Grams

GHG - Greenhouse Gas Emission

H2 - Hydrogen

HHV - High Heating Value

hr - hours

HTL - Hydrothermal Liquafaction

IIEA - Institute of International and European Affairs

IPCC - Intergovernmental Panel on Climate Change

kg – Kilograms

L - Liters

LCA - Life Cycle Assessment

LED - Light Emitting Diode

m - Meters

m3 - cubic meters

Mac-B - Modular Algae Cultivation Biofield

Mg - megagrams

mg - Milligrams

ml - Milliliters

MPa - Megapascals

MPN - Most Probable Number

N2O - Nitrous Oxide

NH3 - Ammonia

NO2 - Nitrites

NO3 - Nitrates

NRC - National Research Council

^{o}C - Degree Celsius

PBR - Photobioreactor

SAR - Sodium Absorption Ratio

SDG - Sustainable Development Goals

SETI - Symbiotic Envirotek Inc

TAG - Triacylglycerol

TAN - Total Ammonia Nitrogen

TNK - Total Kjeldahl Nitrogen

TSS - Total Suspended Solids

UN - United Nations

UV - Ultra-violet

% - percentage

µS - micro Siemens

Chapter 1: Introduction

Reliable supplies of water, food and energy are essential to create vibrant, prosperous and sustainable societies (IIEA, 2013). Unfortunately, inter-dependencies of water, food and energy with each other are under-appreciated based on how these three resources are managed presently. Water is needed to produce food and energy, energy is needed to distribute water and food, and food is needed for people to manage water and energy. A holistic, integrated approach to manage the "water, food and energy nexus" is essential to sustain a growing global population, particularly given the uncertainty around changing climate and its impacts. The need to manage water, food and energy effectively are articulated in the United Nations' 17 Sustainable Development Goals (U.N, 2015). Reliable access to water is probably the most critical of these UN goals since all life depends on water for survival.

It is well documented that Greenhouse Gases (GHGs) emissions are causing global warming and leading to climate change (IPCC, 2018). Based on a report by CBC (CBC, 2018), one of the impacts of climate change in Canada, especially in the Western Canadian Prairies, is predicted to be drought due to low precipitation, which may lead to potable water scarcity. If water availability declines, an important component of resilient, sustainable societies with changing climate will be robust processes to effectively recover clean water from wastewater effluent.

Although Canada has been relatively successful in managing wastewater, there is a need to continue to innovate and develop new technologies and methods to improve wastewater treatment. Continuous improvement of wastewater treatment is of critical importance because of the increasing complexity of wastewater generated in homes, farms, businesses and industrial processes. Contaminants of Emerging Concern (CECs) are a major challenge (Canada Water

Network, 2018) for safe discharge to receiving environments. CECs are unconventional contaminants that have been or will be discovered in wastewater effluents that have potential to impacts human and environmental health that are not yet fully quantified. Therefore, developing wastewater treatment solutions that will effectively remove CECs are of great significance to safeguarding human health and our ecosystems.

The use of microalgae as a wastewater treatment solution presents a promising and attractive solution to address challenges of climate change and CECs. Microalgae treatment is relevant to multiple UN Sustainable Development Goals (SDGs), including Goal 6 (clean water and sanitation) and Goal 7 (affordable and clean energy).

Published research indicates that there has been work done on the efficacy of using microalgae for wastewater treatment. Microalgae have the capability of removing from wastewater organic and inorganic compounds such as nitrogen, phosphorus, heavy metals and toxic organic compounds, thus reducing pollution of receiving waters (Abdel-Raouf, 2012). Wastewater treatment facilities are not generally equipped to economically remove large volume of nitrates and phosphorous from treated wastewater and it has been demonstrated that microalgae can remove 90% of nitrates and 50% of phosphorous from wastewater (Rice University, 2015). The use of microalgae as a wastewater treatment solution may be considered sustainable due to the potential circular economy that can be created by using microalgae to clean wastewater with valuable biomass and clean water as the output of the process (Arashiro, 2016). It has also been demonstrated that hydrothermal liquefaction (HTL) can be used to efficiently covert an algal slurry into biocrude (Elliott, 2013), thereby providing a valuable end-product from the treatment process. The combination of Algae

Cultivation System (ACS) and HTL processes effectively completes the waste-to-wealth potential of using microalgae to treat wastewater.

In concept, a typical wastewater treatment facility consists of the following processing units in sequence (Metcalf & Eddy, 2014):

- **Preliminary treatment unit (screening)** where solids and grits in the raw wastewater are removed
- **Primary treatment unit** that contains a primary settling tank where sludge and scum are removed
- **Secondary Treatment unit** that contains aerobic treatment tank and secondary settling tank where organic wastes are removed using activated sludge
- **Disinfection unit** where the wastewater is disinfected and prepared to be discharged into the environment.

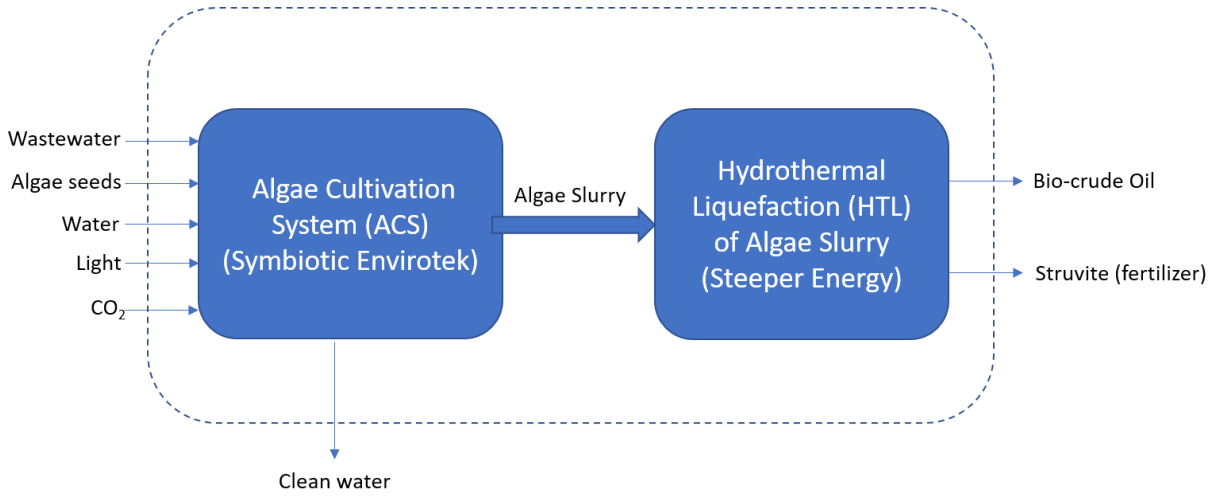
An important advantage of deploying an ACS as a wastewater treatment solution over the typical wastewater treatment facility as described above is the possibility of reducing the complexity of wastewater treatment infrastructure and the amount of land required. The ACS can potentially replace the secondary treatment processing unit. An ACS operation is also very scalable, and may therefore be particularly useful for small, isolated systems and communities.

1.1 The Research Question

The research question for my capstone project is: what are the environmental, energy and economical implications of deploying an Algae Cultivation System as a wastewater treatment solution in Wheatland County in Alberta? Wheatland County has a population of over 8700 and is

located ca. 80 km east of Calgary, Alberta. The county's wastewater treatment facilities are aging, and planners are exploring the possibility of deploying an Algae Cultivation System (ACS) to treat the county's wastewater. My research will focus on the environmental impact of deploying microalgae to clean the county's wastewater, the energy implication of harvesting algae from the ACS as biomass and the economic implications of converting the biomass from the ACS into biocrude by using HTL (Figure 1). My goal is to determine whether the infrastructure described could be a commercially viable waste-to-wealth solution to treating wastewater using microalgae.

Figure 1 ACS and HTL workflow



(Author, 2018)

Chapter 2: Literature Review

The following literature review details why I believe microalgae are a viable source of biofuel. My review highlights different methods to convert microalgae biomass to useful sources of energy and also the environmental challenges of using facultative ponds for wastewater treatment in small/rural communities; this will clearly illustrate the need to explore new processes and methods such as the Algae Cultivation System to efficiently treat and extract value from the wastewater generated in these communities.

2.1 Microalgae as a Source of Biofuel

The concept of extracting energy from cultured microalgae dates back over 140 years and the body of work that has been published over this period has resulted in the emergence of a new field of study called phycology (Borowitzka, 2013a).

Extensive research has demonstrated the ability of microalgae to adapt to different environmental conditions and at the same time accumulate significant amount of triacylglycerol (TAG) lipids or hydrocarbons (Guschina & Harwood , 2013). Lipid accumulation by microalgae can amount to 20-50% of the dry weight and this is the reason it is considered a very promising source of biofuel with equal energy density to gasoline and diesel with additional advantages of being renewable and carbon neutral.

About 35,000 species of microalgae are estimated to have been classified to date and it is believed there are many more species that have not yet been classified. Selection of algae species and strains that have the highest capacity to produce lipids is critical to produce microalgae on a commercial scale for use as a biofuel feedstock (Borowitzka, 2013b). A second factor to consider when

selecting a microalgae species and strain for commercial operation is the growth rate. In general, lipid productivity of a microalgae is defined as:

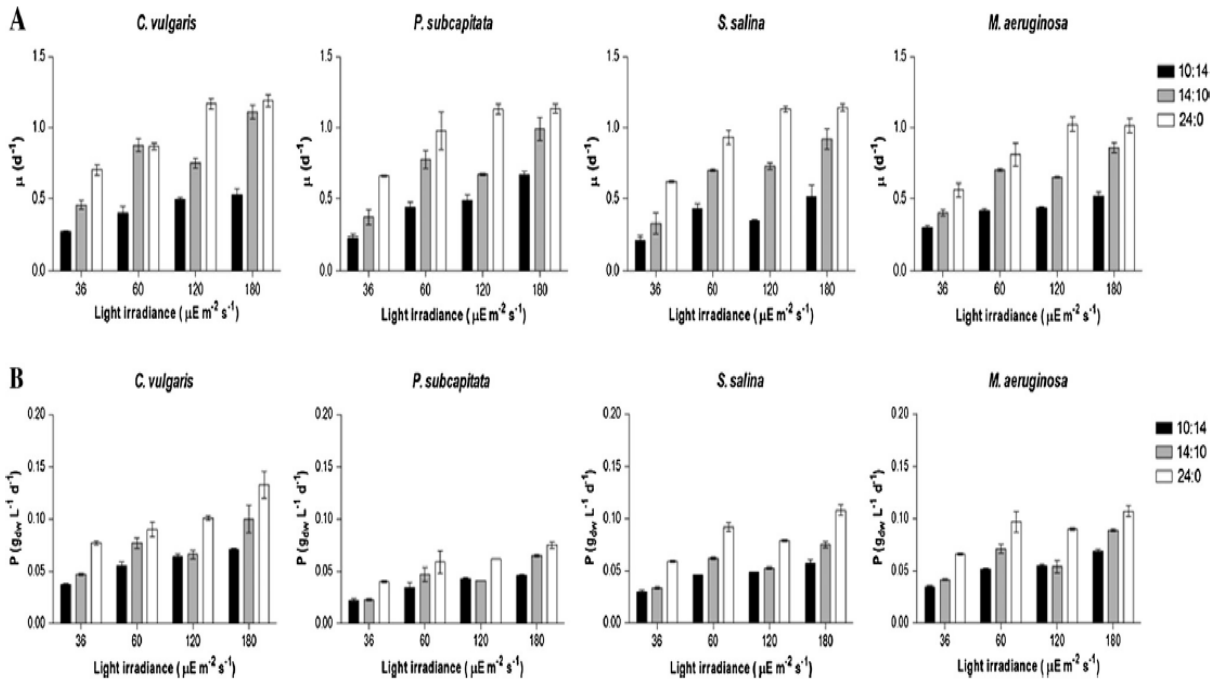
Lipid Productivity = μQ……(Eq 1)

Where μ is the specific growth rate (day^{-1}) of the microalgae species, Q is the quantity of microalgae produced per volume of the liquid medium it is growing in. To grow microalgae on a commercial scale as a biofuel feedstock, the algae species and strain should have high growth rate and high lipid content.

Apart from the intrinsic factors of microalgae species and strain that can influence growth rate and lipid content, three additional factors that influence growth rate and lipid accumulation are light intensity, CO_2 availability and nutrient availability.

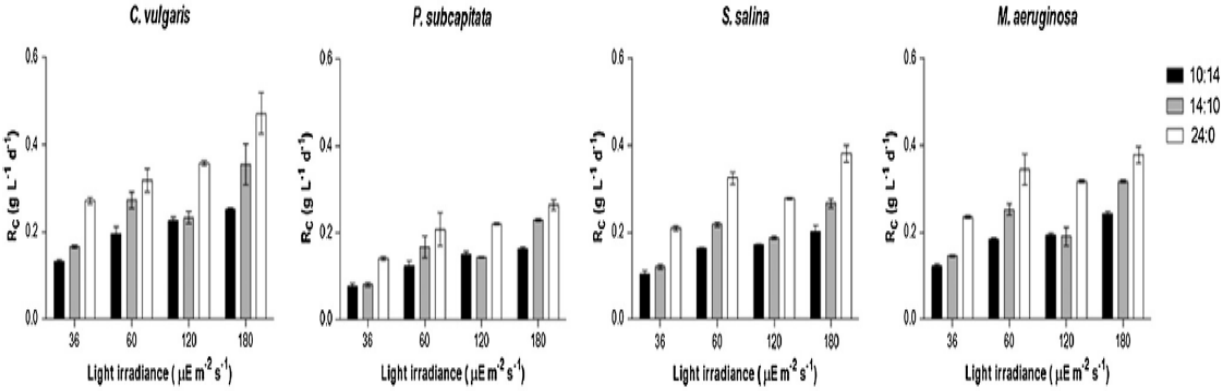
Studies have shown that higher light radiance coupled with higher light:dark ratio resulted in higher growth rate and CO_2 fixation rate (Goncalves, Simons, & Pires, 2014). Studies have also demonstrated that nitrogen and phosphorus uptake in a medium such as wastewater increase as light irradiance and light:dark ratio increase. Figure 2 and Figure 3 below show the results of a study conducted on *Chlorella Vulgaris*, *Pseudokirchneriella subcapitat*a, *Synechocystis salina* and *Microcystis aeruginosa* using wastewater as the growth medium. These results demonstrated that *Chlorella Vulgaris* and *Microcystis aeruginosa* have best increase in growth rate and CO_2 fixation rate as the light irradiation and light:dark ratio increase.

Figure 2 Irradiance and light:dark ratios on growth rate and biomass productivities



(A.L. Goncalves et al, 2014a)

Figure 3 Effect of light irradiance and light:dark ratios on carbon dioxide update rates



(A.L Goncalves et al, 2014b)

Table 1 summarizes the impact of changing light irradiance and light:dark ratios on the removal of nitrogen and phosphorus from wastewater (numbers in brackets are nutrient removal efficiency percentages). The results demonstrate that the four strains of microalgae assessed have mostly 100% efficiency in nitrogen removal at the highest light irradiance and light:dark ratio. Chlorella Vulgaris has the highest phosphorus removal rate of about 67% at the highest light irradiance and light:dark ratio.

Table 1 Light irradiance and light:dark ratios effect on nitrogen and phosphorus removal rates

	Light:dark ratio	Light irradiance ($\mu E\ m^{-2}\ s^{-1}$)	*C. vulgaris*		*P. subcapitata*		*S. salina*		*M. aeruginosa*	
N	10:14	36	6.75 ± 0.20	(42.3 ± 1.6)	6.79 ± 1.57	(43.5 ± 0.7)	7.94 ± 0.10	(48.5 ± 0.7)	8.85 ± 0.26	(53.6 ± 1.7)
		60	9.39 ± 0.20	(53.6 ± 1.0)	8.97 ± 0.30	(52.1 ± 1.7)	8.13 ± 0.51	(46.9 ± 3.6)	11.25 ± 0.08	(66.4 ± 0.6)
		120	12.73 ± 0.69	(76.4 ± 4.0)	12.73 ± 0.10	(76.7 ± 0.0)	14.04 ± 0.98	(87.1 ± 4.9)	14.75 ± 0.53	(90.2 ± 3.1)
		180	15.07 ± 0.38	(86.2 ± 1.7)	12.35 ± 0.16	(68.9 ± 0.8)	15.35 ± 0.15	(86.1 ± 0.6)	16.23 ± 0.18	(89.8 ± 0.4)
	14:10	36	10.58 ± 1.02	(75.6 ± 5.8)	7.72 ± 0.31	(74.4 ± 2.9)	11.51 ± 0.36	(96.1 ± 0.9)	11.36 ± 0.22	(98.8 ± 1.4)
		60	14.64 ± 0.03	(84.9 ± 0.1)	10.18 ± 0.72	(57.8 ± 5.0)	15.75 ± 1.69	(97.1 ± 4.7)	16.85 ± 1.14	(95.1 ± 3.9)
		120	12.30 ± 0.13	(99.0 ± 1.2)	11.97 ± 0.04	(100.0 ± 0.0)	13.00 ± 0.01	(100.0 ± 0.0)	12.00 ± 0.24	(100.0 ± 0.0)
		180	17.31 ± 0.38	(98.0 ± 2.0)	16.40 ± 1.07	(97.7 ± 2.5)	16.97 ± 0.15	(98.6 ± 0.4)	14.57 ± 1.87	(98.0 ± 0.6)
	24:0	36	16.56 ± 1.00	(97.1 ± 1.7)	16.43 ± 0.51	(88.0 ± 2.7)	17.85 ± 1.18	(92.5 ± 1.0)	18.00 ± 0.41	(97.3 ± 1.1)
		60	18.18 ± 0.69	(97.2 ± 2.7)	12.53 ± 3.00	(98.5 ± 2.6)	22.86 ± 4.90	(98.4 ± 2.1)	19.63 ± 2.84	(99.1 ± 1.8)
		120	16.35 ± 0.11	(94.6 ± 1.0)	17.82 ± 0.40	(93.3 ± 2.3)	18.44 ± 0.27	(95.5 ± 0.5)	17.12 ± 0.39	(95.2 ± 0.6)
		180	16.24 ± 1.23	(99.0 ± 1.3)	14.89 ± 0.39	(100.0 ± 0.0)	13.34 ± 0.28	(99.1 ± 0.7)	16.20 ± 0.21	(100.0 ± 0.0)
P	10:14	36	0.68 ± 0.16	(16.9 ± 3.4)	0.55 ± 0.27	(17.5 ± 7.9)	0.71 ± 0.03	(17.3 ± 0.6)	0.50 ± 0.37	(13.4 ± 8.8)
		60	0.76 ± 0.01	(20.2 ± 0.5)	0.98 ± 0.32	(23.0 ± 6.7)	0.72 ± 0.05	(18.0 ± 1.7)	0.72 ± 0.29	(15.1 ± 5.7)
		120	0.75 ± 0.25	(18.7 ± 5.4)	0.82 ± 0.10	(19.8 ± 1.7)	0.38 ± 0.35	(9.8 ± 9.1)	0.93 ± 0.04	(22.7 ± 2.1)
		180	0.79 ± 0.45	(18.3 ± 9.0)	1.07 ± 0.08	(27.0 ± 2.0)	1.39 ± 0.06	(33.9 ± 0.6)	0.99 ± 0.23	(26.3 ± 5.7)
	14:10	36	1.17 ± 0.09	(29.3 ± 1.6)	0.99 ± 0.46	(24.0 ± 9.6)	1.01 ± 0.15	(35.4 ± 3.4)	0.96 ± 0.25	(22.8 ± 6.4)
		60	1.39 ± 0.03	(30.7 ± 0.6)	1.05 ± 0.17	(40.9 ± 2.3)	1.92 ± 0.36	(23.6 ± 3.8)	1.67 ± 0.05	(39.8 ± 1.9)
		120	1.56 ± 0.56	(32.1 ± 1.2)	1.32 ± 0.13	(34.4 ± 3.1)	0.96 ± 0.04	(25.7 ± 0.8)	1.59 ± 0.12	(38.6 ± 2.6)
		180	1.31 ± 0.15	(31.4 ± 4.0)	1.27 ± 0.09	(32.7 ± 2.0)	1.24 ± 0.19	(32.0 ± 4.8)	1.05 ± 0.18	(25.8 ± 4.4)
	24:0	36	1.27 ± 0.42	(29.3 ± 7.4)	1.18 ± 0.26	(34.2 ± 4.9)	1.43 ± 0.16	(35.4 ± 3.4)	1.16 ± 0.31	(29.7 ± 6.0)
		60	1.30 ± 0.05	(35.0 ± 0.5)	1.46 ± 0.08	(34.2 ± 1.8)	1.45 ± 0.21	(34.7 ± 3.7)	1.53 ± 0.14	(36.4 ± 3.1)
		120	1.76 ± 0.24	(42.7 ± 3.6)	2.22 ± 0.26	(51.3 ± 4.4)	1.57 ± 0.32	(37.9 ± 7.1)	1.48 ± 0.12	(36.2 ± 2.8)
		180	2.67 ± 0.13	(67.6 ± 7.1)	1.78 ± 0.32	(51.2 ± 4.8)	1.44 ± 0.16	(36.6 ± 4.3)	1.62 ± 0.33	(41.1 ± 9.2)

(A.L Goncalves et al, 2014c)

Additional factors that can affect microalgae growth rate and lipid accumulation are pH, temperature, salinity and mixing regime. In general, studies have shown that microalgae are best cultured on industrial scale when pH is between 7 and 9 (Bartley, Boeing, Dungan, Holguin, & Schaub, 2013).

Microalgae achieve maximum growth rates when temperature is between 26 – 36 ºC (Ras, Steyer, & Bernard, 2013). Generally, microalgal growth rate can be modelled as a function of temperature with an Arrhenius function, which shows that growth rate will double for every 10 ºC increase in temperature until such temperature that kills the microalgae.

Studies have shown that, in general, there is an inverse relationship between salinity and lipid content of microalgae (L.Bartley, J.Boeing, A.Corcorana, OmarHolguin, & TannerSchaub, 2013).

Also, the ash content of microalgae increases with increasing salinity. Salinity lower than 35 PSU (Practical Salinity Unit) has been observed to give optimum lipid content.

For commercial scale culturing of microalgae, continuous and consistent mixing is critical to ensure the all microalga are optimally exposed to growth-limiting resources, such as light and CO_2, to achieve maximum photosynthesis and growth rate for the microalgae (Zhang, Kurano, & Miyachi, 2002).

Photobioreactors (PBRs) are required to grow microalgae on a commercial scale. PBRs can be placed indoors or outdoors and they can be opened or closed systems (Carvalho, Matsudo, Bezerra, Ferreira-Camargo, & Sato, 2014). The most common configurations of PBRs are open ponds, flat plate, vertical-columns or tubular arrangements. PBRs can also be configured to be inclined, vertical, spiral, conical, helical.

For my capstone project, I have used the Symbiotic Envirotek (SETI) as my model PBR. SETI PBR is an open pond, described in detail in Section 5 below. The SETI algae cultivation system uses a centrifuge to harvest microalgae biomass cultivated in its PBR.

2.2 Microalgae Biomass conversion to Biofuel methods

Thermochemical conversion and biochemical conversion are the two main methods of used to convert microalgae biomass to useful energy (Brennan & Owende, 2010), see Figure 4 below.

The thermochemical conversion method is when the microalgae biomass goes through thermal breakdown of the organic contents of the biomass to produce useful fuels. The thermochemical conversion process could be:

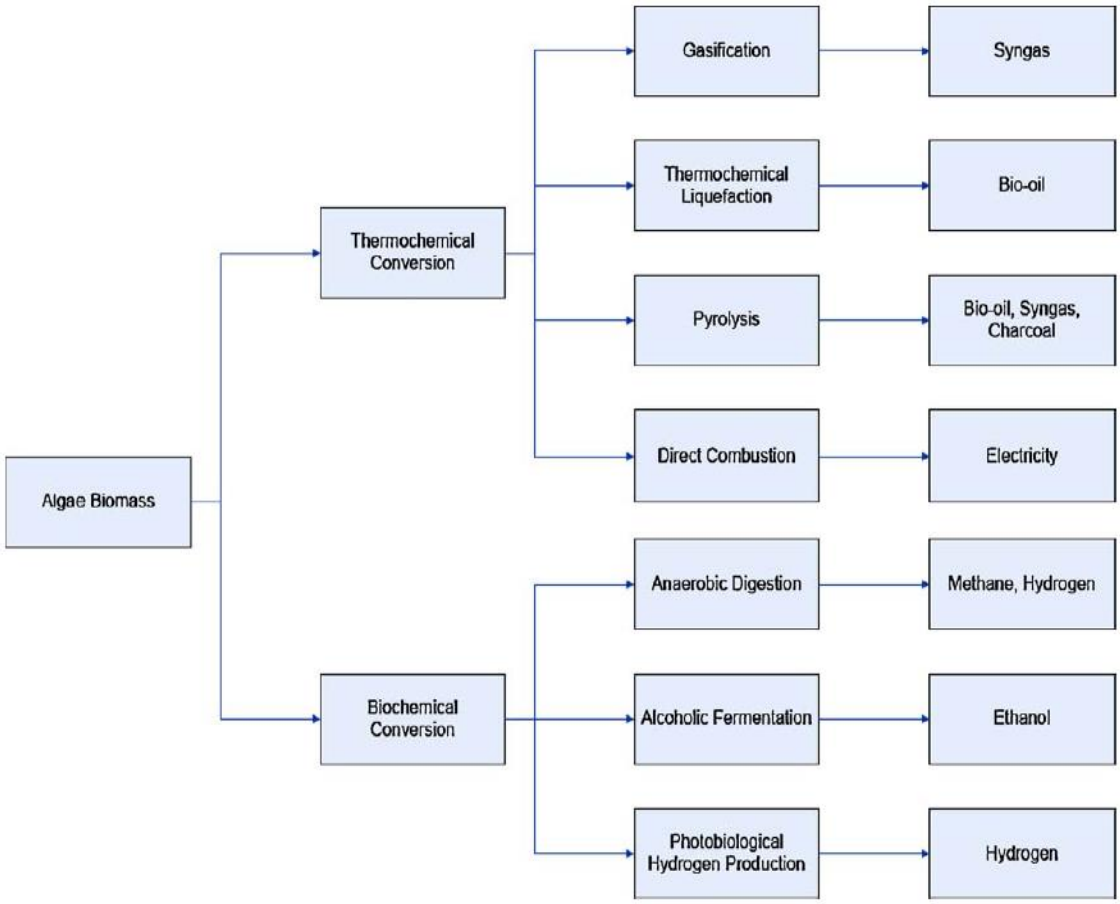
1. Gasification process where the biomass is partially oxidized at high temperature (800-1000 ^{o}C) using oxygen and water steam to produce syngas.
2. Thermochemical Liquefaction process that uses a catalyst in the presence of hydrogen under medium temperature (300-350 ^{o}C) and high pressure (5-20 MPa) to convert microalgae biomass to liquid fuel referred to as bio-oil or bio-crude.
3. Pyrolysis process where microalgae biomass is converted to useful fuel such as bio-oil, syngas and charcoal using medium to high temperatures (350-700 ^{o}C) in the absence of air.
4. Direction combustion process where the microalgae biomass is combusted with air to produce heat for steam turbines to generate electricity.

The biochemical conversion method is when microalgae biomass goes through a biological breakdown of the organic contents of the biomass to produce useful fuels. The biochemical conversion process could be:

1. Anaerobic Digestion (AD) process where microalgae biomass is broken down into biogas (mostly methane and carbon dioxide)
2. Alcoholic Fermentation process where the microalgae is broken down into ethanol.

3. Photobiological hydrogen production process where the microalgae biomass as part of the AD process produces hydrogen (H_2) that can be used for hydrogen fuel.

Figure 4 Energy Conversion Processes from Algae biomass



(Tsukahara and Sawatama, 2005)

This capstone project would focus on using thermochemical liquefaction technology to convert microalgae biomass to bio-crude. Specifically, this project would be evaluating the use of Steeper Energy's Hydrothermal Liquefaction (HTL) technology called Hyrofaction. This technology is covered in detail in Section 6 below.

A major advantage of using HTL to convert microalga biomass to bio-crude is that HTL functions effectively with wet biomass which is the state the microalga biomass would be coming out of the ACS (Gollakota, Kishore, & Gu, 2017). In general, microalgae biomass conversion to bio-crude requires depolymerization, decomposition and repolymerization. The HTL process is also referred to as “hydrous pyrolysis”.

Depolymerization, the first stage of HTL process, involves the dissolution of microalgae biomass under temperature and pressure. The long chain hydrocarbons are broken down into short chain hydrocarbon.

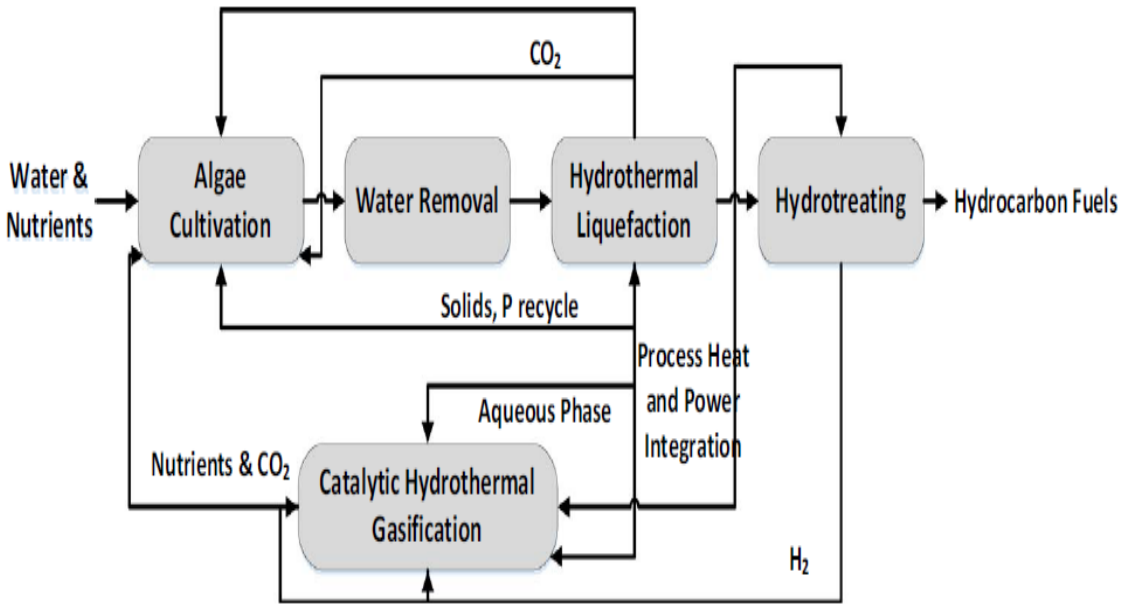
The second stage of HTL process, decomposition, involves the separation of water, carbon dioxide and amino acids from the short chain hydrocarbons, these are referred to as dehydration, decarboxylation and deamination respectively.

Repolymerization is the last stage of HTL process and it involves the conversion of short chain hydrocarbon to longer chain hydrocarbon due to lack of hydrogen rich compounds and this would result in production of char compounds. The char produced is hydrotreated as a final step to produce bio-fuels.

Based on a lab study conducted by Canadian National Research Council (NRC), the high heating value (HHV) of the biocrude produced from converting *Chlorella Vulgraris* microalgae biomass using HTL is about 40 MJ/kg with an algal-biocrude yield of 43% wt % and ash content of 0.2 wt % (Singh, 2016).

The main parameters that can affect the HTL process are temperature, pressure, resident time, catalyst used to reduce the amount of energy required to convert the microalga biomass to biocrude. Figure 5 describes a potential process workflow for an ACS and HTL operation.

Figure 5 A potential Workflow for ACS & HTL system



(Bill and Ross,2016)

2.3 Wastewater facultative ponds and microalgae cultivation

Wastewater treatment ponds, also referred to as stabilization ponds or lagoons, have been used for centuries to treat wastewater. These ponds are very cheap to operate and are used to naturally remove dissolved organic material, suspended solids, pathogens and chemicals in wastewater generated by small communities and industrial activities before discharging the effluent into the environment. Wastewater treatment ponds are used to treat various types of wastewaters, from simple domestic effluent to very complex industrial effluent. These ponds can also operate in a broad range of climatic conditions (U.S EPA, 2011). There are three types wastewater treatment ponds, namely aerobic, anaerobic and facultative ponds.

Aerobic ponds, also referred to as oxidation ponds, are shallow ponds (about 30-45 cm deep) that maintain high levels of dissolved oxygen throughout the system. The aerobic ponds can be used

where biochemical oxygen demand 5 (BOD_5) removal is essential - BOD_5 is the amount dissolved oxygen required to aerobically breakdown organic material in wastewater at 20 ºC over a 5-day period. These ponds are suitable in warm and sunny regions. Because of the shallow depth of aerobic ponds, ultra-violet (UV) light penetrates easily and thus kills off pathogens. The typical retention time for aerobic ponds is between 2-6 days.

Anaerobic ponds are used to treat industrial and agricultural wastewater with heavy organic loading. They are about 2.5-4.5 m deep. The biochemical breakdown in this type of pond produces hydrogen sulfide, methane and carbon dioxide resulting in strong odor. Further treatment is generally required for the effluent from anaerobic ponds before they are discharged. The typical retention time for anerobic ponds is between 5-50 days.

Facultative ponds are the most common wastewater treatment pond. These ponds are between 0.9 – 2.4 m deep. Because of the depth of a facultative pond, it has an aerobic layer on top of anaerobic layer. The aerobic layer helps control odor, remove nutrients and reduce BOD_5 from the wastewater. The anaerobic layer helps with sludge digestion, denitrification and additional BOD_5 reduction processes. The zone between the aerobic and anaerobic layer is referred to as anoxic layer or facultative zone. Facultative ponds are most effective in treating wastewater when oxygen is produced by algae through photosynthesis and there is enough dissolved oxygen at the surface. These ponds are mostly used for treating wastewater produced by small communities. The typical retention time for a facultative pond in a cold climate is between 90-200 days. Wheatland county has four facultative ponds that are used for treating wastewater, which are covered in detail in section 4 below.

Methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) are the three main greenhouse gases (GHGs) emitted into the atmosphere by facultative ponds.

The aerobic layer of the facultative pond produces mostly carbon dioxide while the anaerobic layer produces mostly methane and carbon dioxide. The amount of CO_2 and CH_4 produced by a pond can be estimated using the following equations (RTI International, 2010):

$$CO_2 = 10^{-3} * Q_{WW} * OD * Eff_{OD} \times CF_{CO2} \times (1-MCF_{ww} \times BG_{CH4}) \ldots\ldots\ldots\ldots (2)$$

$$CH_4 = 10^{-3} * Q_{WW} * OD * Eff_{OD} \times CF_{CH4} \times MCF_{ww} \times BG_{CH4} \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where:

CO_2 = CO_2 emission rate (CO_2 kg/hr)

CH_4 = CH_4 emission rate (CH_4 kg/hr)

10^{-3} = Units conversion factor (kg/g)

Q_{WW} = Wastewater influent flow rate (m^3/hr)

OD = BOD_5 (mg/L = g/m^3)

Eff_{OD} = Oxygen demand removal efficiency of the biological treatment unit (up to 95% for facultative pond (U.S EPA, 2002))

CF_{CO2} = Maximum CO_2 generation per unit of oxygen demand 1.375 g CO_2/ g oxygen demand

CF_{CH4} = Maximum CH_4 generation per unit of oxygen demand 0.5 g CH_4/ g oxygen demand

MCF_{WW} = methane correction factor for wastewater treatment unit, indicating the fraction of the influent oxygen demand that is converted anaerobically in the wastewater treatment unit (0.8 for Facultative lagoon)

BG_{CH4} = Fraction of carbon as CH_4 in generated biogas (default is 0.65)

The quantity of nitrous oxide emitted into the atmosphere from a facultative pond is a function of the amount of nitrogen in the wastewater flowing into the pond. The amount of N_2O is also dependent on whether it is produced by aerobic, anoxic or anaerobic layer. In the aerobic layer of the pond, ammonia (NH_3) produced by the oxidation of organic material in the wastewater is oxidized by autotrophic bacteria to nitrites (NO_2) and nitrates (NO_3) through nitrification process. Heterotrophic bacteria can convert nitrites and nitrates to nitrogen gas in the anoxic zone of the pond through denitrification process. Nitrous oxide is produced as a by-product of nitrification and dentification processes.

The amount of N_2O produced by wastewater influent in facultative pond can be estimated by knowing the amount Total Kjeldahl Nitrogen (TKN) in the wastewater flowing into the pond. TKN is defined as the sum of organic nitrogen and free ammonia in the wastewater. Nitrous oxide emissions can be estimated using the following equation:

$$N_2O_{wwtp} = Q_i * TKN_i * EF_{N2O} * 44/28 * 10^{-3} \quad (4)$$

N_2O_{WWTP} = N_2O emissions generated from WWTP process (N_2O kg/hr)

Q_i = Wastewater influent flow rate (m3/hr)

TKN_i = Amount of TKN in the influent (mg/L = g/m3)

EF_{N2O} = N_2O emission factor (g N emitted as N2O per g TKN in influent),

= 0.0050 g N emitted as N2O/g TKN (Chandran, 2010)

44/28 = Molecular weight conversion, g N_2O per g N emitted as N_2O

10^{-3} = Units conversion factor (kg/g).

Chapter 3: Methodology

My data gathering focussed on evaluating the quality of wastewater treatment facilities presently used in Wheatland county and how they meet environmental standards and guidelines as set by the regulator, Alberta Environment and Parks (AEP). I also gathered data on energy usage and cost of operating these wastewater facilities including the cost of disposing treated wastewater generated in these facilities. The data I gathered from the evaluation of how Wheatland county presently treats wastewater and the associated cost was compared with the performance of deploying ACS and HTL processes.

The performance of ACS-HTL combo was compared with present Wheatland County wastewater treatment facilities from environmental perspective by quantifying the GHG emissions of the two systems. The annual quantity of algae biomass that could be produced from Wheatland county wastewater using ACS and the subsequent volume of biocrude that could be produced using HTL to convert the algae biomass to by biocrude were determined. The economic implication of deploying ACS and HTL processes was evaluated by determining the NPV of the investment cost of ACS-HTL combo based on revenue streams from tipping fee and sales of biocrude.

I integrated Symbiotic Envirotek's ACS and Steeper Energy's HTL technologies to evaluate the commercial viability of deploying microalgae as a waste-to-energy wastewater treatment solution for Wheatland county. Therefore, my project's success did not depend on technology development but on commercial potential of the wastewater volume produced in Wheatland County.

Chapter 4: Wheatland County

4.1 Background

Created in 1954, Wheatland County is located about ca. 80 km to the east of Calgary in Alberta and has a population of over 8700 (Figure 6). Majority of the county's terrain can be classified as prairie, but the county also has badlands (arid land) in northeast region.

The county is situated in the South Saskatchewan River basin with Red Deer River and Bow River forming a northeastern and southern boundary respectively. The county has streams such as Crowfoot Creek and Parflesh Creek that drain into Bow River and Serviceberry Creek and Rosebud River that drain into the Red Deer River.

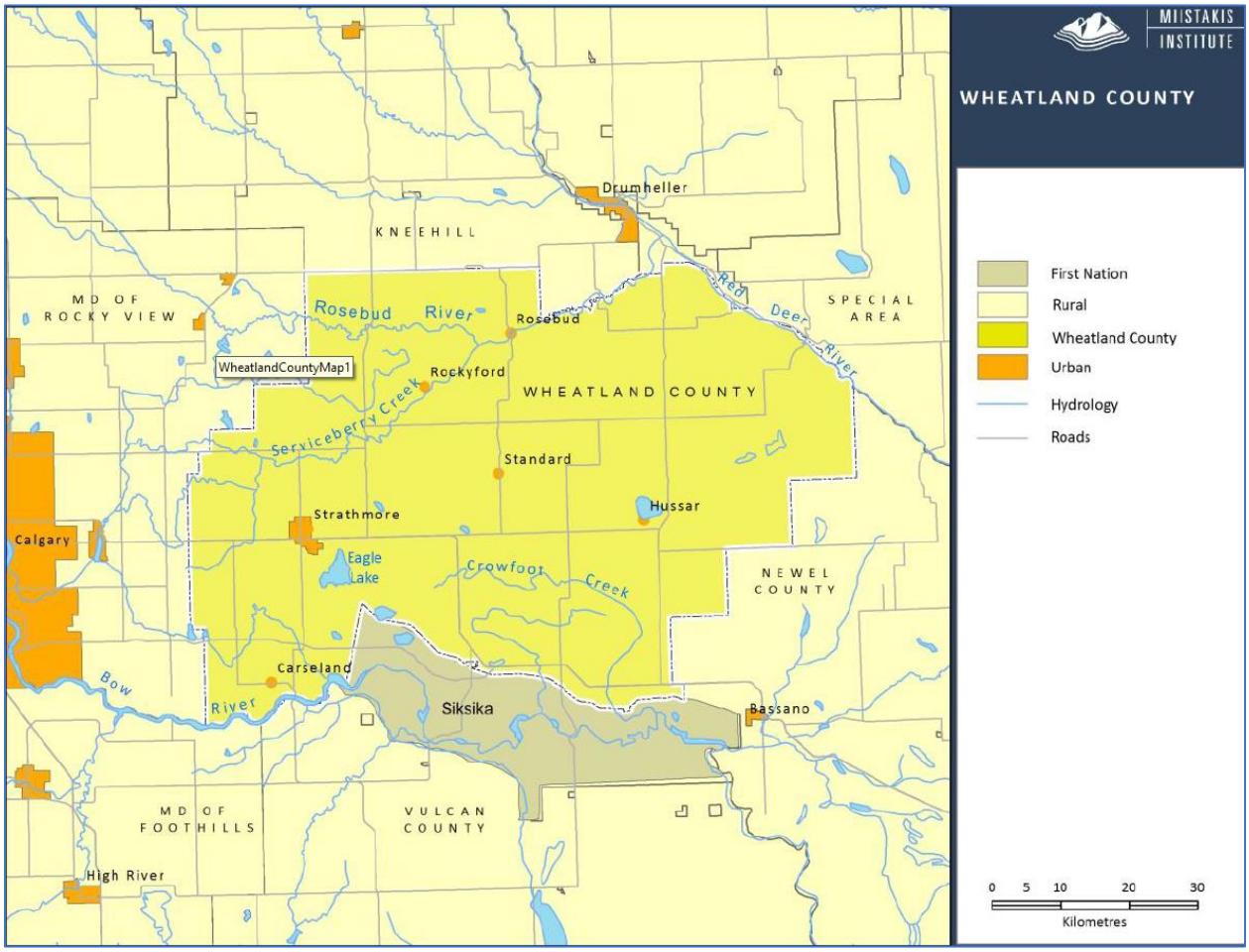
The county is made up of a mix of small communities and hamlets. The main communities managed by the county are Carseland, Gleichen and Cluny, and the main hamlet is Rosebud. There are four major communities that are within the boundary of the county but are not managed by the county namely, Strathmore, Hussar, Rockyford and Standard.

Wheatland county economy is mostly powered by agricultural industry with over 780 farms. The farmers grow wheat, canola, barley, lentils, peas. The county also has cattle feedlot farms. There is about 1100 km of irrigation canal supporting these farms. In a survey conducted by Miistakis Institute for the county in 2015 (Lee & Good, 2015), majority of the farmers strongly agreed that the quality of the county's water needs to be protected and are concerned about deteriorating water quality. The farmers are concerned about the health of riparian regions, phosphorus concentration in waterways, wetland loss and degradation due to development, algae bloom and phosphorus build up blocking irrigation and livestock water canal. The farmers are particularly worried about

the health of Eagle Lake and Bow River. The farmers believed poor wastewater and storm water management coupled with poor fertilizer application and easy access of livestock to riparian and wetland systems are some of the causes of water quality deterioration.

In terms of Wheatland County's wastewater treatment systems that is the subject of this capstone project and the management of which the farmers in the county believed is one the reasons water quality is deteriorating based the Miistakis Institute survey, there are four wastewater treatment facultative ponds located in Carseland, Gleichen and Cluny and a septic tank in Rosebud under the county's management. These wastewater treatment facilities are aging, and this is the reason Wheatland county commissioned the ACS wastewater treatment pilot project in Rosebud to explore the possibility of using microalgae to clean its wastewater. The following sections will review the environment, energy and economics of using these facultative ponds to treat wastewater.

Figure 6 Wheatland County



(Miistakis Institute, 2015)

4.2 Energy

As described in section 2.3, a facultative pond uses natural process to treat wastewater. In the case of facultative ponds in Wheatland county, gravity is used to drain the wastewater from homes into the ponds, so there is no electricity required to help pump the wastewater into the ponds. Because electricity is not used to pump wastewater into the ponds, there is no need to account for any pollution due to the primary source of energy used to generate the electricity.

4.3 Environment

As described in section 2.3, CO_2 is produced in the aerobic layer of a facultative pond, CH_4 is produced in the anaerobic layer and N_2O is produced in both the aerobic and anoxic layers. In the case of Wheatland county, there are four facultative ponds. Two ponds are located Carseland with capacities of 45,986 m^3 and 171,875 m^3. One pond is in Gleichen with a capacity of 98,000 m^3 and the fourth pond is in Cluny with a capacity of 37,474 m^3. Based on the data provided by Wheatland County, the maximum volume discharged to the waterbodies and thus the environment is about 70% of the total volume annually. So, with a combined capacity of 353,335 m^3 for the four ponds out of which 70% is released to the environment annually, the average flowrate of wastewater influent into these ponds is about 28.24 m^3/hr. The average BOD_5 of municipal wastewater influent is about 400 g/m^3 and the average TNK is about 60 g/m^3 (Henze & Comeau, 2008). Using equations 2, 3 and 4 in section 2.3 above, and the average flowrate, BOD_5 and TNK of municipal wastewater influent as highlighted in this section, the estimated CO_2 emitted into the atmosphere by the four ponds is 7.08 kg/hr, the estimated CH_4 is 2.79 kg/hr and the estimated N_2O is about 0.013 kg/hr. The estimated annual emissions of CO_2, CH_4 and N_2O are 62 tonnes, 24.4 tonnes and 0.116 tonnes respectively (see Appendix A for calculation details). Since CH_4 has 25 times global warming potential when compared to CO_2 and N_2O has 298 times global warming potential when compared to CO_2 (Climate Change Connection, 2016), the total CO_2 equivalent emission of the three gases from the four ponds is 707.8 tons of CO2 equivalent annually. To put this in perspective, this amount of emission is equivalent to the annual CO_2 emission of about 154 cars with each car emitting at the rate of 4.6 tons of CO_2 per year (U.S EPA, 2018).

4.4 Economics

Construction cost of a facultative pond is primarily a function of the size required to accommodate required flow rates to receive influent. They generally have a low operating and maintenance cost. In the case Wheatland County, there is no information about the construction cost but based on the annual financial statement of the county, it is costing an average of $162,895.00 to maintain the four facultative ponds under the county's management.

Chapter 5: Symbiotic Envirotek

5.1 Background

Symbiotic EnviroTek Inc (SETI) is a Calgary, Alberta based company that was incorporated in 2008. The goal of the company is to develop a commercially viable Algae Cultivation System (ACS) that can operate outdoors in most climatic conditions all day long, all year round, and is modularized to enable scalability and easy deployment (SETI, 2019). After a series of research and development activities, SETI introduced ACS called Modular Algae Cultivation Biofield (Mac-B) system.

The Mac-B system is designed to operate in a wide range of climatic conditions and cultivates microalga using domestic, industrial and agricultural wastewater as the growth medium. Depending on the source of the wastewater, the microalga biomass harvested from the Mac-B can be classified as food grade or non-food grade.

The Mac-B system is engineered in modular photobioreactor units to enable easy deployment and scalability. The system uses a combination of natural and artificial light coupled with specially designed media agitation and gas mixing systems to optimally accelerate the growth of microalga. The modularized design enables Mac-B system to be located close to the source of wastewater stream. The system is also designed to enable easy harvest of microalga biomass that can be used as feedstock to produce carbon neutral useful energy.

On a commercial scale, a Mac-B system consists of four (4) photobioreactor (PBR) units and are connected to form a microalga cultivation and biomass production cell. Each PBR unit has a capacity of 106,000 liters (106 m^3) and is equipped with supplementary submersible Light Emitting Diodes (LEDs) specifically designed for Mac-B for artificial lighting. The LEDs are

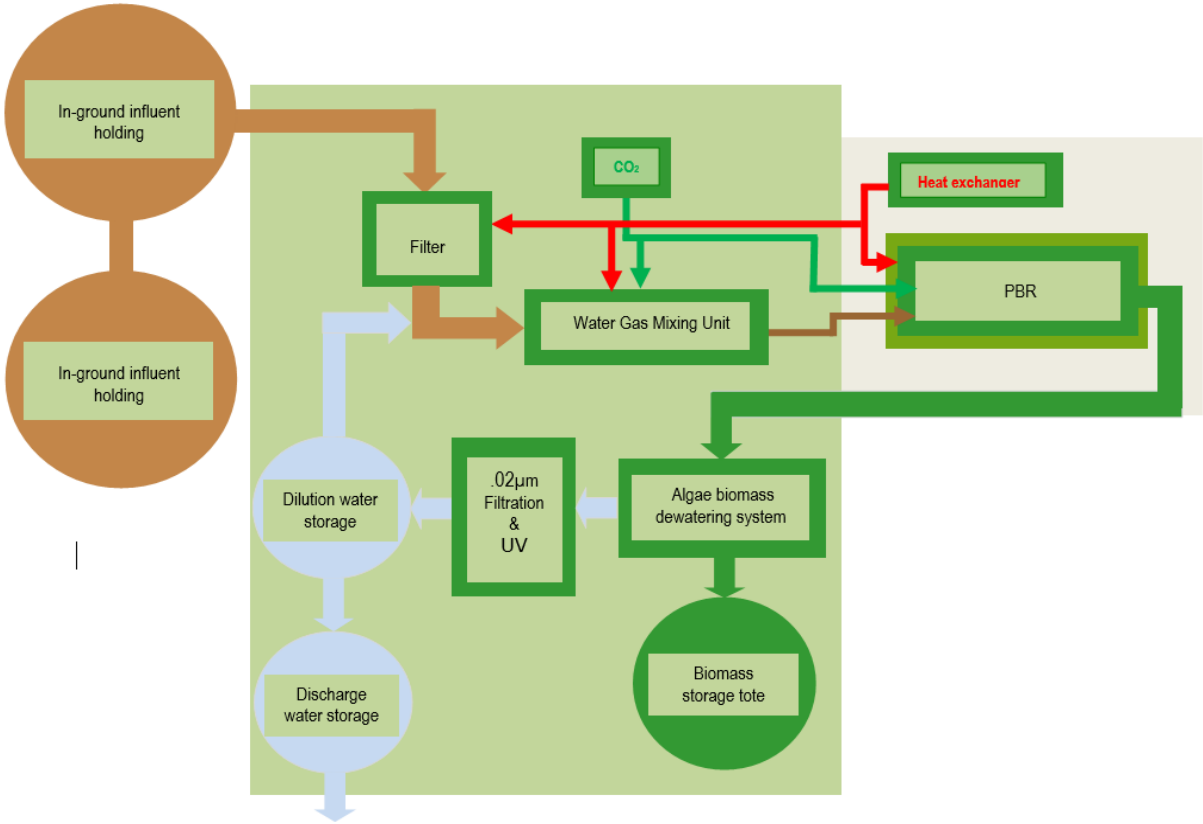
designed with irradiance range for optimal photosynthetic light input to support accelerated microalgae cell growth when there is no natural sunlight at night. The spectrum, intensity and duty cycle of the LEDs are programable to accommodate different algae strains growth characteristics. The heat released by the LEDs also support the heating of the PBR in cold climate. Each PBR is equipped with a mechanical mixing system that ensures the media is effectively being stirred to achieve homogeneity within the aquaculture and at the same time avoid any physical damage to the microalga cells. Each production cell has Head Control Unit (HCU) that is consist of nutrient feed system, Water Gas mixing system, circulating pump and Process Logic Controls.

Figure 7 below describes the workflow of SETI's ACS (SETI, 2019). The wastewater is pumped through a 100-micron bag filter to remove suspended solids and grits. The filtered wastewater then flows into the Water Gas Mixing Unit (WGMU) where it is pre-conditioned to the required temperature and pH by using captured waste heat and CO_2 respectively. The secondary function of CO_2 introduced into wastewater in the WGMU is to accelerate the photosynthesis process for microalga growth in the PBR. The conditioned wastewater is then transferred from WGMU to the PBR where it is inoculated with microalgae seeds and the growth cycle starts. The microalgae species used by SETI is *Chlorella vulgaris*.

The temperature, pH, agitation (mixing) and lighting are automatically controlled throughout the growth cycle. The aquaculture is physically checked twice a day to monitor growth rates and ensure there is no contamination of the culture. Both ammonia and phosphate levels are monitored throughout the process to ensure there is enough nutrients to support the growth of microalga. Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and microalga cells density are measured real-time throughout the growth cycle.

When the microalga density has reached between 200 to 400 million cells/ml and growth has plateaued, and nutrients in the wastewater have been mostly metabolized (typically in four days), the microalga biomass is ready to be separated from the resulting clean water. About 80% of the volume of the clean water rich microalga slurry is removed from the PBR and the microalga biomass is separated from the clean water using a centrifuge system. The clean water is passed through a 0.02-micron filter to remove particulates and ultraviolet (UV) light to kill pathogens in the water. Some of the clean water is used to mix with wastewater influent and the remaining clean water is ready to be discharged as effluent or used for irrigation or treated further for portable water. The remaining 20% microalga slurry in the PBR is used as part of the conditioning process for the next growth cycle. As indicated above, the microalga growth cycle of a PBR is about four days, so a set of four (4) PBRs are required to enable daily harvesting of microalga biomass.

Figure 7 Algae Cultivation System Workflow



(SETI, 2018a)

As mentioned in the introduction section of this project, the wastewater treatment facilities in Wheatland county are aging, and the county management are exploring the possibility of using Algae Cultivation System (ACS) to treat the county's wastewater. The first step in determining the technical feasibility of using ACS to treat wastewater was the commissioning of a pilot project in 2017 to use ACS to treat Rosebud wastewater. This pilot project was supported not only by Wheatland County but also by Federation of Canada Municipalities (FCM) and National Research Council of Canada (NRC).

The objective of the pilot project is to obtain the approval of Alberta Environment and Parks (AEP) to use SETI's ACS as a wastewater treatment solution for small communities with population less

20,000 people. To secure AEP approval, the pilot project must meet the effluent quality standard as specified by the Standards and Guidelines for Municipal Waterworks, Wastewater and Storm Drainage System (Alberta Government, 2013). The project is also expected to meet the Water Quality Based Effluent Limits (WQBEL) standards as specified by the Environmental Quality Guidelines for Alberta Surface Waters (Alberta Government, 2018a)

A key technical performance objective for SETI's ACS during the pilot project is to demonstrate the ability of the system to adapt consistently to varying conditions including weather, influent composition seasonal variation and effluent release environment.

A single $2m^3$ ACS was used to conduct the pilot project in Rosebud. A total of 42 runs of microalgae cultivation and harvesting were conducted between March and November of 2018 using wastewater influent samples from Rosebud and Gleichen. Each run was planned to last for four (4) days.

The following section describes the results of the Rosebud pilot project and the viability of a commercial scale ACS operation in Wheatland County.

5.2 Energy

Although the pilot project was in Rosebud next to the hamlet's septic tank that is about 18 m^3 in capacity, the commercial scale opportunity is with the larger facultative ponds in Carseland, Gleichen and Cluny. One of the key objectives of the pilot project was to validate the amount of microalga dry weight per cubic meter of wastewater that can be harvested from the PBRs because this will determine the amount of useful energy that can be extracted from the microalga biomass.

Figure 8 and Figure 9 show plots of microalgal growth rates using Rosebud wastewater and Gleichen wastewater respectively. In general, microalga growth rate in Gleichen wastewater

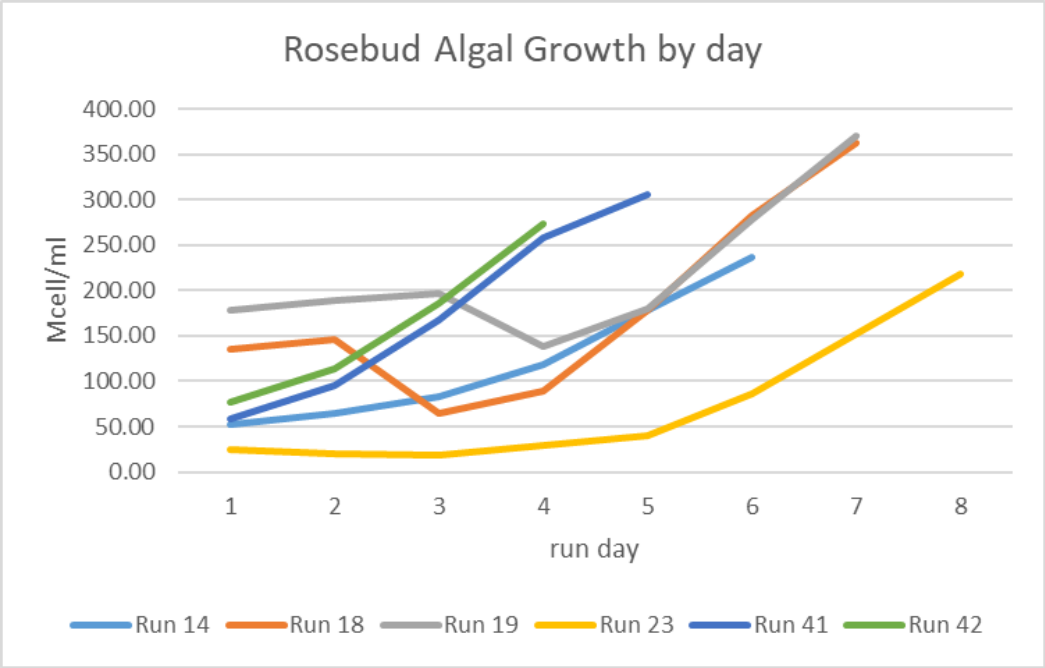
outperformed that of Rosebud wastewater. The difference in performance is being attributed to chemical additives in the Rosebud wastewater that is hindering the growth rate of microalga. Chemicals such as humic acid, fulvic acid, caustic potash, citric acid are being added to Rosebud wastewater by the residents to improve solids decomposition and aid drainage into the septic tank. The improvement in growth rate observed in Run 41 and 42 in Figure 7 was achieved when NRC's Bio-Electrochemical Anaerobic Sewage Treatment (BEAST) equipment was introduced into the workflow just before the Rosebud wastewater was pumped into the PBR.

Samples of microalga harvested from the pilot runs were dried and it was determined that based on the average yield rate of 200 million microalga cells per ml of wastewater over a 4-day period, the average dry weight of microalga per liter of wastewater is 5 g/l (5kg/m^3).

As mentioned in section 3.3 above, the combined capacity of the four facultative ponds managed by Wheatland county is 353,335 m^3 of which 70% (247,335m^3) is discharged annually to the environment. Using 5 kg/m^3 as the expected yield of dry microalga weight per cubic meter of wastewater, then the estimated annual weight of dry microalga biomass that can be harvested from cleaning 247,334.5 m^3 wastewater is 1,236,6773 kg (1,237 tons).

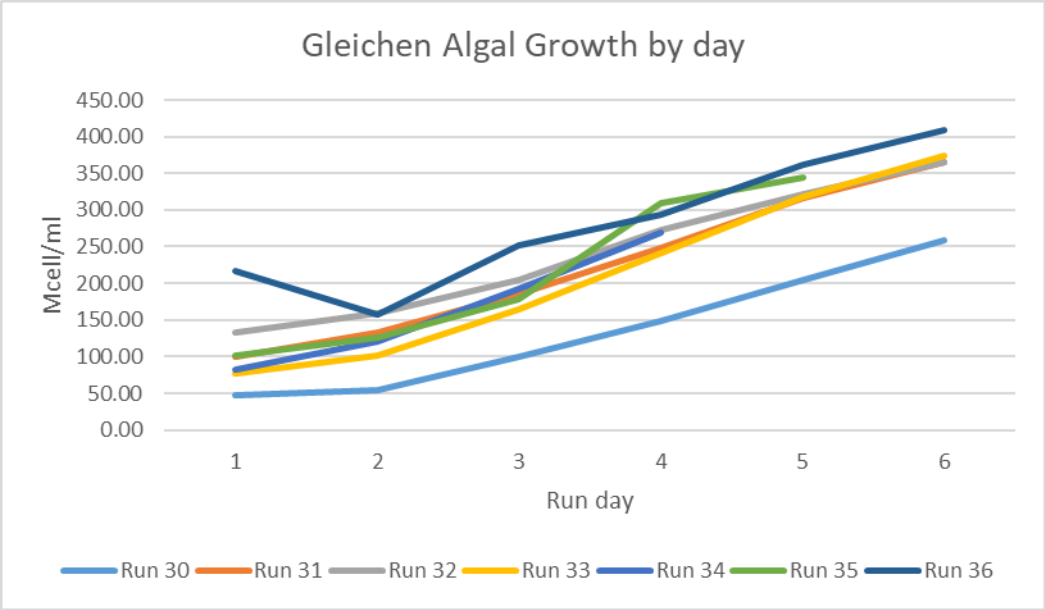
Section 6.2 below describes the volume of biocrude that can be extracted from microalga biomass using Hydrothermal Liquification (HTL) System.

Figure 8 Rosebud Wastewater Algae Growth



(SETI, 2018b).

Figure 9 Gleichen Wastewater Algae Growth.



(SETI, 2018c)

5.3 Environment

As mentioned above, for AEP to approve SETI's ACS as a wastewater treatment solution for a community with population of less than 20,000 people, the pilot project must meet the Standards and Guidelines for Municipal Waterworks, Wastewater and Storm Drainage System and the Water Quality Based Effluent Limits (WQBEL) standards as specified by the Environmental Quality Guidelines for Alberta Surface Waters.

Table 2 below highlights the variation in operating parameters throughout the pilot project. The mean exterior and media temperature were 16.01 ºC and 26.28 ºC respectively. The mean pH of the effluent was 6.71. The mean growth rate for the duration of the project was 34.32 MCell/ml/day and mean growth time was 5.29 days.

Table 2 Pilot Project Operating Parameters.

Parameter	Description	min	max	mean
Temperature °C	exterior	-6	31.1	16.01
Temperature °C	media	6.06	27.35	26.28
pH	(effluent. lab value)	6.94	8.36	7.53
pH	(avg PBR run value)	4.81	6.89	6.71
Light (run cycle)	red/red/blue	85/100/20	85/100/20	85/100/20
Fill time (min)		9	60	17.37
Harvest time (min)		21	81	36.54
Growth Mcell/ml/d		-6.22	78.35	34.31
Growing time (days)		3.89	9.86	5.29

(SETI, 2018d)

In terms of key parameters that need to meet regulatory requirements, Table 3 below compares regulatory requirements for wastewater effluent discharge to what was achieved during the pilot runs.

Carbonaceous Biological Oxygen Demand (CBOD) is an important parameter to quantify for wastewater effluent. CBOD is a measure of the oxygen required by bacteria and microorganism to biologically oxidize carbonaceous component of organic material in wastewater. Effluent with high CBOD discharged into water bodies can result in eutrophication and have negative impact on aquatic life because of the potential depletion of dissolved oxygen in rivers and lakes by CBOD. The maximum regulatory requirement for CBOD for wastewater effluent discharge is 25 mg/L and through out the 42 runs of the pilot project, the ACS consistently achieved less than 2 mg/L.

Total Suspended Solids (TSS) is the dry weight of undissolved particles in wastewater. The higher the TSS, the higher the turbidity of the wastewater effluent. The maximum regulatory limit for TSS in wastewater effluent is 25 mg/L. Throughout the 42 runs of the pilot project, the ACS consistently achieved less than 1 mg/L.

Coliform bacteria are generally harmless bacteria found in the environment and feces of animals and humans. Presence of coliform bacteria in water is an indication of potential harmful pathogens contamination of the water. There are two groups of coliform bacteria that are monitored in wastewater effluent for regulatory compliance in Alberta. The first group is the Total Coliform bacteria (T-Coliform) that exist in the environment (soil and vegetation) and are generally harmless. The second group is the Fecal Coliform bacteria (F-Coliform) that are present in the intestines and feces of animals including humans. The maximum regulatory limits for T-Coliforms and F-Coliforms in wastewater effluent are 1000 MPN/100mL and 200 MPN/100 mL respectively. As indicated in Table 3, the ACS consistently achieved less than 1 MPN/100 mL for all the 42 runs of the pilot project.

Table 3 Effluent Organic Content Regulatory requirements.

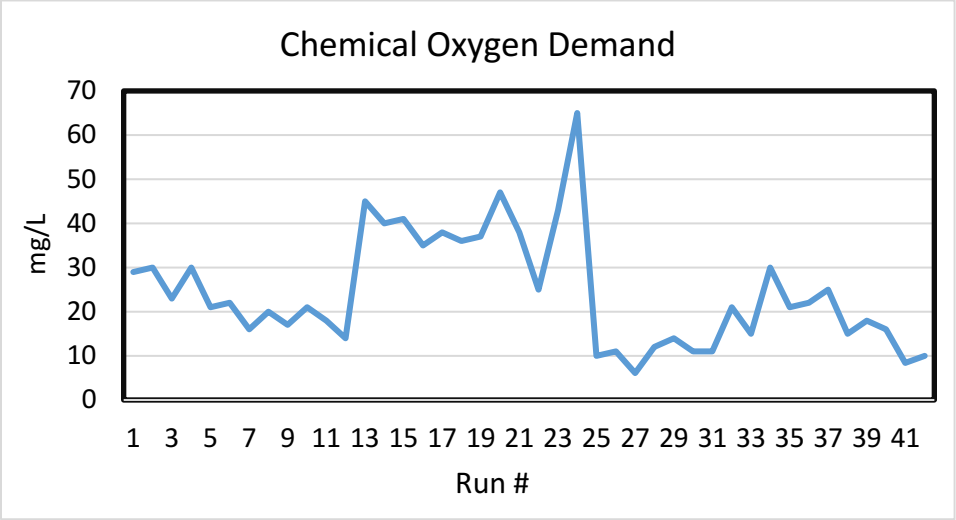
AEP Mandated Tests	Regulatory Standards	Results From 4-day Run Cycle			
Analytical	For population <20,000	Units	Run 1 - 27	Run 28 - 38	Run 39 - 42
CBOD	25	mg/L	<2.0	<2.0	<2.0
TSS	25	mg/L	<1.0	<1.0	<1.0
T-Coliforms	1,000	MPN/100mL	<1.0	<1.0	<1.0
F-Coliforms	200	MPN/100mL	<1.0	<1.0	<1.0

Run 1 - 27 : Rosebud Septage
Run 28 – 37: Gleichen Septage
Run 38 – 42 : Rosebud Septage with NRC Beast Technology pre treatment

(SETI, 2018e)

Another important parameter regulated in wastewater treatment is Chemical Oxygen Demand (COD). COD is the amount of oxygen required to chemically oxidize carbonaceous organic and inorganic substances in wastewater influent. The impact of high COD in wastewater effluent discharge into rivers and lakes is similar to CBOD in that it has the effect of depleting dissolved oxygen in bodies of water and thus negatively affecting aquatic life in rivers and lakes. The maximum regulatory limit of COD in wastewater effluent in Alberta is 150 mg/L. Figure 10 below is a plot of the wastewater effluent COD for the 42 runs and the ACS consistently achieved lower COD than required by regulations.

Figure 10 Rosebud wastewater effluent COD measurements.

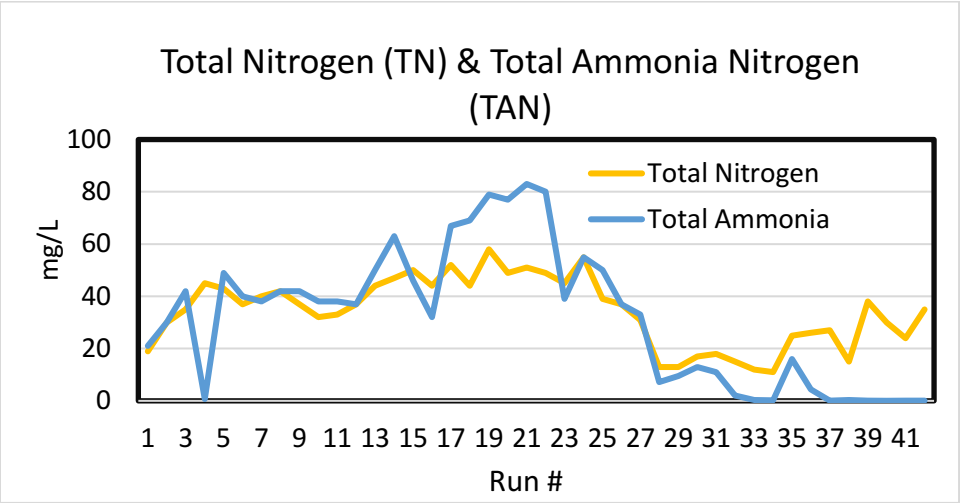


(SETI, 2018f)

Total Ammonia Nitrogen (TAN) which is the summation of un-ionized ammonia (NH_3) and ionized ammonia (NH_4^+) in wastewater effluent is also regulated in Alberta but limits are site specific because limits are set based on pH and temperature of the receiving freshwater body. Generally, un-ionized ammonia is toxic to fish and aquatic life, and the recommended limit for aquatic life protection by Canadian Council of Ministers of the Environment (CCME) is 0.019 mg/L (CCME, 2010). TAN also plays a complimentary role as a source of nutrient, specifically nitrogen, for algae growth. Figure 11 below shows a plot of all Total Nitrogen and Total Ammonia Nitrogen of the 42 runs during the pilot project. As can be observed, the TAN level for the wastewater effluent was above CCME guideline for most of the runs although an average of 40% reduction in TAN of the influent wastewater was achieved by the ACS. The high TAN was because of the time required to establish nitrifying bacteria in the ACS aquaculture but once established, the wastewater effluent TAN was below the guideline as shown from runs 37 through 42. One of the key decisions to be made in the future for commercial operation is how to strike a balance between accelerating nitrification to meet regulatory requirements and at the same time ensure the

microalga has enough TAN as nutrient for growth because of microalgae affinity to use as nutrient nitrogen from ammonia rather than nitrate produced due to nitrification of ammonia; this should put into consideration that oxygen released by microalgae will contribute to ammonia nitrification.

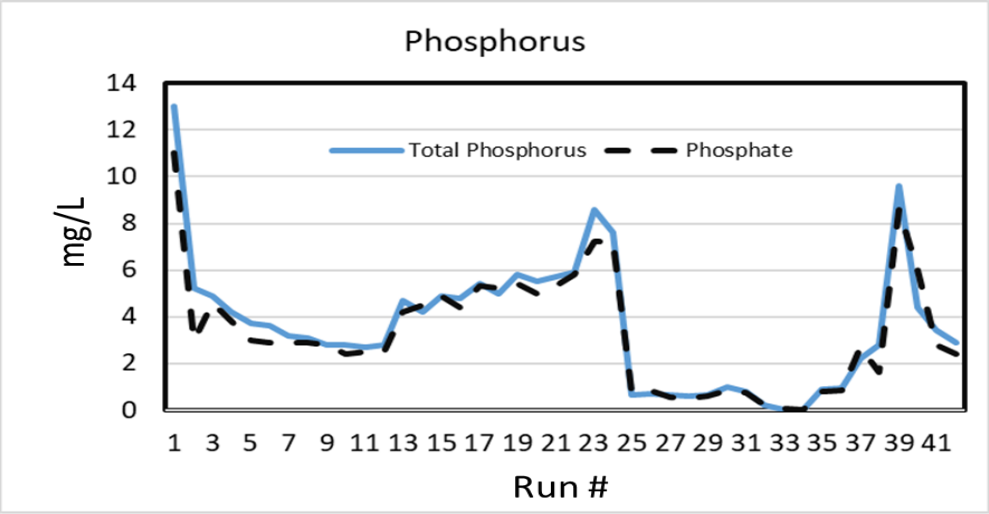
Figure 11 Total Nitrogen & Total Ammonia Nitrogen Plot



(SETI, 2018g)

Although phosphorus in wastewater is another important nutrient source for microalga growth but it is regulated by Alberta government because excess discharge of phosphorus in wastewater effluent into freshwater bodies could lead to eutrophication that can negatively impact fish and aquatic life. Based on CCME guideline enforced in Alberta, phosphorus in wastewater effluent should not exceed 1 mg/L (CCME, 2004). As shown in Figure 12 below, all the runs using Gleichen wastewater achieved phosphorus levels below CCME levels but the runs using Rosebud wastewater had phosphorus levels above CCME levels, this was attributed to the additives in Rosebud septic tank. In general, the ACS achieved between 30-87% reduction in phosphorus levels in the wastewater influent for both Gleichen and Rosebud.

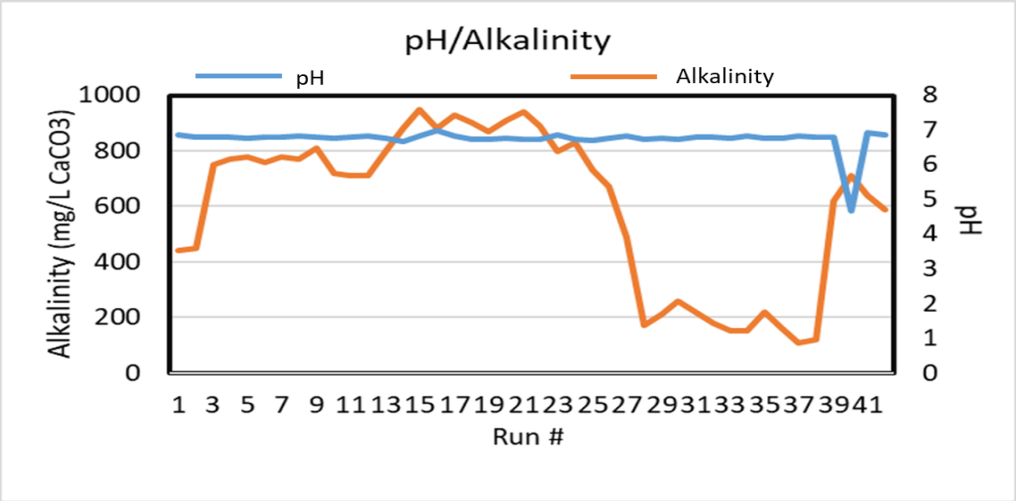
Figure 12 Phosphorus and Phosphate plot



(SETI, 2018h)

High or low pH of wastewater effluent for discharge into rivers or lakes could have negative impact on fish and aquatic life. CCME set guideline of between 6.5 and 9.5 for pH of wastewater effluent (CCME, 1999), this guideline is enforced in Alberta. As shown in Figure 13 below, the ACS was able to maintain pH at about 7 even though the alkalinity of Rosebud wastewater influent was higher than that of Gleichen due to the additives in Rosebud wastewater influent. The steady pH was achieved for most of the run due to continuous infusion of CO_2 into the aquiculture as the microalga grew in the ACS. This pH range is also very suitable for a healthy microalga growth.

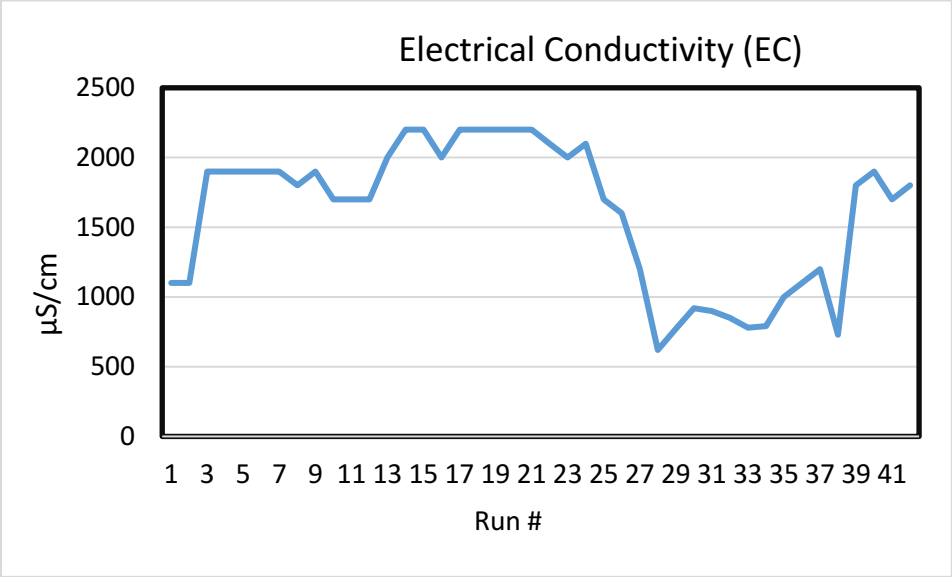
Figure 13 pH and Alkalinity Plot



(SETI, 2018i)

Electrical Conductivity (EC) of wastewater effluent is also regulated in Alberta, especially if the wastewater effluent is going to be used for irrigation. EC is the measure of the capacity of wastewater effluent to allow electric current to flow through it due to free ions in the wastewater. High conductivity has a correlation to dissolved salts in the wastewater and these can have a negative impact on plant growth if used for irrigation. Wastewater effluent EC must not exceed 2500 µS/cm in Alberta. As shown in Figure 14 below, the ACS was able to maintain EC below the regulatory requirement of 2500 µS/cm throughout the 42 runs even though the Rosebud wastewater effluent EC was higher than that of Gleichen, again due to the additives in the Rosebud wastewater influent.

Figure 14 Electrical Conductivity Plot

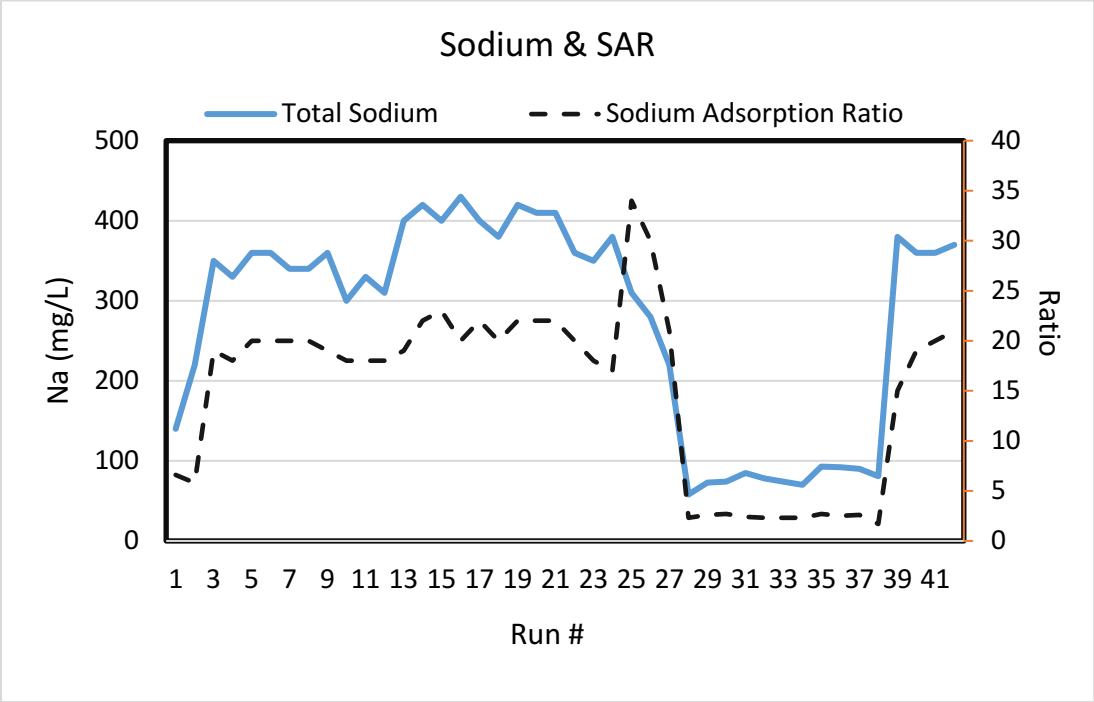


(SETI, 2018j)

Sodium Absorption Ratio (SAR) is another wastewater effluent parameter that is regulated in Alberta, especially if the wastewater effluent is going to be used for irrigation. SAR is a ratio that compares the relative quantities of sodium, calcium and magnesium in a sample of wastewater effluent. Sodium accumulated in soil can result in degradation of the soil structure, and this can result in poor crop yield. SAR measurement is quite important if wastewater effluent would be used for irrigation to avoid degradation of the soil structure. The regulatory requirement for SAR in Alberta is less than nine (9). As shown in Figure 15 below, Gleichen wastewater effluent SAR is below the regulatory requirement (Runs 28-37) but the Rosebud wastewater effluent is above the regulatory requirement due to the additives in the wastewater.

As mentioned earlier, CO_2 infusion into the aquaculture in the ACS serves a dual role of maintaining a neutral pH and support a healthy accelerated microalga growth rate. Based on the pilot project results, about 2 tons of CO_2 was required to grow 1 ton of dried microalga biomass.

Figure 15 Sodium and SAR Plot



(SETI, 2018k)

Lastly, water toxicity test was performed on the wastewater effluent by introducing rainbow trout into samples of wastewater effluent in runs 34, 35, 36, and 41. This test was performed in accordance with Alberta Government guideline (Alberta Government, 2018b). The resulting Lethal Concentration 50 (LC_{50}), defined as the concentration of the wastewater sample that would result in the death of 50% of the rainbow trout over a 96-hour period, was zero (0) because no trout died over the 96-hour period. Both Rosebud and Gleichen wastewater effluents for all the 42 runs were confirmed to be non-toxic based on the results of lab tests performed by Maxxam, see Table 4 below.

Table 4 Water Toxicity Test Result

AEP Mandated Tests	Regulatory Standards	Results From 4-day Run Cycle	
Water Toxicity Test	Mortality Rate	Hours	Runs 34 – 35 – 36 – 41
Fish Mortality	0	96	0
Micro-Toxicity Test	Toxicity Limit	Measurement	Runs 1 – 42
Water Toxicity	0	% CI	0

Run 1 - 27 : Rosebud Septage
Run 28 – 37: Gleichen Septage
Run 38 – 42 : Rosebud Septage with NRC Beast Technology pre treatment

(SETI, 2018l)

5.4 Economics

As mentioned in section 5.1 above, a commercial scale SETI's ACS is a Mac-B consisting of four 106 m^3 photobioreactors connected to form a cell. Each Mac-B cell cost about five million dollars ($5 million). Based on the volumetric capacity of the lagoons in Carseland, Gleichen and Cluny, this project would be evaluating the economics of installing three Mac-B cells in Carseland, two Mac-B cells in Gleichen and one Mac-B cell in Cluny (see Appendix B for calculation detail). The capital expenditure for six cells of Mac-b is about $30 million. Based on a 4-day cycle of treating wastewater and harvesting microalga biomass, a total of 232,140 m^3 of wastewater would be treated annually and this could potentially yield about 1,160,700 kg dry weight (1160.7 tons) of microalgae biomass.

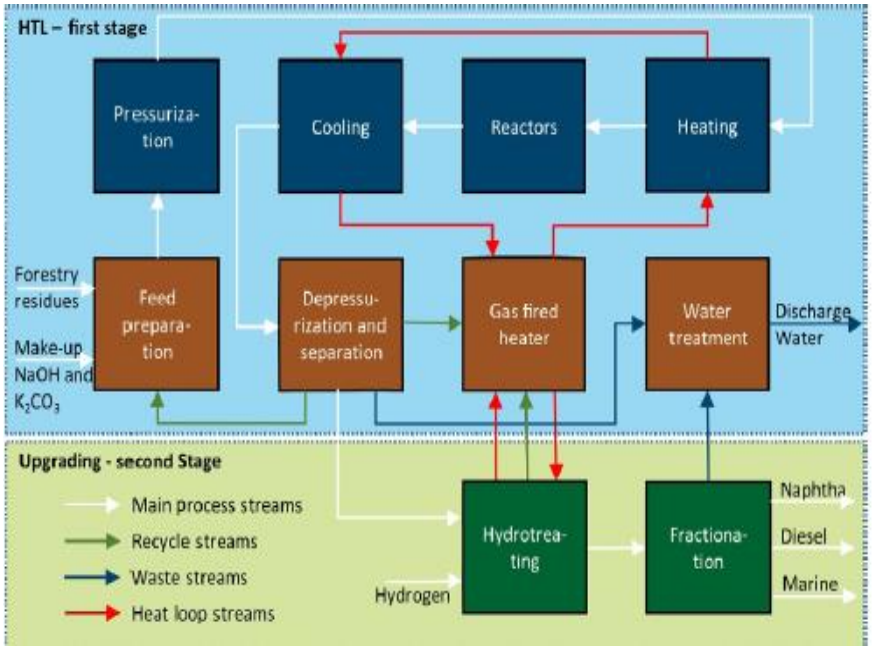
Chapter 6: Steeper Energy

6.1 Background

Steeper Energy is a Danish-Canadian company founded in 2011 with a primary focus of commercializing an HTL technology called Hydrofaction (Steeper Energy, 2019). The company's goal is to use Hydrofaction to transform low value biomass (forestry waste, agricultural residue) as feedstock to produce valuable and cost-competitive bio-fuels that will be compatible with existing fossil-fuel-based systems and infrastructures, and thus help in reducing global carbon footprint.

The Hydrofaction system operates within a pressure range of between 300-350 bars and a temperature range of between 390-420 ^{o}C (Jensen, Guerrero, Karatzos, Olofsson, & Inversen, 2018). The pressure and temperature parameters operate above water critical point, this is a unique feature of the Hydrofaction system that helps in representing different reaction phases using density and temperature rather than pressure and temperature. It uses potassium carbonate (K_2CO_3) and Sodium Hydroxide (NaOH) as catalyst and to help control the pH to reduce corrosion. Hydrofaction process of converting biomass to biocrude is as described in section 2.2 above and Figure 16 below shows a schematic of the system process workflow using a forestry waste feedstock.

Figure 16 Hydrofaction process workflow



(Steeper Energy, 2018a)

In 2013, the company commissioned a 0.5-bpd Hydrofaction pilot plant in Denmark and as of November of 2017, the system exceeded 4750 hours of operation and 1750 hours of bio-crude production, an equivalent of 36 bbl produced. The feedstock for this system is mostly forestry waste.

Steeper Energy is in the process of constructing and commissioning a EUR 50.6 million industrial scale Hydrofaction pilot plant located at a former pulp mill in Tofte, Norway. This project is in partnership with Silva Green Fuel, a Norwegian-Swedish joint venture.

Although the primary focus of Steeper Energy is to use forestry waste as feedstocks for the Hydrofaction system, but the company is interested using microalgae biomass harvested from wastewater treatment and organic-rich wastewater sludge as feedstocks.

The following sections describes the energy, environmental and economical implication of using a 50-barrel-per-day (bpd) Hydrofaction system to convert the microalgae biomass harvested from using SETI's Mac-B system to biocrude.

6.2 Energy

As mentioned in section 5.4 above, the six Mac-B cells recommended for Carseland, Gleichen and Cluny have the potential of generating about 1,160,700 kg of microalgae biomass annually. Using the NRC HTL results as highlighted in section 2.2 above, 1,160,700 kg of microalgae biomass would produce 499,101 kg of biocrude annually at 43% yield. This is equivalent to about 3658 barrels of biocrude annually or 10 bpd (1000 kg of biocrude = 7.33 barrel of biocrude). The amount of microalgae biomass to be harvested from the three locations under consideration would underutilize a 50-bpd HTL that requires about 6,000,000 kg dry weight of microalgae biomass as feedstock annually. Aggregation of other sources of organic waste such was wastewater sludge and agricultural waste will be required to operate this system at full capacity.

6.3 Environment

The Hydrofaction HTL process produces biogenic CO_2 and significant electricity power is required to operate the system and to produce the hydrogen required for hydrotreating. Table 5 below shows a comparison of GHG emissions of a 2000-bpd Hydrofaction system using forestry waste as a feedstock and petroleum-based diesel fuel. Steeper Energy estimates that Hydrofaction system reduces GHG emissions by 77%.

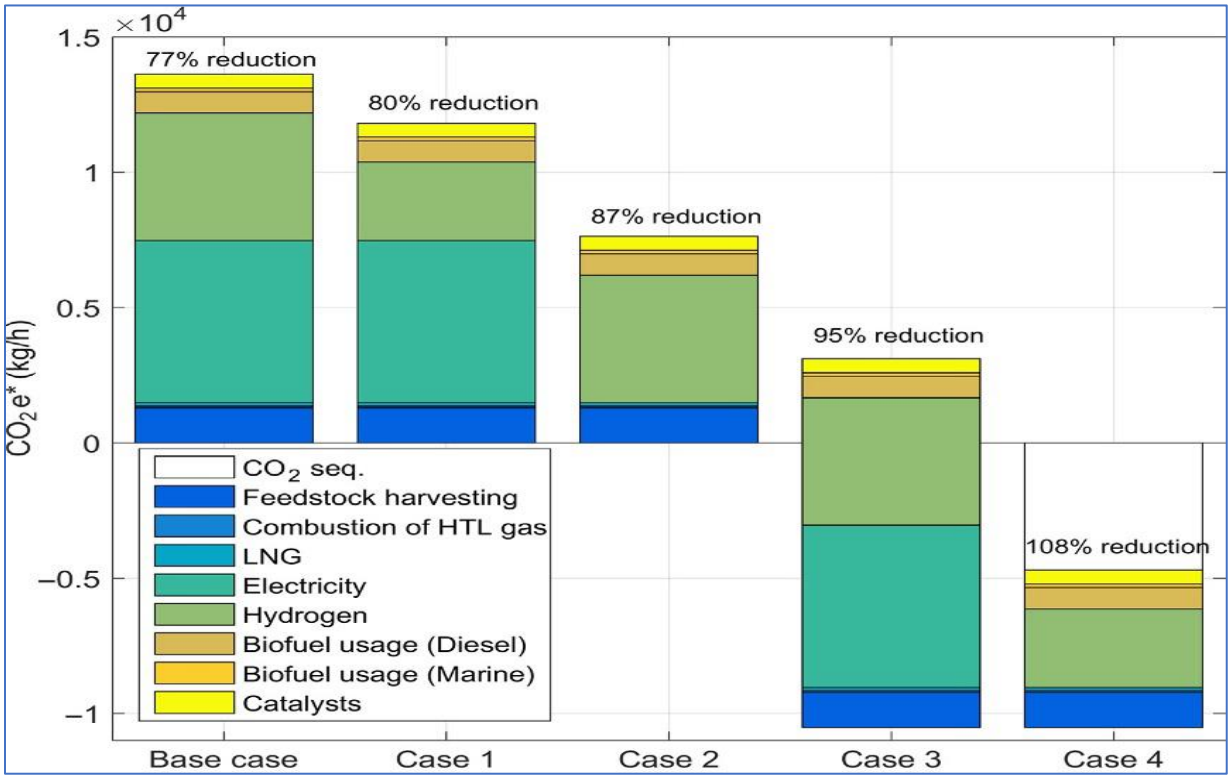
Table 5 Hydrofaction system Vs fossil fuel GHG emissions comparison

Emission source	Amount		CO_2 (kg/h)	CH_4 (kg/h)	N_2O (kg/h)	CO_2e* (kg/h)
2000 BPD Hydrofaction™ plant						
Feedstock collection and transport	29.2	tonne/h	1.2E+03	6.2E−02	1.9E−01	1295
Combustion of HTL process gas	3436	m^3 LNGe/h	Biogenic	1.3E+00	1.1E−01	66
Combustion of purchased LNG for heat	60.9	m^3/h	1.2E+02	2.3E−02	2.0E−03	118
Purchased electricity	9362	kWh/h	BNA	BNA	BNA	5992
Purchased hydrogen	530	kg/h	BNA	BNA	BNA	4717
Drop-in diesel fuel usage	6.5	m^3/h	Biogenic	8.6E−01	2.6E+00	791
Drop-in marine fuel usage	6.5	m^3/h	Biogenic	2.2E−01	4.1E−01	129
Make-up catalysts	1087	kg/h	BNA	BNA	BNA	443
CO2 sequestration	0	tonne/h	BNA	BNA	BNA	0
Hydrofaction™ GHG emission total						13550
Petroleum baseline						
Extraction and refining of petroleum diesel and fuel oil	12.9	m^3/h	1.8E+03	1.4E+02	5.2E−02	5313
Diesel combustion	6.5	m^3/h	1.7E+04	8.6E−01	2.6E+00	17974
Heavy fuel oil combustion	6.5	m^3/h	2.0E+04	2.2E−01	4.1E−01	20287
Wood waste stockpiling, decomposition	29.2	tonne/h	Biogenic	5.9E+02		14642
Baseline GHG emission total						58216
GHG emission reduction						44666
GHG emission reduction relative to baseline						77

(Steeper Energy, 2018b)

Figure 17 below describes four different scenarios that can result in GHG reduction above 77% when compared to petroleum-based diesel fuel. The volume of hydrogen required for purchase can be reduced if the hydrogen generated during the HTL process is captured and used for the hydrotreating; Steeper Energy estimates this can result in 80% reduction in GHG emissions when compared to diesel fuel (case 1). If the source of electricity for Hydrofaction is from renewable energy and not fossil energy, Steeper energy estimates that GHG emission would be reduced by 87% when compared to diesel fuel (case 2). If the biogenic CO_2 generated is sequestered or used as a feedstock for the Algae Cultivation System, it is estimated that GHG emission reduction by Hydrofaction would be 95% when compared to diesel fuel (case 3). If cases 1-3 are implemented together, Steeper energy estimates that the hydrofaction system would reduce GHG emission by 108% when compared to diesel fuel, effectively becoming a carbon sink system.

Figure 17 Hydrofaction GHG Emissions reduction scenarios



(Steeper Energy, 2018c)

Nutrient rich wastewater is also produced during the HTL process that can be used in the ACS. Lastly, ashes are also by produced by Hydrofaction system that would require a disposal plan, most likely ending up in a landfill.

6.4 Economics

As highlighted earlier, Steeper Energy primary focus is to use forestry waste as feedstock for the Hydrofaction system. The cost of a 2000-bpd system, requiring 700 tons of dry weight biomass per day, is estimated to be about $250 million. Steeper is also exploring manufacturing a 50-bpd Hydrofaction system that would be integrated into a wastewater treatment plant and can use wastewater sludge and microalgae biomass harvested from ACS as feedstock. Using the rule of seven-tenths (recommended by Steeper Energy) as against the rule of six-tenths (Whitesides, 2012)

on a 2000-bpd, $250 million Hydrofaction system, the cost estimate for a 50-bpd Hydrofaction system is about $18.9 million with a +/- 20% accuracy (see appendix C for calculation details). For this equipment to be economical, Steeper Energy would be relying on wastewater sludge tipping fee as the main revenue stream with the sale of biocrude as a secondary revenue stream.

Chapter 7: Analyses, Discussion and Limitations of Findings

7.1 Energy

As highlighted in section 6.2 above, an annual production of 1,160,700 kg dry weight of microalgae biomass feedstock will produce about 10 bpd of biocrude by Hydrofaction. This amount of microalgae biomass will underutilize a 50-bpd Hydrofaction system that requires an estimated 6,000,000 kg dry weight biomass annually to operate at full capacity. Since Hydrofaction is not restricted by biomass types, wastewater sludge and agricultural wastes could be aggregated with the microalgae biomass to operate the Hydrofaction system at full capacity, but different biomass sources will affect the effective production rate of the system.

There are some research works that can be conducted to increase the biocrude daily production rate. As an example, 10% increase ACS microalgae yield and a 10% increase in the volumetric capacity of the ACS photobioreactor in the base case above will result in 21% increase microalgae dry weight biomass and thus 21% increase in biocrude volume produced per day. If HTL biocrude yield can be increased from 43% to 50% in addition to the 21% increase in microalgae biomass dry weight, then the daily biocrude production rate will increase by about 41% when compared to the base case.

To increase the microalgae biomass yield from 5 kg/m^3 in the ACS, exploring the use of other microalgae species or strain would be important. Also, optimizing the Carbon:Nitrogen:Phosphorus (C:N:P) supply ratio by adding nutrients to supplement growth rate over the four-day cycle to match the cultured species' optimal growth ratio can also be explored (Lee, et al., 2013).

Increasing the capacity of the ACS photobioreactor could also help increase the ACS microalgae biomass yield. This will require re-engineering the Mac-B system, including ensuring the LEDs providing artificial light required for photosynthesis and the aquaculture mixing system are still effective to support a 4-day harvesting cycle.

Optimizing parameters such as temperature, pressure, water/feedstock ratio, resident time to increase the biocrude yield in the Hydrofaction is another area of research that can support the attractiveness of the HTL system.

Another method of extracting useful energy from microalgae biomass is to use the biomass as a feedstock for anaerobic digestion (AD). When compared to hydrothermal liquefaction system, AD systems are well established and are used in converting organic waste to biogas. An AD system has the flexibility to aggregate other organic wastes such as manure and other agricultural wastes as feedstocks.

Lastly, aggregating feedlots organic wastes in a place like Alberta will be of major economic and environmental importance whether an HTL or AD process is used to extract useful energy from microalgae biomass. This is because of the abundance of feedlots in Alberta, especially in the southern part of the province.

7.2 Environment

The Rosebud Algae Cultivation System pilot project demonstrated the potential of the system to treat wastewater to meet critical regulatory requirements to discharge the wastewater to the environment and for irrigation. Critical parameters, such as CBOD, COD, TSS, T-Coliforms and F-Coliforms were below regulatory requirements as highlighted in section 5.3 above. The results of the pilot project also demonstrated that the performance of the ACS depends on the source

wastewater based on different results using Rosebud or Gleichen wastewater. The Rosebud pilot project also demonstrated the capability of the system operate in cold climate with exterior temperature as low as -38°C.

As mentioned in section 5.3 above, 2 tons of CO_2 is required to grow a ton of dry weight microalgae biomass (ratio 2:1) using the ACS. So, about 2,320,400 kg of CO_2 will be sequestered annually in the microalgae biomass based on an annual production of 1,160,700 kg if the Mac-B cells are deployed to treat the county's wastewater. This is in addition to the estimated 707,800 kg of CO_2 equivalent that will be prevented from being released by the facultative ponds in Carseland, Gleichen and Cluny by using the Mac-B systems. Also, as mentioned in section 6.3, the biocrude produced by HTL has a potential to significantly reduce GHG emissions when compared to petroleum-based diesel fuel with a base case of 77% reduction.

Further study should be conducted on optimizing wastewater nutrients removal by the ACS. A comprehensive Life Cycle Assessments (LCAs) should be performed on both the ACS and HTL to quantify the GHG emissions reduction potential of these systems. In most likelihood, a combination of Mac-B cells in multiple locations and a single HTL system will be required for the operation, and emissions from transporting of organic biomass from multiple locations need to be factored into the LCA.

7.3 Economics

As highlighted in section 5.4 and section 6.4, the total capital expenditure to deploy Mac-B cells in Carseland, Gleichen and Cluny is about $30 million and to deploy a 50-bpd Hydrofaction unit is approximately $20 millions. This brings the total capital expenditure to $50 million.

There are two main revenue streams from this operation. The first revenue stream is the tipping fee which is the price the County is willing to pay a third party to clean its wastewater. The tipping fee Wheatland County agreed to pay SETI is $2.5 per cubic meters of wastewater treated. As mentioned in section 5.4, the Mac-B cells will treat 232,140 m^3 annually, so the annual revenue from tipping fee is $580,350.

The second revenue stream is the sale of biocrude. Assuming there is no premium paid for the biogenic CO_2 produced by burning biocrude, the price that a refinery is willing to pay for the biocrude is the price of crude oil per barrel minus the refining cost (or crack spread). Assuming the Hydrofaction is operating at full capacity by aggregating other sources of biomass, the price of crude oil is $60, and the refining spread is $15, the annual revenue from the sale of biocrude is $821,250. Obviously, the price of crude oil and the refining spread will fluctuate based on supply and demand of the commodity.

Assuming a 20% profit from the revenue, a generous discount rate of 6% and a 20-year lifetime for the Mac-B cells and Hydrofaction system (with zero value at end of lifetime), the NPV at a constant annual cashflow of $280,320 over 20 year on an initial invest of $50 million is -$46.8M (see appendix D for calculation details). This will not be a profitable venture if this system is deployed.

Assuming a tipping fee of $10 per cubic meters of wastewater treated, biocrude price of $60 per barrel, the capital cost of $25 million and a simplistic case of the cost of goods sold and cost of operation staying the same as above base case, then the NPV at a constant annual cashflow of $2,295,194 over 20 years on an initial investment of $25 million is +$1,325,684.

Based on the two financial scenarios above, the economical viability of deploying this wastewater treatment solution depends mostly on the tipping fee and initial capital expenditure. The revenue stream from biocrude sale should not be the basis for determining the economic viability of this system because biocrude is a commodity with price variation that is mostly driven by supply and demand.

To objectively determine the true cost of treating wastewater and thus the tipping fee, externalities such as the costs of poor water quality on human health and agricultural yields, GHG emissions causing climate change and eutrophication of rivers and lakes affecting aquatic life need to be put into consideration. Although the price of biocrude can vary widely, there should be a premium on its price compared to fossil crude oil because of the biogenic CO_2 produced when biocrude is burn as fuel. Revenue can also be generated by using this wastewater solution as a carbon offset instrument because of its ability to significantly reduce non-biogenic GHG emissions from burning fossil fuel.

Lastly, one of the key avenues of reducing the initial overall capital cost of deploying the Mac-B cells and Hydrofaction systems is going to be economic of scale. These two systems are still at a very early developmental stage and until these systems are adopted and widely deployed in large quantities, the cost of deploying them may stay prohibitively high.

Chapter 8: Conclusion and Future Research

This capstone project has demonstrated the technical efficacies of using an Algae Cultivation System to treat wastewater and the conversion of microalgae biomass to biocrude using a Hydrothermal Liquefaction system. Based on the work that has been done so far, there is a high level of confidence in technically scaling up SETI's ACS and Steeper Energy HTL to commercial operations.

A major milestone was achieved by SETI through the results obtained from the Rosebud pilot project. SETI's ACS is closer to being approved by AEP as a wastewater treatment solution due to the quality of wastewater effluent produced during the project. As mentioned above, the ACS produced wastewater effluent that met most of the regulatory requirements for discharge or reuse for irrigation. In addition, the project was able to demonstrate the effectiveness of the ACS using two different wastewater streams. The resilience of the ACS in cold climate was also demonstrated during the pilot project. The commercial viability of Mac-B will depend on the cost of deploying the system and the tipping fee that will be charged for treating wastewater.

Similar to SETI's Mac-B, Steeper Energy's Hydrofaction has not been deployed on a commercial scale yet but the results obtained from the 0.5-bpd pilot plant have been encouraging. One of the key findings of this project is that the volume of wastewater available in Wheatland County is not enough to cultivate and harvest microalgae biomass to operation a 50-bpd Hydrofaction at full capacity, so aggregation of other sources of organic waste such as wastewater sludge will be required. The commercial viability of Hydrofaction will depend on the cost of deploying the system, effective aggregation of appropriate organic waste such wastewater sludge and the tipping fee for handling these waste streams. The commercial viability of a 50-bpd Hydrofaction system

cannot depend on biocrude sale because of the low volume produced and the unpredictability of biocrude price as a commodity.

There two main future research works that is recommended for this project. The first research work is around increasing the yield of microalgae biomass produced by Mac-B and increasing the volume of biocrude produced by Hydrofaction system. To improve the yield of microalgae biomass, research on microalgae species and on how to effectively increase the capacity of Mac-B PBRs will be important. To increase the volume of biocrude produced by Hydrofaction, research on the optimal operating parameters such as temperature, pressure, resident time, biomass/water ratio will be important.

The second research work recommended for this project is how to logistically integrate the Mac-B and Hydrofaction system. Aggregation of biomass from multiple locations will be required to operate the 50-bpd Hydrofaction system at full capacity if deployed in Wheatland County. Research on the optimum location of the Hydrofaction system relative to the locations of biomass cultivation and harvesting will be important.

In general, there are about 400 municipal wastewater lagoons in Alberta. It is not too far fetched to envision decommissioning these lagoons and replacing them with a series of Mac-B cells and centrally located Hydrofaction systems to convert biomass from these multiple locations to biocrude. As an analogy to oil and gas industry, each wastewater lagoon location can be thought of as a “well head” and the Hdyrofaction system handling biomass from these multiple locations as a “refinery”.

The circular economy solution proposed in this project is a viable solution to treating wastewater in rural communities and at the same time produce biomass that can be used to generate useful

energy. The cost of deploying this solution today is prohibitively high and it may well take government sponsorship to achieve the economic of scale that will enable a wide adoption of this wastewater treatment solution.

References

Abdel-Raouf. (2012). *Microalgae and Wastewater Treatment.* Riyadh: Elsevier.

Alberta Government. (2013). *Standards and Guidelines for Municipal Waterworks , Wastewater and Storm Drainage Systems.* Edmonton: Alberta Queen's Printer.

Alberta Government. (2018a). *Environmental Quality Guidelines for Alberta Surface Waters.* Edmonton: Alberta Queen's Printer.

Alberta Government. (2018b, March 02). *Guidelines for conducting toxicity testing on wastewaters*. Retrieved from Alberta Government: https://open.alberta.ca/dataset/guidelines-for-conducting-toxicity-testing-on-wastewaters

Al-Qasmi, M., Raut, N., Talebi, S., Al-Rajhi, S., & Al-Barwani, T. (2012). A review of effect of light on microalgae growth. *World Congress on Engineering* (p. No pages reference). London: researchgate.

Arashiro, L. (2016). *Microalgae as a sustainable alternative for wastewater treatment.* International Water Association.

Bartley, M. L., Boeing, W. J., Dungan, B. N., Holguin, O. J., & Schaub, T. (2013). pH effects on growth and lipid accumulation of the biofuel microalgae Nannocloropsis Salina and invading organisms. *Journal of Applied Phycology*, 1431-1437.

Bill, P., & Ross, A. (2016). Production of biofuels via hydrothermal conversion. In C. L. Rafael Luque, *Handbook of Biofuels Production* (pp. 509-547). Duxford: Woodhead Publishing.

Borowitzka, M. (2013a). Energy from Microalgae: A Short History. In N. M. Micheal Borowitzka, *Algae for Biofuel* (pp. 1-15). New York: Springer.

Borowitzka, M. (2013b). Species and Strain Selection. In M. Borowitzka, & N. Moheimani, *Algae for Biofuels* (pp. 77-89). New York: Springer.

Brennan, L., & Owende, P. (2010). Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products. *Renewable and Sustainable Energy Reviews*, 557-577.

Canada Water Network. (2018). *Canada Challenges and Opportunities to Address Contaminants in Waterwater.* Ottowa: Canada Water Network.

Carvalho, J. C., Matsudo, M. C., Bezerra, R. P., Ferreira-Camargo, L. S., & Sato, S. (2014). Microalgae Bioreactors. In R. Bajpai, A. Prokop, & M. Zappi, *Algal Biorefineries* (pp. 83-126). New York: Springer Science.

CBC. (2018, Mar 22). *Here are the places in Canada — yes, Canada — vulnerable to drought*. Retrieved from Canada Broadcasting Corporation: https://www.cbc.ca/news/technology/water-at-risk-canada-drought-1.4570333

CCME. (1999). *Canadian Water Quality Guidelines for Protection of Aquatic Life - pH.* Hull: CCME.

CCME. (2004). *Canadian Water Quality Guidelines for Protection of Aquatic Life - Phosphorus.* Hull: CCME.

CCME. (2010). *Canadian Water Quality Guidelines for Protection of Aquatic Life - Ammonia.* Gatineau: CCME.

Climate Change Connection. (2016, April 27). *CO2 EQUIVALENTS*. Retrieved from Climate Change Connection: https://climatechangeconnection.org/emissions/co2-equivalents/

Elliott. (2013). *Process development for hydrothermal liquefaction of algae feedstocks in a continuous-flow reactor.* Richland: Elsevier.

Gollakota, A., Kishore, N., & Gu, S. (2017). A review on hydrothermal liquefaction of biomass. *Elsevier*, 1378-1392.

Goncalves, A., Simons, M., & Pires, J. (2014). The Effect of Light dupply on microalgal growth, CO2 uptake and Nutrient removal from wastewater. *ElSevier*, 530-536.

Guschina, I., & Harwood , J. (2013). Algal Lipids and Their Metabolism. In M. Borowitzka, & N. Moheimani, *Algae for Biofuels* (pp. 17-36). New York: Springer.

Henze, M., & Comeau, Y. (2008). Wastewater Characterization. In M. Henze, & Y. Comeau, *Biological Wastewater Treatment: Principles, Modeling and Design* (pp. 33-52). London: IWA Publishing.

IIEA. (2013, Feb 20). *YouTube*. Retrieved from YouTube: https://www.youtube.com/watch?v=CKW_ux2Xo_w

IPCC. (2018). *Global Warming of 1.5 Deg.* Switzerland: Intergovernment Panel of Climate Change.

Jensen, C., Guerrero, J., Karatzos, S., Olofsson, G., & Inversen, S. (2018). Hydrofaction™ of forestry residuers to drop-in renewable transportation fuels. In L. Rosendahl, *Direct Thermochemical Liquefaction for Energy Applications* (pp. 319-343). Duxford: Elsevier.

L.Bartley, M., J.Boeing, W., A.Corcorana, A., OmarHolguin, F., & TannerSchaub. (2013). Effects of salinity on growth and lipid accumulation of biofuel microalga Nannochloropsis salina and invading organisms. *Biomass and Bioenergy*, 83-88.

Lee, S.-H., Ahn, C.-Y., Jo, B.-H., Lee, S.-A., Park, J.-Y., An, K.-G., & Oh, H.-M. (2013). Increased Microalgae Growth and Nutrient Removal Using Balanced N:P Ratio in Wastewater. *Journal of Microbiology and Biotechnology*, 92-98.

Lee, T., & Good, K. (2015). *Wheatland County Water Resources - Perspectives of the Agricultural Producers.* Institute: Miistakis.

Metcalf, & Eddy. (2014). Wastewater Engineering: treatment and resource recovery, Fifth Edition. In M. Eddy, *Wastewater Engineering - treatment and resource recovery* (p. 16). New York: McGraw-Hill Education.

Ras, M., Steyer, J.-P., & Bernard, O. (2013). Temperature effect on microalgae: a crucial factor for outdoor production. *Environmental Science Biotechnology*, 153-164.

Renaud, S., & Parry, D. (1994). Microalgae for use in tropical aquaculture II: Effect of salinity on growth, gross chemical composition and fatty acid composition of three species of marine microalgae. *Journal of Applied Phycology*, 347-356.

Rice University. (2015). *Algae from wastewater solves two problems: Biofuel and clean-up.* Houston: Science Daily.

RTI International. (2010). *Greenhouse Gas Emissions Estimate Methodologies for Biogenic Emissions from Selected Source Categories: Solid Waste Disposal, Wastewate Treatment, Ethanol Fermentation.* North Carolina: U.S Environmental Protection Agency.

SETI. (2019). *Symbiotic Envirotek Inc Rosebud Hamlet Wastewater Treatment Pilot Project Final Report.* Calgary: SETI.

SETI. (2019, June 18). *Who We Are*. Retrieved from Symbiotic EnviroTek Inc: https://symenv.com

Singh, D. (2016). *Process Development for Hydrothermal Liquefaction of Alae.* Phoenix: NRC.

Steeper Energy. (2019, June 05). *About Us*. Retrieved from Steeper Energy: https://steeperenergy.com/about/

Tsukahara, K., & Sawayama, S. (2005). Liquid Fueld Production Using Microalgae. *Journal of the Japan Petroleum Institute*, 251-259.

U.N. (2015, Sep 6). *United Nations*. Retrieved from United Nation: https://www.un.org/development/desa/disabilities/envision2030.html

U.S EPA. (2002). *Wastewater Technology Fact Sheet - Facultative Lagoons.* Washington D.C: U.S EPA.

U.S EPA. (2011). *Principles of Design and Operations of Wastewater Treatment Pond systems for plant operators, engineers, and Managers.* Cincinnati: US EPA.

U.S EPA. (2018). *Greenhouse Gas Emissions from a Typical Passenger Vehicle.* Ann Arbor: EPA. Retrieved from United States Environmental Protection Agency.

Whitesides, R. (2012). *Process Equipment Cost Estimating by Ratio and Proportion.* Fairfax: PDHonline.

Yeh, K.-L., Chang, J.-S., & Chen, W.-M. (2010). Effect of light supply and carbon source on cell growth and cellular composition of a newly isolated microalga Chlorella vulgaris ESP-31. *Engineering Life Science*, 201-208.

Zhang, K., Kurano, N., & Miyachi, S. (2002). Optimized aeration by carbon dioxide gas for microalgal production and mass transfer characterization in a vertical flat-plate photobioreactor. *Bioprocess and Biosystems Engineering*, 97-101.

Appendix A: Chapter 4 Calculations

Total volume of four (4) ponds in Wheatland County = 353,335 m^3

70% of 353,335 m^3 is released to the environment annually = 247, 335 m^3

Average flow rate = 28.24 m^3/hr, BOD_5 = 400 g/m^3 and TNK = 60 g/m^3

Using equations 2, 3 and 4 in section 2.3,

$CO_2 = 10^{-3} * Q_{WW} * OD * Eff_{OD} \times CF_{CO2} * (1-MCF_{ww} * BG_{CH4})$……..(2)

CO_2 kg/hr = 10^{-3} * 28.24 * 400 *.95 * 1.375 * (1 – 0.8 * 0.65) = 7.08 kg/hr

$CH_4 = 10^{-3} * Q_{WW} * OD * Eff_{OD} \times CF_{CH4} \times MCF_{ww} \times BG_{CH4}$……...(3)

CH4 kg/hr = 10^{-3} * 28.24 * 400 * 0.95 * 0.5 * 0.8 * 0.65 = 2.79 kg/hr

Where:

CO_2 = CO_2 emission rate (CO_2 kg/hr)

CH_4 = CH_4 emission rate (CH_4 kg /hr)

10^{-3} = Units conversion factor (kg/g)

Q_{WW} = Wastewater influent flow rate (m^3/hr)

OD = BOD_5 (mg/L = g/m^3)

Eff_{OD} = Oxygen demand removal efficiency of the biological treatment unit (up to 95% for facultative pond (U.S EPA, 2002))

CF_{CO2} = Maximum CO_2 generation per unit of oxygen demand 1.375 g CO_2/ g oxygen demand

CF_{CH4} = Maximum CH_4 generation per unit of oxygen demand 0.5 g CH_4/ g oxygen demand

MCF_{WW} = methane correction factor for wastewater treatment unit, indicating the fraction of the influent oxygen demand that is converted anaerobically in the wastewater treatment unit (0.8 for Facultative lagoon)

BG_{CH4} = Fraction of carbon as CH_4 in generated biogas (default is 0.65)

$N_2O_{wwtp} = Q_i * TKN_i * EF_{N2O} * 44/28 * 10^{-3}$……(4)

N20 kg/hr = 28 * 60 * 0.005 * 44/28 * 10^{-3} = 0.013 kg/hr

N_2O_{WWTP} = N_2O emissions generated from WWTP process (N_2O kg/hr)

Q_i = Wastewater influent flow rate (m3/hr)

TKN_i = Amount of TKN in the influent (mg/L = g/m3)

EF_{N2O} = N_2O emission factor (g N emitted as N2O per g TKN in influent),

= 0.0050 g N emitted as N2O/g TKN (Chandran, 2010)

44/28 = Molecular weight conversion, g N_2O per g N emitted as N_2O

10^{-3} = Units conversion factor (kg/g).

Global warming potential of CH_4 = 25 and N_2O = 298

Annual CO2 Equivalent (tonnes per year) = (7.08 + 2.79 * 25 + 0.013 * 298) * 24 * 365 *10^{-3}

= 707.8 tons

Appendix B: Chapter 5 Calculations

Total volume of four (4) ponds in Wheatland County = 353,335 m^3

70% of 353,335 m^3 is released to the environment annually = 247, 335 m^3

A commercial cell of Mac-B has 4 PBRs with 106 m^3 each and enables 1 PBR harvest per day.

Number of PBR cells required to treat 247, 335 m^3 of wastewater = 247, 335 / (106 * 365) = 6.39 (approximately 6 cells required)

Dry Algae weight produced per cubic meters of wastewater = 5 kg/m^3

Potential annual dry algae biomass = 6 * 106 * 365 * 5 = 1,160,700 kg * 10^{-3} = 1161 tons

Two tons of CO^2 to grow one ton of dry weight algae biomass

Annual CO^2 required to grow 1161 tons of algae biomass = 2 * 1161 = 2322 tons

Appendix C: Chapter 6 Calculations

Rule of seventh for cost estimation is:

$B_p = A_p * (B_c/A_c)^{0.7}$

Where:

A_p = Price of A

A_c = Capacity of A

B_p = Price of B

B_c = Capacity of B

Steeper has cost a 2000-bpd HTL system at $250 million.

A 50-bpd system cost estimate = $250 * (50/2000)^{0.7}$ = $18.9 millions (+/- 20%).

For the purpose of this project a cost of $20 million is used

Appendix D: Chapter 7 Calculations

The NPV for the two scenarios were calculated as follows:

Scenario 1

Initial investment for ACS and HTL = $50M

Wastewater treatment tipping fee = $2.5 per m^3

Volume of wastewater to be treated annually = 232,140 m^3

Price of biocrude per barrel = $45 per barrel

If the 50-bpd HTL is operating at full capacity by aggregating other sources of biomass, the volume of biocrude produced annually = 50 x 365 = 18,250 barrels

Annual revenue from operation = 2.5 x 232,140 + 45 x 18,250 = $1,401,600.00

If profit before tax is 20%, annual cash flow = 0.2 x 1,401,600 = $280,320.00

Cost of Goods Sold and Operating Cost = $1,401,600 – $280,320.00 = $1,126,280.00

If this annual cash flow is earned over 20 years lifetime of ACS and HTL (with zero salvage value of asset) at a discount rate of 6%, the NPV of the investment = $-46.8M using Excel NPV function.

Scenario 2

Initial investment for ACS and HTL = $25M

Wastewater treatment tipping fee = $10 per m^3

Volume of wastewater to be treated annually = 232,140 m^3

Price of biocrude per barrel = $60 per barrel

If the 50-bpd HTL is operating at full capacity by aggregating other sources of biomass, the volume of biocrude produced annually = 50 x 365 = 18,250 barrels

Annual revenue from operation = 10 x 232,140 + 60 x 18,250 = $2,540,880.00

If Cost of Goods Sold and Operating Cost is equal to scenario 1 = $1,126,280.00

Annual cash flow before taxes = $3,416,400.00 - $1,126,280.00 = $2,295,120.00

If this annual cash flow is earned over 20 years lifetime of ACS and HTL (with zero salvage value of asset) at a discount rate of 6%, the NPV of the investment = $+1.3M using Excel NPV function.