UNIVERSITY OF CALGARY

ALGAE CULTIVATION AND HYDROGEN PRODUCTION FROM THE WASTE STREAMS OF ELECTRICITY GENERATION

by

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Abstract

To reduce greenhouse gas emissions (GHGs) and preserve freshwater resources, this study assessed the techno-economic feasibility of utilizing waste streams from natural gas combined cycle (NGCC) power plants to cultivate algae, reuse process waters, and produce hydrogen via hydrothermal gasification (HTG) of algae biomass. Algae cultivation trials indicated that *Chlorella vulgaris* can be grown in NGCC wastewaters and that the effluent is suitable for industrial reuse. Aspen Plus process simulations showed that the HTG of algae biomass is not economically competitive and that HTG methane emissions must be abated to enable low-carbon hydrogen production. A feasibility analysis of an NGCC-integrated algae cultivation-gasification system (ACGS) concluded that it would be challenging to implement the ACGS due to the high capital and operating costs of the current technology. Further investigation of algae-treated water for NGCC applications and the optimization of HTG processes is recommended to identify a sustainable model for ACGS implementation.

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List of Abbreviations

Abbreviation	Meaning
ACS	Algae Cultivation System
CCUS	Carbon Capture Utilization and Storage
CHP	Combined Heat and Power
FCEV	Fuel Cell Electric Vehicle
GoC	Government of Canada
GGPPA	Greenhouse Gas Pollution Pricing Act
HTG	Hydrothermal Gasification
HTL	Hydrothermal Liquefaction
ICE	Internal Combustion Engine
MBSP	Minimum Biomass Selling Price
MHSP	Minimum Hydrogen Selling Price
NGCC	Natural Gas Combined Cycle
NPV	Net Present Value
PBR	Photobioreactor

Chapter 1: Introduction

Clean electricity will be instrumental to society's path towards net-zero greenhouse gas emissions (GHGs) and sustainable development (SD). Despite this, most developed countries still rely heavily on fossil fuel energy to provide electricity, mostly with natural gas combined cycle (NGCC) power plants. The world is projected to utilize NGCC as an integral component of the energy mix for the coming years, mainly for its dispatchable, reliable generation capabilities and scarce economic alternatives (IEA, 2021). There is consensus that NGCC is a suitable alternative to conventional coal-fired power (CFP) since it is the most efficient method of fossil fuel electricity generation. The NGCC generation process combusts natural gas to spin turbines and recovers the waste heat to generate steam, all of which is used to generate electricity at roughly twice the efficiency and half the carbon-intensity of CFP (Martín-Gamboa et al., 2018). Even though it is comparably cleaner than CFP, NGCC still has significant environmental impacts through its combustion and cooling processes that release GHGs and consume water resources. This is of particular significance in Alberta, Canada: the most emissions-intensive province and one of the most water-restricted regions of Canada, powered by an electricity grid with more than 49% of NGCC supply (GoC, 2017; CER, 2020). Considering that more capacity is set to come online within the next decade to replace CFP, this study is focused around mitigating the impacts of NGCC electricity while we rely on it in our transition towards SD.

For the coming decades, NGCC power will be used to transition society away from more carbon-intensive fossil fuels while we can develop economic and socially acceptable net-zero alternatives for hydrocarbon-dependent regions such as Alberta. Part of SD is the balance between social, environmental, and economic aspects in decision-making, and that means accepting a certain level of environmental risk to accommodate social and economic needs. Since NGCC is still required for stable electricity grids in many regions of the world, we must

strive to curb GHGs and maximize water-use efficiency from NGCC facilities. The typical NGCC power plant can release upwards of 2 Mt of CO_2 every year and consume around 749 L of water per MWh of electricity generated (James & Skone, 2012). These impacts are not congruent with the principles of SD, and we must develop economically valuable approaches to decrease the carbon- and water-intensity of NGCC operations.

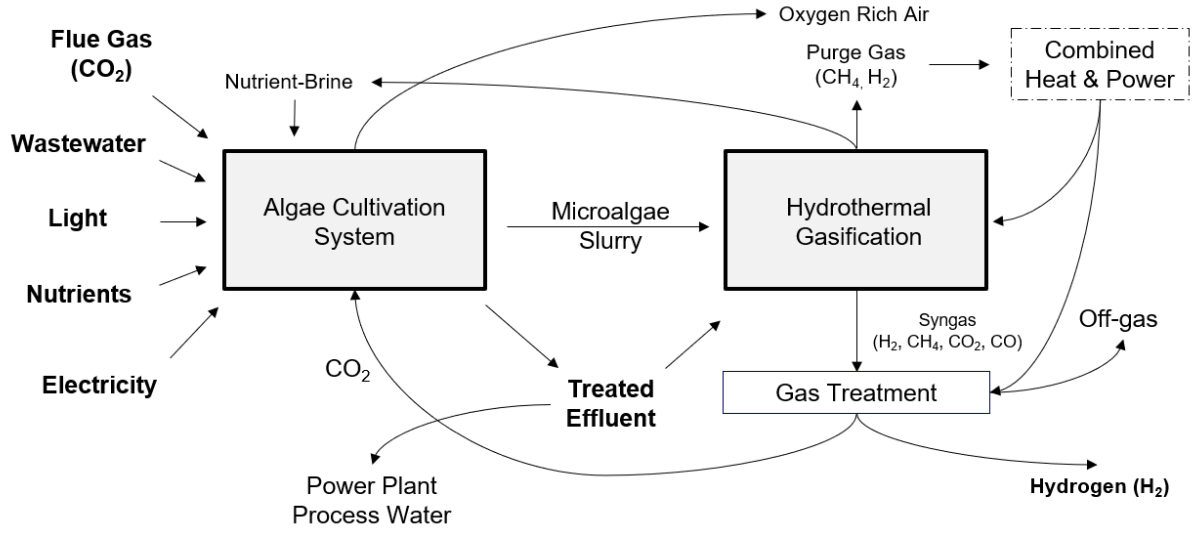
The first step to reducing GHGs from the combustion of fossil fuels like natural gas is carbon capture technology. Many technologies exist to capture carbon dioxide (CO_2) from flue gas; these include chemical and physical absorption, adsorption, and cryogenic distillation, while the most well-established approach for carbon capture from NGCC facilities is amine-based chemical absorption (Nanda et al., 2016). It is important to note that the carbon capture field is rapidly evolving, and new technologies aimed at NGCC-carbon capture such as solid adsorption are becoming increasingly practical in pursuit of net-zero GHGs (Kearns et al., 2021). The focus of this study is not on carbon capture, but what to do with the CO_2 after it has been isolated. Most of the CO_2 captured from NGCC plants is currently stored in geological formations and what is not captured is sent to the atmosphere. Some of the CO_2 released into the atmosphere is naturally consumed by photosynthesis, where plants absorb sunlight to convert CO_2 and water into glucose and oxygen. This study focuses on utilizing microalgae, one of the smallest and oldest types of aquatic plants, as a deliberate carbon sink that can be converted into clean fuels while remediating industrial wastewaters.

To mitigate the impacts of NGCC electricity, I tested a process based on existing algae cultivation and thermochemical conversion technologies. This process is called an algae cultivation-gasification system (ACGS); it is based on modular photobioreactors (PBRs) for climate-independent algae cultivation and hydrothermal gasification (HTG) for continuous

syngas production from algae biomass. The ACGS is designed to be coupled with NGCC power generation to absorb CO_2 emissions and treat wastewaters for industrial reuse. The ACGS embraces a circular economy concept by recycling its own waste streams to sustain operations, particularly the CO_2 and nutrients that are released through HTG processes. The HTG process uses supercritical pressures and temperatures to fluidly decompose an algae biomass slurry, separate the nutrients for recycling, and convert the algae into synthetic gas (syngas). The syngas can then be separated into hydrogen, CO_2 for algae growth, and a combustible purge gas that can be used to power the system. This study focuses on evaluating the ACGS as an NGCC-integrated wastewater and carbon management tool that can improve water-use efficiency and supply zero-emission hydrogen fuel to offset NGCC carbon-intensity. To evaluate the ACGS, I developed a framework aimed at quantifying energy, environmental, and economic indicators based on the system outlined in Figure 1.

Figure 1

Process Schematic of an Integrated Algae Cultivation-Gasification System.



Note: (Author, 2021).

1.1 The Research Question

The research question for this capstone project is: what are the economic and environmental implications of implementing an ACGS at a natural gas combined cycle power plant?

To address this, a set of underlying questions was developed with industry partners (see Appendix A). The broad framework of this study will provide a holistic basis for evaluation that can be used as a screening tool to assess pathways for future research, development, and investment decisions.

1.1.1 The Inter-Disciplinary Approach

Developing sustainable solutions for complex issues requires a balance between the various economic, social, and environmental aspects. This study aims to address these inter-disciplinary aspects by addressing different scenarios that include isolated algae cultivation and hydrothermal gasification systems, an integrated ACGS with hydrogen production, and the same ACGS with the benefits of climate policy. Consideration was also given to the global pursuit of the SD Goals, particularly Goals 6 (Clean Water), 7 (Clean Energy), and 13 (Climate Action), all of which are addressed through the ACGS design (United Nations, n.d.).

In each section of this study, I have focused on energy, environment, and economic performance. Energy was assessed by energy consumption and generation; environment was assessed by the water, land, and GHG footprints; and economics was assessed by capital and operating costs, minimum biomass selling price (MBSP), minimum hydrogen selling price (MHSP), and net present value (NPV). Chapters 2 and 3 outline the background literature and analysis methods, respectively. Chapter 4 describes NGCC processes, and the power plant focused on for this study. Chapter 5 illustrates the stand-alone viability of algae cultivation (AC) with respect to the MBSP. Chapter 6 outlines the performance of the stand-alone HTG system and its MHSP, while Chapters 7 and 8 outline the results and discuss the feasibility analysis of

the ACGS as a NGCC-integrated system. The feasibility analysis also considered the effects of policy in terms of carbon credit potential that may come with carbon capture and hydrogen fuel applications, consistent with the principles of the *Federal Carbon Pricing Backstop System* (GoC, 2021b), the *Greenhouse Gas Pollution Pricing Act* (2018), and the *Clean Fuel Standard* (GoC, 2021a). This interdisciplinary approach aims to assess the holistic performance of the ACGS and how the current federal policy structure in Canada can enhance the economic feasibility of low-carbon developments.

Chapter 2: Literature Review

This section provides an overview of existing literature related to microalgae cultivation, biomass utilization, and thermochemical conversion technologies. It will illustrate a basis of current understandings and how this study aims to addresses existing gaps in knowledge.

2.1 Microalgae

Sustainable biofuels are essential to achieving a net-zero energy system. The current trajectory of biofuel consumption suggests that we must move away from conventional crop sources like corn and palm oil that were originally intended to displace fossil fuels. Although a prominent part of our transport sector, conventional corn-based biofuels consume four litres of water for every one litre of fuel produced; the same amount required to produce food for one person for one day (Sharifi et al., 2019). These biofuel crops occupy and consume arable land and freshwater that should be used to grow food for society. In the interest of addressing these issues, microalgal biofuels have been gaining traction as a sustainable fuel source. This is because they can utilize *non*-arable lands, grow in (and remediate) non-potable water, and exhibit unparalleled growth rates (Daliry et al., 2017; Dalai et al., 2021a).

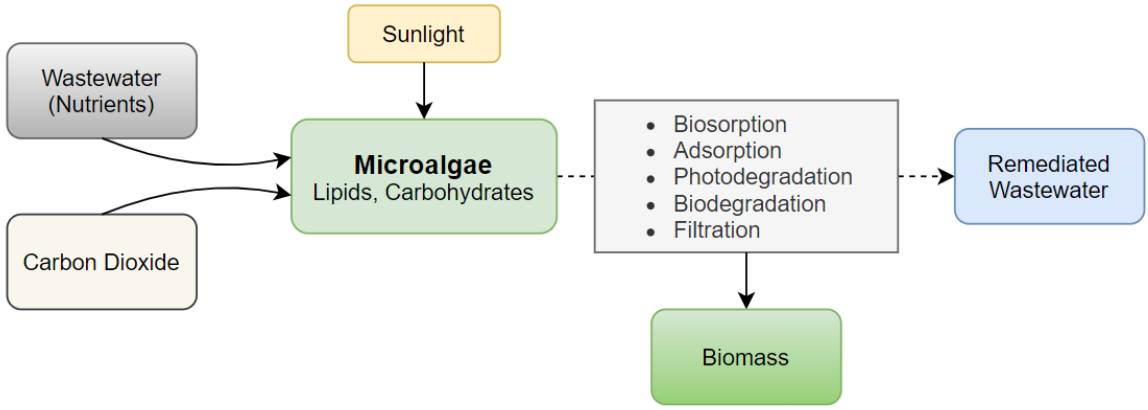
Microalgae are a collective of prokaryotic and eukaryotic unicellular microorganisms that convert nutrients from their surroundings into valuable biomass through various phototrophic, heterotrophic, and mixotrophic means of growth. Phototrophic growth is the primary mechanism; it uses energy from light to convert carbon dioxide (CO_2) and water into glucose and oxygen via photosynthesis. The CO_2 used in photosynthesis can come from various sources, such as soluble carbonates or flue gas from industrial processes, while the light can come from the sun or artificial radiation ranging from 400 to 700 nm wavelengths (Berberoglu et al., 2007). Heterotrophic growth uses organic carbon sources such as glucose, acetate, glycerol, or maltose that can be found in various wastewaters to supply energy to the cells for biochemical synthesis

(Dalai et al., 2021a). Mixotrophic uses a combination of the former options to provide a more dynamic means of growth that is utilized in the natural environment. Both heterotrophic and mixotrophic growth mechanisms can achieve some the highest growth rates, depending on the environmental conditions and algae species (Daliry et al., 2016; Pankratz et al., 2020). The resulting biomass is rich in carbohydrates, proteins, lipids, triglycerides, carotenoids, and other pigments that pose great potential for value-added products, particularly clean fuels and chemicals (Dalai et al., 2021b; Kumar et al., 2018).

The various mechanisms of growth utilized by microalgae allow them to be resilient through exposure to a wide variety of environmental conditions. Generally, the most important parameters for algae growth are light exposure, temperature, and sufficient carbon availability; given these conditions, microalgae will likely find a way to flourish (Pankratz, 2019a; Dalai et al., 2021b). While algae growth relies on basic nutrients such as nitrogen, phosphorous, and other micronutrients (e.g., iron) in addition to the key parameters, microalgae can still grow in a mix of unbalanced conditions when deprived of nutrients (Dalai et al., 2021b). Nutrient deprivation can often result in significant increase in lipid production, which improves biomass energy content (Sharma et al., 2012). This resiliency enables many strains to thrive in contaminated wastewaters, where their mechanisms of growth and extraction methods result in the remediation of the water and significant biomass production (Figure 2). To enable economically viable operations at a meaningful scale, the remediation potential and resilient growth of microalgae must be exploited to generate revenue from wastewater treatment tipping fees that can be coupled with the valuable biomass products (Pankratz, 2019b; Adelodun, 2019).

Figure 2

Schematic Diagram Representing the Growth and Wastewater Remediation Mechanisms of Microalgae.



Note: (Author, 2021). Based on Dalai et al. (2021b) and Wang et al. (2017).

Growth rates of microalgae are 30 to 300 times higher than most agricultural and forest-based biomass (Ugoala et al., 2012). The high surface area and robust metabolic uptake mechanisms of unicellular organisms such as *Chlorella vulgaris* allow them to double in mass in less than 19 hours under controlled conditions (Daliry et al., 2017). Although thousands of algae strains exist, species such as *Chlorella vulgaris, Scenedesmus obliquus, Chlorella protothecoides, and Chlorella zofingiensis* have gained particular interest for wastewater treatment and biofuel applications due to their high lipid and carbohydrate production rates under resilient growth patterns (Dalai et al., 2021b; Pancha et al., 2015). Most algae strains can grow in a wide variety of wastewaters and do not require arable crop lands, which is why they are considered as a sustainable alternative to first- and second-generation biofuels such as palm oil, sunflower oil and lignocellulosic wastes, respectively (Daliry et al., 2017). Given their unique properties and ability to produce energy-rich lipids and carbohydrates, algae have solidified a promising role as a third-generation biofuel (Dalai et al., 2021a).

2.1.1 Cultivation Methods

Algae can be efficiently cultivated through several different approaches, each offering a range of benefits and challenges. The main algae cultivation methods are open pond raceways (OPR), closed ponds, and photobioreactors (Dalai et al., 2021b). Open pond raceways are typically considered the most cost-effective option and have been proven to be successful in the appropriate climate (Pankratz et al., 2019b). Although they are less expensive, relying on OPR systems for biomass production leaves the culture susceptible to contamination and dependent on seasonal conditions, both of which can have detrimental effects on growth rates and the bottom line of operations (Pankratz et al., 2019b). Closed pond systems help address contamination concerns by providing overhead coverage, although the protection may impede UV absorption and corresponding growth rates. Photobioreactors (PBRs) use enclosed systems equipped with artificial UV light, CO_2 diffusion, and controlled environmental conditions to optimize growth rates and minimize contamination threats (Adelodun, 2019; Pankratz et al., 2017; Dalai et al., 2021b). Since PBRs require a reactor vessel for controlled conditions, they are generally a less cost-effective option compared to conventional cultivation systems.

To cultivate microalgae in the colder Canadian climate, we would need PBRs to augment environmental conditions for optimum growth. Recent studies on advanced PBR technology show that they can be competitive with OPR systems at large scales mainly because they can be operated year-round, irrespective of environmental conditions (Pankratz, 2019b). Field studies in Canada have shown that PBRs growing *Chorella vulgaris* can yield biomass concentrations between 3 to 5 g per L after 96 hours of growth when treating sewage rerouted from municipal lagoon systems (Adelodun, 2019). These commercial-scale growth rates are comparable to or greater than reported averages for other cultivation methods (Dalai et al., 2021b). PBR microalgae cultivation also has potential for growth and remediation in the waste streams of

industrial wastewaters, such as NGCC electricity generation. This study examines PBR cultivation as a potential solution for industrial wastewater treatment, carbon utilization, and sustainable fuel production from NGCC facilities.

2.1.2 Wastewater Treatment

Regardless of the growth method, algae cultivation systems have the potential to treat raw municipal and industrial wastewaters to acceptable standards for a variety of industrial applications (Adelodun, 2019; Dalai et al., 2021a; Barreiro et al., 2015). Microalgal strains, such as *C. vulgaris,* have also been shown to remediate recalcitrant organic contaminants that pass through conventional wastewater treatment systems (Xiong et al., 2018). The remediation and production potential of microalgae cultivation allows it to treat raw sewage, industrial process water, and reclaimed municipal wastewater, although the process must be modified to achieve specific effluent standards. In addition to high growth rates and treatment capabilities, cultivating algae to treat wastewater can also utilize 1.8 tonnes of CO_2 for every tonne of biomass produced (Pankratz et al., 2019b; Adelodun, 2019).

Algae-based wastewater treatment exhibits the best performance when it is carried out in photobioreactors (PBRs) since conditions can be optimized. The PBR that will be examined for this study is the Modular Algae Cultivation Biofield™ (MAC-B) technology developed by a Canadian company, Symbiotic Envirotek Inc. (SETI). The MAC-B technology has been proven to operate in the harshest Canadian climate, treat a variety of wastewater sources, and produce consistent yields of algal biomass of 3-5 kg m^{-3} every four days (Adelodun, 2019; SETI, 2021). The MAC-B is a modular algae cultivation system (ACS) that comes in "cells", each with a 125 m^3 capacity. Within each cell, a monoculture of *Chlorella vulgaris* is grown to remediate wastewater and carbon emissions simultaneously; however, any strain of algae can be grown upon inoculation. *C. vulgaris* is a photosynthetic unicellular microorganism of 2 to 20 microns in

size; it has a doubling time of approximately 19 hours and can grow exponentially in a wide range of environmental conditions (Daliry et al., 2017). As with most algae strains, the resulting biomass of *C. vulgaris* is rich in carbohydrates and lipids, which makes it a viable feedstock for thermochemical fuel production.

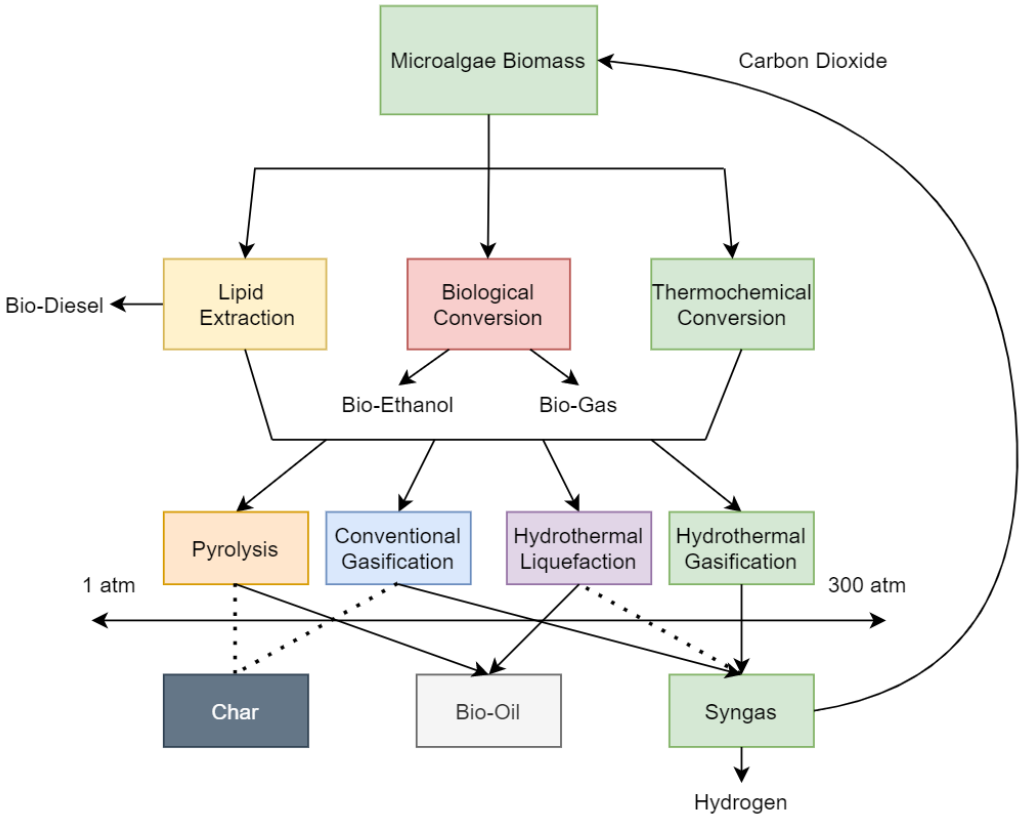
For industrial applications, the MAC-B would be situated in "bio-fields", consisting of 128 cells for a total bio-field capacity of 16 ML of media (Deane, A., personal communication, January 11, 2021; SETI, 2021). One bio-field would utilize around 17 tonnes of CO_2 each day of operation while producing approximately 9.6 tonnes of biomass (Appendix D). Cultivating algae on this scale could provide a sustainable feedstock for thermochemical fuel production and an industrial carbon sink for emissions captured from NGCC electricity generation. It would also provide clean water that could potentially be used for cooling water or boiler feedwater pre-treatment supply.

2.2 Biomass Utilization

Commercial scale algae cultivation requires a means to utilize the resulting biomass. Although algae biomass is typically viewed as a source for lipids that can be extracted for biodiesel, there is also significant potential for it to be used directly as a fuel feedstock through biological or thermochemical conversion. Figure 3 outlines the major energy utilization pathways for algae biomass that have been selected from existing literature. It is important to note that other pathways involving hydrothermal carbonization, torrefaction, microwave-assisted and plasma pyrolysis are also promising utilization techniques that were excluded from this study's limited scope (Fan et al., 2020; Sharma et al., 2020). The following sections outline a set of focused pathways that can be taken to utilize energy from microalgae (algae) biomass and other biogenic feedstocks to produce fuels.

Figure 3

Microalgae Biomass Utilization Pathways for Fuel Production.



Note: (Author, 2021). The Green Sections Highlight the Pathway Examined in this Study and the Dotted Lines Indicate Secondary Products of the Thermochemical Conversion Technologies.

In the simplest pathway, algae can be dried and combusted as a fuel like conventional biomass sources such as wood. Dried algae biomass typically has a higher heating value (HHV) of between 14 and 24 MJ kg^{-1} (Chen et al., 2015). If an immense supply were available, dried algae biomass could be used directly for heat or power generation, but the required mass is impractical. The biomass of algae species is better suited for more sophisticated means of utilization, as drying and burning the biomass degrades the value of lipid and carbohydrate content, which decreases energy efficiency (Kumar et al., 2018).

One conversion option is to use biological mechanisms that can convert algal biomass into fuels such as biogas or bioethanol. The most common and cost-effective method for biological conversion is anaerobic digestion (AD), which breaks down the biomass into biogas and digestate. Biogas produced from AD is approximately 50% methane with a remaining mass balance of mostly carbon dioxide, and variable amounts of ammonia, and hydrogen sulfide depending on the feedstock. Biogas typically provides has an average HHV of between 15-20 MJ kg^{-1}, which makes it a suitable low-carbon substitute for natural gas (McAllister et al., 2011). The digestate produced from AD can also be used as a fertilizer as it is typically comprised of key nutrients required for agricultural applications, but this application may be restricted by hazardous compounds present in the digestate after treatment (Drapcho et al., 2020). AD is a viable option for algal biomass utilization that can be coupled with municipal organic waste or sewage sludge disposal for increased revenue and biogas production (Sarker et al., 2019). Despite its potential, the passive nature of AD restricts throughput and therefore limits economic viability. Studies have also shown that ammonia inhibition can limit the biogas production from algae biomass AD (Drapcho et al., 2020). The alternative bio-conversion route is to ferment the algae biomass, particularly the carbohydrates, into ethanol that can be integrated into petroleum-based fuels to reduce carbon intensity. Current research suggests that the economical conversion of microalgae to bioethanol poses significant challenges compared to competing sources such as corn-based ethanol (Dalai et al., 2021a). Although biological conversion routes show potential, current methods do not yet offer a viable alternative to conventional biofuel sources.

Another microalgae conversion option is to separate the lipids from the algal biomass and convert them into bio-diesel, a fuel source compatible with existing internal combustion engine vehicles. Lipids can be extracted from algae biomass via water or solvent extraction, mechanical

pressing, or other evolving processes (Dalai et al., 2021b). The solvent extraction pathway has been studied extensively and successfully demonstrated; the resulting lipid-extracted biomass can also be utilized as a thermochemical feedstock (Nurcahyani et al., 2020). Although it is an attractive option, the solvent extraction process has proven to be uneconomical in many respects as it is having to be compete with conventional bio-diesel industries supplied by feedstocks such as corn or palm oil (Chen et al., 2011). Coupling solvent extraction with thermochemical conversion methods for the residual waste shows promising results but research in this area is in relatively early stages and remains uncompetitive with conventional 1st or 2nd generation biofuel production (Dalai et al., 2021a). Due to inefficient solvent extraction methods and the energy penalty of feedstock processing, algae biomass utilization shows the most promising results when it can be utilized in its raw dewatered, or fully-dried state, an approach that is taken by the key thermochemical conversion technologies (TCTs) shown in Figure 3.

2.2.1 Thermochemical Conversion Technologies

With a primary interest of displacing fossil fuels, there are several key TCTs that have gained interest for producing fuels from biogenic, waste, or plastic feedstocks. The most promising TCTs for microalgae biomass are based on pyrolysis, gasification, hydrothermal liquefaction, and hydrothermal gasification (Chen et al., 2015; Pandey et al., 2019; Okolie et al., 2020a; Kumar et al., 2018). These technologies range from well-practiced (e.g., conventional gasification), to more advanced and still-developing (e.g., hydrothermal processing). All TCTs outlined in this section can utilize minimally algae biomass but hydrothermal processing-based TCTs are the only options that avoid an energy-intensive drying step. Table 1 outlines the process conditions and generalized product yields exhibited for the TCTs examined in this study.

Table 1

Process Conditions and Generalized Product Phase Yields for Pyrolysis, Conventional Gasification, Hydrothermal Liquefaction, and Hydrothermal Gasification of Microalgae Biomass.

Process	Conditions			Products (wt. %)		
	Temperature (°C)	Pressure (MPa)	Time	Solid	Liquid	Gas
Pyrolysis[a]	300-800	0.1	1 s – 20 h	12-35	30-75	13-35
Conventional Gasification[b]	800-1000	0.1-1	< 60 s	58	14	28
Hydrothermal Liquefaction[c]	200-350	5-20	5-60 min	<5	25-65/60-20 (Oil/Aqueous)	<10
Hydrothermal Gasification	400-600	>22.4	1-60 min	-	<5	>95

Note: Table Adapted from Dalai et al. (2021c). Based on Krylova & Zaitchenko (2018); Chen et al. (2015); and Khoo et al. (2013).

a: Based on range of slow, intermediate, and fast pyrolysis-based processes; b: Based on Khoo et al. (2013), limited studies for microalgae; c: highly dependent on process design and may vary.

Pyrolysis is a suitable pathway for heating dried (<10% water content) algae biomass at ambient pressure in the absence of oxygen to thermally decompose it into bio-oils, chars, and non-condensable gases (Chen et al., 2015). Temperatures for the pyrolysis of algae biomass range between 300 °C and 800 °C depending on reactor design and the application of catalysts. The yield of pyrolysis products is dependent on the microalgae properties and temperature; chars are the major product at lower temperatures, moderate temperatures (400 - 550 °C) favour oil production, and higher temperatures increase gas yield (Akhtar & Saidina Amin, 2012). Oils produced from algae pyrolysis are the favourable product for fuel applications; they are typically

high in oxygen content and can contain hundreds of chemical compounds such as aldehydes, cresols, and acids, similar to crude oil (Brennan & Owende, 2010). Due to its oxygen content, bio-oil yielded from pyrolysis requires upgrading before it can be used as fuel through conventional means. Upgrading requires hydrogen in some form, which in Canada is typically sourced from natural gas (Layzell et al., 2020). Also, the primary energy source for drying the biomass in pyrolysis is usually natural gas, which is a significant contributor to greenhouse gas emissions (GHGs) and the energy-intensity of the process (Chen et al., 2015). The drying and hydrotreatment requirements for pyrolysis have shown to contribute to uneconomic process requirements for algae biomass conversion to fuels (Pankratz et al., 2020); therefore, it was not considered in detail for this study.

Like pyrolysis, conventional gasification (CG) can also convert dried biomass to gaseous fuels under ambient pressures. CG is a well-established technology that uses oxygen and/or steam at high temperatures (800 - 1000 °C) to convert carbonaceous feedstocks into syngas, mainly comprised of H_2 and CO, and the remaining balance of CO_2, CH_4, and short chain (C_2-C_{4+}) hydrocarbons (Chen et al., 2015). The CG process is complex and variable dependent on the feedstock; it generally involves the partial oxidation, water-gas shift, methanation, Boudouard, combustion, and reduction reactions (Pandey et al., 2019). Most studies around CG with algae have examined co-gasification with coal (Chen et al., 2015). This is typically carried out in a fluidized or fixed bed reactor, where tars and ash are commonly reported to contribute to clogging of the equipment (Dalai et al., 2021c). The energy penalties for drying biomass and the operational issues with ash agglomeration and process control are the key contributing factors to CG's exclusion from this study's preferred biomass utilization pathway.

2.2.2 Hydrothermal Processing

Hydrothermal processing techniques have been gaining significant research attention as fuel production options that can utilize various biogenic feedstocks, particularly algae, using the sub-critical and supercritical properties of water (Dalai et al., 2021c). Sub-critical and supercritical conditions are a function of pressure and temperature that alter the physicochemical properties of water, allowing it act as a reactant, solvent, and catalyst as the process is manipulated (Kumar et al., 2018; Okolie et al., 2021a). Sub-critical water is termed at pressure above 20 MPa with temperatures between 100 °C to 374 °C, while supercritical water is active at temperatures and pressures above 374 °C and 22.1 MPa, respectively (Tran, 2016). As the water temperature increases under high pressure (>20 MPa) conditions, the dielectric constant and viscosity of the water decrease; this results in increased reactions rates and free radical formation that can fluidly decompose complex organic molecules (Dalai et al., 2021c; Okolie et al., 2020a). Utilizing these unique properties is known as hydrothermal processing, which was first demonstrated in 1788 to convert biomass into bio-crude via liquefaction (Dimitriadis & Bezergianni, 2017). These technologies have since been overlooked because of low fossil fuel prices but are now becoming increasingly important to develop as we pursue a diverse energy mix that can alleviate dependence on fossil fuels.

The two most researched approaches to hydrothermal processing are based on hydrothermal liquefaction (HTL) and hydrothermal gasification (HTG) (Kumar et al., 2018; Okolie et al., 2020a; Fan et al., 2020). HTL is the most common pathway for algae biomass utilization since the feedstock can achieve high bio-oil yields with no solvent extraction or drying pre-treatment (Table 1; Kumar et al., 2018). The HTL process mimics the tectonic forces within the Earth within a controlled reactor to produce a crude oil-like product in a comparatively small fraction of time. It generally requires an operating temperature of 300 - 350

°C at 5-20 MPa for 5-60 min (Kumar et al., 2018). The bio-oil product is low in oxygen compared to other TCTs like pyrolysis, and its production can exhibit superior energy efficiency since there is no drying required and it occurs at lower temperatures (Kumar et al., 2018). HTL of biogenic wastes such as forestry residues, sewage sludge, and algae has been successfully demonstrated in many studies, proving its viability for clean fuel production from various wastes (Dimitriadis & Bezergianni, 2017). One Danish-Canadian company, Steeper Energy, has demonstrated their HTL-based Hydrofaction™ technology on a commercial scale to produce upgraded bio-oil that is comparable to conventional fossil fuels (Adelodun, 2019). HTL also produces an aqueous phase after the oil is extracted, which may require considerable treatment investment depending on the waste discharge requirements. Significant attention has been given to the HTG of the HTL aqueous phase to integrate hydrothermal processing techniques for a circular and sustainable process (Fan et al., 2020). Although HTL is a promising technology with potential synergies for HTG, this study excluded it from its focus to pursue a pathway focused on zero emission products and feedstocks for circular algae cultivation.

All the TCTs discussed in this section show potential for economic biomass-to-fuel applications, but they still produce significant GHG emissions. With our global objective of reaching net-zero emissions by 2050, I wanted to investigate a carbon-neutral process that could produce non-emitting hydrogen fuel, rather than conventional carbon-based biofuels. Hydrogen is widely regarded as a crucial component of a net-zero energy system mainly because it produces zero emissions at end-use. With an energy content of 120 MJ kg^{-1}, hydrogen can be used as versatile replacement for natural gas in process heating and as an energy source that can provide electricity for the power grid or propulsion in transport (Bataille et al., 2018). The following section focuses in on hydrogen and how it can be produced from HTG.

2.2.2.1 Gasification for Hydrogen Production.

HTG produces hydrogen-rich syngas from biogenic feedstocks with minimal solid by-products compared to other TCT pathways. It does so by operating at high pressure (>22.1 MPa) and temperature (>500 °C) to utilize the unique properties of supercritical water (Okolie et al., 2020a). HTG does not require the energy-intensive drying step, which is crucial for maintaining the efficient conversion of an aqueous biomass like microalgae. The supercritical conditions maintained through HTG allows water to efficiently break down recalcitrant, energy-rich molecules and produce hydrogen-rich syngas that has vast potential for clean fuel production (Kumar et al., 2019).

The HTG process depends on a variety of complex chemical reactions and the product gas composition is highly temperature dependent (Okolie et al., 2020b). Although complex to maintain, supercritical conditions allow HTG to utilize a wide variety of feedstocks such as crop residues, carbohydrates, lignin, municipal solid waste, manure, sewage sludge, petrochemical residues, and most notably, microalgae (Okolie et al., 2020a). This study focused on microalgae as a feedstock for HTG, but it should be noted that HTG technology has shown significant potential for hydrogen yields from biogenic waste products that would otherwise be a liability for neighbouring industries (Correa & Kruse, 2018). The use of alkali salts (e.g., KOH, K_2CO_3, Na_2CO_3) and nickel- and ruthenium-based catalysts have also shown to increase hydrogen yields significantly (Yakaboylu et al., 2015; Norouzi et al., 2016; Tiong & Komiyama, 2019). Despite their benefits, catalysts can contribute to corrosion and easily be deactivated by trace sulfurous compounds commonly found in waste streams, which can reduce equipment life and add extra costs to operations. For simplicity and cost savings, this study focused on utilizing only the catalytic effects of supercritical water for HTG.

The HTG of biogenic feedstocks has been widely researched and there is significant interest in microalgal biomass due to its high concentration of energy-dense lipid and carbohydrate molecules. Lab-scale experiments using HTG for hydrogen production from algal biomass have exhibited yields of 10-13% hydrogen per kg of dry biomass feedstock. The remaining mass balance of the HTG products is mainly comprised of CO_2 and nutrient-brine that can be recycled for algae cultivation (Tiong & Komiyama, 2019; Onwudili et al., 2013; Chakinala et al., 2010; Norouzi et al., 2016). The major challenges found with the HTG of microalgal biomass are achieving high energy efficiencies, avoiding mineral clogging, and identifying suitable reactor designs with superalloy materials that can accommodate large-scale continuous processes under supercritical conditions (Correa & Kruse, 2018; Pandey et al., 2019; Tiong & Komiyama, 2019; De Blasio et al., 2021).

There are limited examples of HTG technology at a commercial scale. Boukis et al. (2007) provided the most relevant demonstration with the results of the VERENA HTG pilot plant in Karlsrhue, Germany. The plant was able to produce hydrogen gas yields as high as 77% from a 100 kg/h feed of corn silage and ethanol. The VERENA demonstration used operating conditions of around 600 °C and 28 MPa with integrated heat exchangers for feedstock heating to increase the process efficiency. VERENA also used a sub-critical/supercritical zone reactor design to mitigate the precipitation of minerals, based on the MODAR reactor initially proposed by Hong et al. (1989). The integrated design creates a subcritical zone in the bottom of the reactor to dissolve minerals that would otherwise be precipitated and clog the reactor under supercritical conditions. For processing algal biomass, a VERENA-type design would produce a nutrient-rich brine that may be recycled for algae cultivation while avoiding operational issues cited as concerns in existing research (Onwuldii et al., 2013; Reimer et al., 2016).

Since the VERENA demonstration, there have been numerous studies on HTG processes, lab-scale experiments, and analyses of analogous models (Chakinala et al., 2010; Correa & Kruse, 2018; Norouzi et al., 2016; Nurcahyani et al., 2020; Tiong & Komiyama, 2019; Yakaboylu et al., 2015). Pankratz et al. (2020) analyzed a similar HTG pathway using a life cycle assessment that found hydrogen could be produced with a net energy ratio of 1.15, given a 2000 tonne per day operation. Kumar et al. (2019) conducted a techno-economic assessment of a modernized HTG model for hydrogen production from algal biomass; the study found that a 2000 tonne per day plant equipped with pressure swing adsorption, carbon capture, water-gas shift, and steam reforming would require a capital investment of 277.8 million CAD and produce hydrogen at a levelized cost of \$4.59 (+/- 0.10) kg^{-1}. Similarly, Okolie et al. (2021b) modelled a conceptual plant for HTG of soybean straw to produce hydrogen. They found that the break-even price was \$1.94 (US) kg^{-1} H_2, excluding storage and transportation costs. The methods used in this study were based on the process model constructed and analyzed by Kumar (2018) and Kumar et al. (2019). Building from this previous work, I provided replication and verification of the Aspen Plus model and a techno-economic assessment of the system integrated with an ACS.

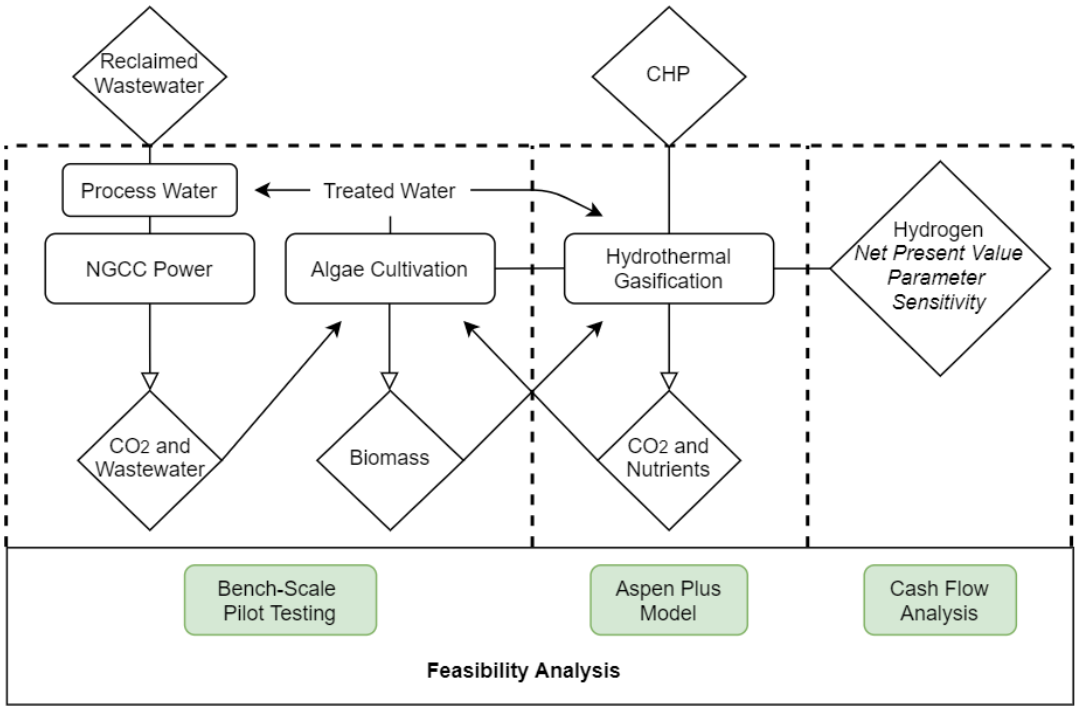
Previous research has recommended that further techno-economic evaluation be conducted to assess the feasibility of algae cultivation and HTG technology paired with industrial processes, such as electricity generation (Kumar et al., 2019; Pankratz et al., 2020; Okolie et al., 2020a; Dalai et al., 2021b). This study aims to address these recommendations through the integration of ACS and HTG with natural electricity generation processes. The intention of this work to assess the synergistic potential of these integrated systems and identify a practical approach in which they can be deployed on a meaningful scale at NGCC facilities.

Chapter 3: Methods

This section outlines the structure for the feasibility analysis of the algae cultivation-gasification system (ACGS). The three key components of the analysis were the bench-scale pilot testing, Aspen Plus process simulation, and the cash flow analysis of the integrated process, as outlined in Figure 4. The following sections provide details on these various components.

Figure 4

Conceptual Framework of the Study and the Methods used for the Feasibility Analysis of the NGCC-integrated Algae Cultivation-Gasification System.



Note: (Author, 2021).

3.1 Natural Gas Combined Cycle Electricity Data

For this study, a NGCC power plant provided access to emissions and wastewater data to determine the quantity and composition of the waste products emitted from operations. The source facility has requested anonymity and is referred to as the "Power Plant" throughout this

report. The values obtained from the Power Plant were used to size the conceptual algae cultivation system (ACS), quantify biomass production rates, and estimate CO_2 remediation potential. A pure CO_2 supply and direct wastewater streams were assumed to be available.

3.2 Pilot Testing

Bench-scale pilot testing was used to assess the feasibility of treating the Power Plant wastewater with algae cultivation technology. SETI provided lab space, materials, and equipment for pilot testing to evaluate their algae cultivation technology. Two samples (one 24-hour composite and one grab sample) of Power Plant effluent were used to cultivate *C. vulgaris* in a 20 L bench-scale setup of the MAC-B technology to determine if meaningful biomass could be grown and if the treated effluent may be suitable as NGCC process water. A characterization analysis of the aggregated samples was performed by a commercial lab before and after treatment to assess the system's capabilities. The complete pilot testing details and results are outlined in Appendix C and discussed in Chapter 5.

3.3 Algae Cultivation-Gasification System Design

A literature review was used to derive operating details from analogous research and construct a design basis for the ACGS. The economics and performance data for the algae cultivation system was provided by SETI, derived from their MAC-B design. The HTG Aspen Plus model was based on Kumar (2018) and the VERENA pilot project (Boukis et al., 2007). The NGCC-integrated ACGS process model was evaluated based on the criteria in Appendix A.

3.3.1 Aspen Plus Model

Aspen Plus v.10 was used to simulate a hydrothermal gasification (HTG) process with a capacity of 192 metric tonnes per day (tpd) of a biomass water slurry (5% dry wt.). This study replicated a process model developed by Kumar (2018) for the HTG of algae biomass to produce pure (>99%) hydrogen gas. The original model was designed for 2000 tpd capacity; the stream results

were replicated within a 5% margin of error for verification. The verified model was then scaled down to accommodate the daily biomass yield from the ACS sized for the Power Plant, calculated to be 9.6 tonnes and a corresponding 192 tpd of biomass slurry (5% dry wt.) HTG plant capacity (Appendix C). The results of the scaled Aspen Plus simulation were used to estimate the material and energy flows from the HTG process. Mass flow rates, the associated energy consumption of the process unit operations, and material outputs were used to estimate costs requirements for the cash flow analysis of the integrated Algae Cultivation-Gasification System (ACGS).

3.4 Feasibility Analysis

This study conducted a discounted cash flow analysis to calculate the Minimum Biomass Selling Price (MBSP) and Minimum Hydrogen Selling Price (MHSP) for the stand-alone ACS and HTG systems, respectively, along with the Net Present Value (NPV) and MHSP of the integrated ACGS at a 10% discount rate (Appendix E). Costs of the system components were estimated from technology suppliers and existing techno-economic analyses at different scales using the chemical engineering plant cost index and the ratio cost assessment method (Kumar et al. 2019; Okolie et al. 2021b; Green & Southard, 2019). A base discount rate of 10% was used for the calculations to account for the technological and policy risks related to low-carbon technology development. All values were converted to 2020 CAD. This study also considered sensitivities for capital costs, operating costs, discount rate, water revenue, and hydrogen price at +/- 30% to account for uncertainty in the preliminary assessment (Appendix E). A techno-economic feasibility analysis of the ACGS performance was completed for a Technical Summary; this considered energy efficiency, emissions, water footprint, land footprint, economic indicators, and technology risks centered around a qualitative assessment of practical concerns related to commercial implementation based on Appendix A.

Chapter 4: Natural Gas Combined Cycle Electricity

This section will provide a background on the natural gas combined cycle (NGCC) electricity generation with respect to greenhouse gas emissions (GHGs) and wastewater management. NGCC electricity is an important tool for the energy transition and decarbonization as it provides relaible, dispatchable power at nearly half the GHG intensity and water discharge as conventional coal-fired power (Cormos, 2015). In Canada, around 9% of the electricity generation comes from natural gas-fired power plants; in Alberta, it currently makes up around 49% of the supply (GoC, 2020; CER, 2020). This share of NGCC power contributes to a disproportionate amount of Canada's GHGs. Despite it being viewed as a 'clean' alternative to coal power, NGCC facilities still release millions of tonnes of GHGs every year; they also consume millions of liters of water every day for cooling and steam generation. In the interest of mitigating GHGs and maintaining freshwater resources, it is important to develop systems that can reduce the negative impacts of NGCC electricity generation. The following sections will frame the environmental impacts of NGCC electricity and how they compare to the Power Plant focused on in this study.

4.1 Greenhouse Gas Emissions

The average GHG intensity of NGCC generation is typically around 0.35 tonne CO_2 per MWh of generation (Cormos, 2015; James & Skone, 2012). Although it is one of the most GHG-intensive sources of electricity, it is also one of the most cost-competitive for natural gas-rich areas of the world such as North America. Due to the strong economic case for NGCC and its flexible generation capabilities, it is likely that these assets will continue operations for the next several decades and continue to release GHGs (IEA, 2021). Considering the ongoing impacts that are likely to continue, it is important that we identify economic opportunities to create value from the existing waste streams released from NGCC electricity generation, such as CO_2 emissions.

The 860 MW Power Plant examined for this study has a GHG intensity of 0.375 tonnes of CO_2 per MWh, which equates to more than 2.6 million tonnes per year at 95% capacity. The sheer mass of carbon dioxide released NGCC is only practical to manage if we can sequester it in geological formations, which is still not economically competitive without government policy (IEA, 2021). This study does not focus on sequestration; it evaluates the prospect of utilizing the NGCC facility as a node to start up carbon-reducing projects that can offset environmental impacts. The Power Plant studied for this project has an adjacent pilot scale amine-based carbon capture plant that provides up to 25 tonnes of CO_2 per day for carbon capture, utilization, and storage (CCUS) research. The ACGS proposed in this study would utilize the carbon supply on-site to prime the system's operations. Since the ACGS captures and recycles its own CO_2 emissions, the amine-captured emissions would only be needed as a start-up supply.

4.2 Wastewater Management

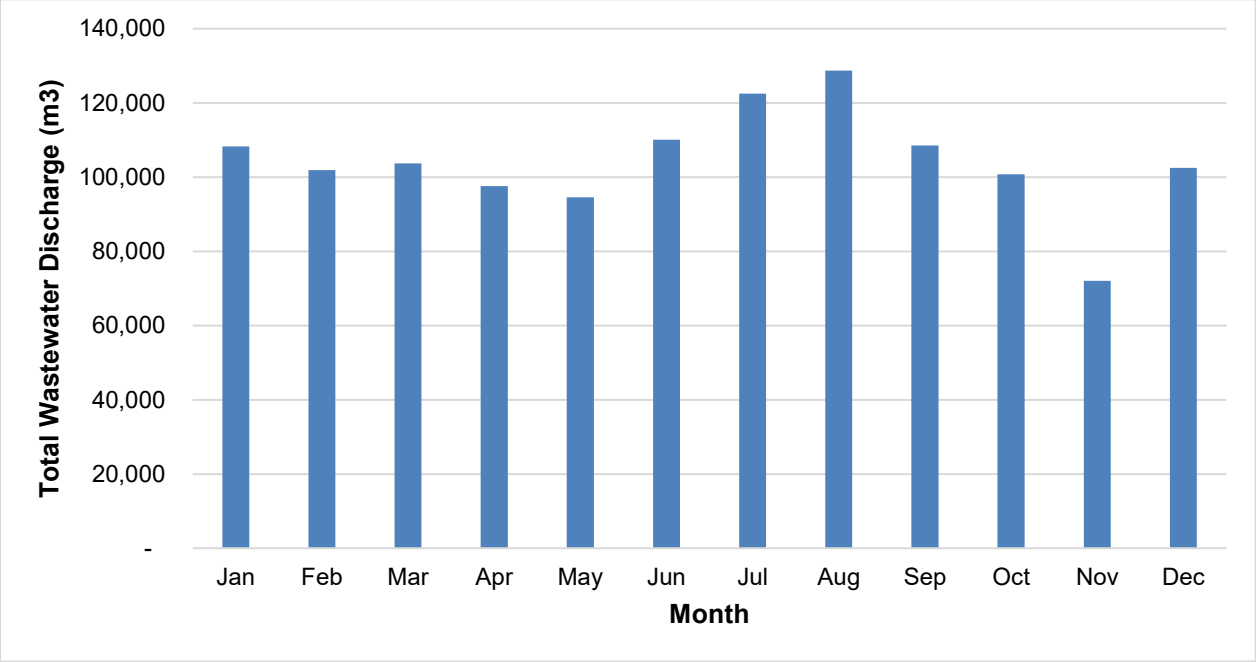
NGCC power plants withdraw and consume water for cooling and steam generation and discharge a portion of wastewater that is not consumed in the process. A typical NGCC facility will consume around 749 L per MWh and discharge around 220 L of wastewater per MWh, the latter of which is typically released into municipal water treatment or directly into surface water bodies (James & Skone, 2012). These water-use intensity factors equate to millions of litres being consumed and discharged every day, adding stress to our water resources and treatment infrastructure. In Canada, nearly all the fossil fuel electricity generation is situated in the most water-stressed regions of the country, forcing some facilities to identify alternative sources such as reclaimed wastewater streams (GoC, 2017). If these assets are to continue to operate in a framework compatible for SD, mitigating the impacts of wastewater discharge and freshwater consumption must be a priority.

The NGCC facility focused on for this study (the Power Plant) uses reclaimed municipal wastewaters for all its process needs. Despite the environmental benefits of using reclaimed wastewater in place of freshwater, the existing supply causes significant operational issues such as equipment fouling. The largest proportion of water uptake is used in a cooling and condensing circuit. The remainder must be purified for use as boiler feedwater. The purification process consists of ultrafiltration and reverse osmosis systems, followed by mixed bed ion exchange demineralization. The fouling issues are reluctantly accepted by the Power Plant because of the lack of alternative water sources and the modest intake charge of \$0.62 m^{-3}. Finding solutions to these problems is a high priority for the plant operators.

In 2020, the Power Plant consumed around 6,025 ML of the raw water supply for cooling water and boiler pre-treatment combined. Out of this total intake volume, approximately 840 ML were used in the boiler water pre-treatment. The existing reclaimed water supply at \$0.62 m^{-3} is a relatively minor expense for the 860 MW facility compared to standard costs of freshwater that could otherwise be nearly five times higher per unit (Renzetti, 2017). One objective of this study is to determine if the water produced by an algae cultivation system could offer substantial benefits in NGCC operations as a boiler water pre-treatment or cooling water supply to replace the existing reclaimed water supply. The practicality of substituting reclaimed wastewater with algae-treated NGCC wastewater was assessed by comparing the analytical testing results of the effluent compared to the existing NGCC supply. Preliminary trials suggested that algae-treated water is too concentrated in minerals to replace the existing pre-treatment boiler water supply. Alternatively, the algae-treated may be a suitable supplement for cooling water supply but this application requires further investigation to determine its practical feasibility. The complete trial results are discussed further in Chapter 5 and Appendix C.

Figure 5

Total Wastewater Discharge Volumes of the Natural Gas Combined Cycle Power Plant Used for This Study Measured as Monthly Averages from 2019 to 2020.



Note: (Author, 2021).

In addition to consuming water, the Power Plant examined for this study also discharges around 1,290 ML of wastewater into the municipal sewer system every year at a \$1.90 m^{-3} charge. The Power Plant's wastewater discharge rates are nearly 19% lower than a typical NGCC facility, releasing around 3.5 ML every day (Figure 5; James & Skone, 2012). One potential benefit of an ACS integrated with these processes is to reallocate the wastewater discharge expenses to low-carbon infrastructure development. Although the ACS would still require a tipping fee of at least the same price, the funds would be financing a sustainable operation and could provide equity and carbon credits if the Power Plant were invested into the treatment system. To help utilize the wastewater management expenses for NGCC facilities, the ACGS examined in this study is designed to divert approximately 3 ML of water per day from

the sewer system. It would also produce more than 3 ML per day of treated water as a pre-treatment boiler feed or cooling water supply in the NGCC process. The following sections will expand on the design and assessment of the ACGS components and how integrating these systems as an NGCC-integrated process can affect their performance metrics.

Chapter 5: Algae Cultivation Systems

The algae cultivation system (ACS) outlined for this study was conceptually matched with a practical design for NGCC integration. This section discusses the alternative options available throughout the industry and the ACS developed by Symbiotic Envirotek (SETI). For this study, the performance of the MAC-B system developed by SETI was assessed using primary data to determine a baseline for comparison to the integration of its components in an ACGS.

5.1 Industry Background

There is a growing network of organizations setup across the world with successful ACS and fuel production operations, a list of which was recently put together by Dalai et al. (2021b). The style of cultivation and their target markets varies greatly between the industry players. For example: Duke Energy (USA) produces "green crude" with a tubular PBR-liquefaction systems that take CO_2 directly from the flue gas of coal-fired power plants; Algae System (USA) uses membrane PBRs to diffuse atmospheric CO_2 with natural solar irradiation to produce bio-oil and biochar; other companies such as Earthrise Nutritionals (USA) and East India Distilleries (India) take a different approach with the large open pond systems that cultivate more than 600 tonnes of *Spirulina* powder every year as a nutritional supplement (Dalai et al., 2021b). This list here is not exhaustive, and there are likely more unrecognized companies that are taking new approaches. The variety indicates that the algae cultivation industry is prevalent and that there are many pathways that offer economic potential. To the best of my knowledge, there are no active organizations pursuing algae cultivation and hydrogen production from the waste streams of NGCC facilities as described in this study.

5.2 MAC-B Technology

The high volume (125 m^3 per cell) and modularity of the modular algae cultivation Biofield™ (MAC-B) technology makes it appealing for commercial applications. As discussed in Chapter 2,

this study focuses on a 128-module Biofield™ that would offer 16 million litres of media capacity (Figure 6). At this scale, the system would provide around 9.6 tonnes of biomass every day by harvesting 32 cells at 80% volume at an assumed 3 kg m^{-3} yield (Appendix D). This assumed yield provides a meaningful amount of daily biomass production that can be used for the hydrothermal gasification process. It is important to note that although previous demonstration projects have shown the potential of the MAC-B technology, the 125 m^3 design has yet to be implemented on a commercial scale (Adelodun, 2019; SETI, 2021). The specified biomass yield used for this study is also uncertain as these systems have yet to cultivate algae at-scale using NGCC wastewaters. The assumptions used for the ACS in this study are performance estimates based on SETI's design and the preliminary testing results outlined in Appendix B.

To determine the efficacy of SETI's technology to remediate wastewater from NGCC facilities, I conducted four bench-scale trials at SETI's facilities with two 20 L composite samples taken from the Power Plant. All four trials resulted in significant algae growth. The water quality analysis conducted by a commercial lab indicated that the effluent is not suitable as pre-treatment boiler feedwater but that it may be suitable as a supplemental cooling water supply for the Power Plant. Additional trials and analysis are required for a reliable conclusion on the practicality of algae-treated water in the NGCC process (Appendix B). The following sections discuss the estimated energy metrics of 128-module system, the environmental impacts including the trial results, and the estimated economic requirements to build and operate the MAC-B technology.

Figure 6

Visualization of an Algae Cultivation System configured with 16-million Litre Capacity in 128 Modules.

Note: Image Copyright Symbiotic Envirotek (2021).

5.3 Energy

Unit operations of the MAC-B technology consist of 30 nano-LED light fixtures, a chiller, and a mixer in every module. Each production cell, consisting of four modules, requires two pumps for water transfer, a proprietary dewatering system, and a finishing filter with UV disinfection to purify the effluent. These various components would require an estimated 1376.50 kWh per growth cycle (96 hours), equating to an average 344.13 kWh per day for each module (Deane, A., personal communication, January 11, 2021). The total average daily energy consumption for a 128-module Biofield™ would be approximately 40.11 MWh. It is important to note that these estimates assume that the light fixtures are on 24/7. However, the modules are designed to allow natural exposure to sunlight and leave the lights off when possible, which would substantially reduce the energy intensity of operation. For this study, I assumed that the lights were active on a continuous basis.

5.4 Environment

Some important environmental aspects of the ACS are its land footprint, carbon utilization rate, and the quality of the treated waters. The land footprint of a 128-module Biofield™ would equate to roughly 4-acres including ancillary facilities for biomass conversion (Figure 6). In this footprint, the system would also sequester 17.28 tonnes of CO_2 per day based on biomass production rates of 9.6 tonnes per day (dry wt.) and 1.8 tonnes of CO_2 per tonne of phototrophic algae biomass growth (Pankratz et al., 2019b; Adelodun, 2019). The daily carbon emissions offset by the 128-module Biofield™ could be eligible for around 6205 tonnes of carbon offsets every year upon third party verification of production (GoC, 2021b).

Algae cultivation also has significantly positive impacts on water quality, particularly with the growth of *C. vulgaris* (Daliry et al., 2019). The trials conducted for this study with NGCC wastewater indicated that there are significant reductions in heavy metal concentrations, biological oxygen demand, total solids content, and nutrients such as nitrogen, phosphorous, and total organic carbon; marginal reductions in sulphate, chloride, and hardness concentrations were also observed in the four trial analyses (Appendix B). It is important to note that the four trials with the NGCC wastewater do not provide enough data to draw any reliable conclusions; this was merely a screening test to see if the system could produce significant biomass and improve water quality. Additional trials should also investigate the proven potential for algae to remediate emerging contaminants of concern that pass through conventional wastewater treatment systems, such as endocrine disrupting compounds that can have detrimental effects to ecological systems upon release (Wang et al., 2017). This is of particular interest for utilizing reclaimed wastewaters that would otherwise be discharged or in this case, used by the NGCC facility in place of freshwater. Microalgae strains such as *C. vulgaris* have shown to decrease the levels of pharmaceutical contaminants through various growth mechanisms; this added benefit would add

significant value to a municipal wastewater system for addressing emerging contaminants of concern (Xiong et al., 2018). Overall, the environmental impact of the MAC-B technology is significantly positive and has the potential to purify wastewaters discharged from municipalities.

5.5 Economics

Large capital investments for algae cultivation have always been the biggest challenge for driving commercial-scale developments, especially in colder climate where PBRs are necessary for reliable operations (Pankratz et al., 2017). The MAC-B faces similar challenges with an estimated total installed cost of $71,680,000 to build a 128-module Biofield™ with its ancillary equipment (Deane, A., personal communication, January 11, 2021). The MAC-B technology is also designed for a 25-year lifetime of continuous operations in a temperate climate, which adds value not captured in this 20-year analysis. It is important to note that this cost assessment is a preliminary design estimate (+/- 30%) and it may vary greatly as the company continues with cost optimization of their technology (Deane, A., personal communication, January 11, 2021).

The cost of the MAC-B equates to roughly $560,000 per 125 m^3 module including all the tankage and harvesting equipment necessary for operations. Based on the estimated utilities and scale of operations, it would cost approximately $878,409 per year for power and an additional $450,000 for 9 operations staff to operate a stand-alone Biofield™ of this size. These costs equate to a minimum biomass selling price (MBSP) of $2,772 per tonne at a 10% discount rate (Appendix E), which is far greater than the $392-$649 per tonne targets set by the U.S. National Renewable Energy Laboratory (NREL) for economical biofuel production from open pond algae systems (Chen & Qunn, 2021; Davis et al., 2016). However, these referenced targets are set for biomass sale or conversion to liquid fuels such as ethanol; they are not for PBR-based thermochemical feedstock production and wastewater treatment. The integrated algae cultivation-gasification system (ACGS) evaluated for this study should be evaluated by

independent metrics since it is an entirely different process that integrates the ACS with syngas, hydrogen, and CO_2 production via hydrothermal gasification (HTG). The following section will provide an overview of the HTG system, and Chapter 7 will outline the economics of the ACGS and how its integration with NGCC processes may improve the viability of each process.

Chapter 6: Hydrothermal Gasification

The process of HTG has recently attracted more attention for clean fuel production in the interest of alleviating dependence on fossil fuels and decreasing GHG emissions. HTG poses great potential for its ability to produce syngas from biogenic materials, which can be combusted as fuel, converted to liquid fuels via Fisher-Tropsch synthesis, or reformed into hydrogen and CO_2 to capture the carbon with physical solvents in a high pressure process (Okolie et al., 2021b; Kapetaki et al., 2015; Kumar, 2018).

Despite its potential, HTG has faced challenges in scaling to meaningful operations past 24 tonnes per day of feedstock capacity (IEA Bioenergy, 2020). This bottleneck of development can be generally attributed to the costs of reactor materials to withstand high pressures, enabling continuous processes with uniform temperature distribution, and obtaining an optimal energy efficiency for fuel production (Pandey et al., 2019; Kumar et al. 2018; Okolie et al. 2021a). The restricted scale for reactor design requires modular units to accommodate the complex HTG process that depends on a set of competing reactions (Table 2). It is important to recognize that the HTG process model applied to this study has yet to be deployed at the 192 tonne per day scale assumed for the analysis (Kumar, 2018); therefore, its practical viability is uncertain.

This section outlines an HTG process design at a practical scale that provides estimates of the material and energy flows for the process. The process simulation results should be interpreted with the understanding that a practical application of the gasification stage would likely require eight 1000 kg hr^{-1} units, as developed by Treatech (n.d) and described by IEA Bioenergy (2020). The practical use of modular units compared to the consolidated design used for this study may affect the performance metrics but will provide a preliminary estimate of the products and energy consumption for the algae biomass HTG process.

Table 2

General List of Reactions Involved in the Hydrothermal Gasification Process.

Reaction Type	Stoichiometric Equation	Heat (ΔMJ/kmol)
Water-Gas Shift	$CO + H_2O \rightleftharpoons CO_2 + H_2$	-42
Boudouard	$C + CO_2 \rightleftharpoons 2CO$	+172
Steam Methane Reforming	$CH_4 + H_2O \rightleftharpoons CO + 3H_2$	+206
Dry Reforming	$CH_4 + CO_2 \rightleftharpoons 2CO + 2H_2$	+247
Methane Formation	$C + 2H_2 \rightleftharpoons CH_4$	-74
Methanation of CO_2	$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O$	-165
Methanation of CO	$CO + 3H_2 \rightleftharpoons CH_4 + H_2O$	-206
Hydrogenation of CO_2	$CO_2 + 2H_2 \rightleftharpoons C + 2H_2O$	-90
Hydrogenation of CO	$CO + H_2 \rightleftharpoons C + H_2O$	-131

Note: Based on Okolie et al. (2020a); Kumar et al (2018); and Hantoko et al. (2018).

6.1 Industry Background

There are several companies that were identified in this study who claim to have commercialized HTG technology for waste-to-energy applications. These companies include: Treatech (n.d.), based in Switzerland; Genifuel (n.d.), based in the U.S.A; and HyFlexFuel (n.d.), based in Germany. Each of these companies has developed unique processes, but the one common factor is the use of catalysts to reduce the energy requirements to operate. All companies have successfully piloted their technologies with feedstocks such as sewage sludge, algae biomass, and other lignocellulosic materials; however, the maximum feedstock capacity identified in this study was 1000 kg hr^{-1} (Treatech, n.d.). To the best of my knowledge, there are no operational HTG facilities at a capacity greater than what Treatech has achieved in their design.

6.2 Process Model Description

The HTG model applied to this study was originally created by Kumar (2018) and later analyzed by Kumar et al. (2019). The model encompasses feedstock preparation, mineral removal for continuous processes, hydrothermal gasification for syngas, separation and purification of the product gas for hydrogen. Since the HTG process involves complex reactions and kinetics (Table 2), the model assumes a fixed composition of biomass defined as a "non-conventional" component and chemical equilibrium for all the reaction processes (see Appendix C).

The following list of assumptions were made for the process model development:

- All model operations assume chemical equilibrium and infinite reaction times at a set pressure and temperature to minimize the Gibbs energy of the defined components in the reacting streams.
- The mineral separation stream contains ash, nitrogen, and a 10% of organics. The nutrients in the stream can be utilized and treated by the ACS (Onwudili et al., 2013).
- The off-gas from the H_2S absorber is processed out-of-scope to manage desulfurization (Kumar, 2018).
- The process is heated with electrical resistance and recovered waste heat (Appendix D).
- The purge gas released from the PSA unit is used in the CHP engine to offset natural gas consumption.
- Steam for the reformer is purchased from an out-of-scope boiler and is superheated with the CHP engine fuelled by a 90/10 natural gas/purge gas fuel mixture.
- Emissions released from steam generation and the CHP engine are accounted for as Scope 2.
- The CO_2 released from the second absorber is directly recycled for algae cultivation.

- Emissions not recycled into the ACS are accounted for as Scope 1 (direct emissions).

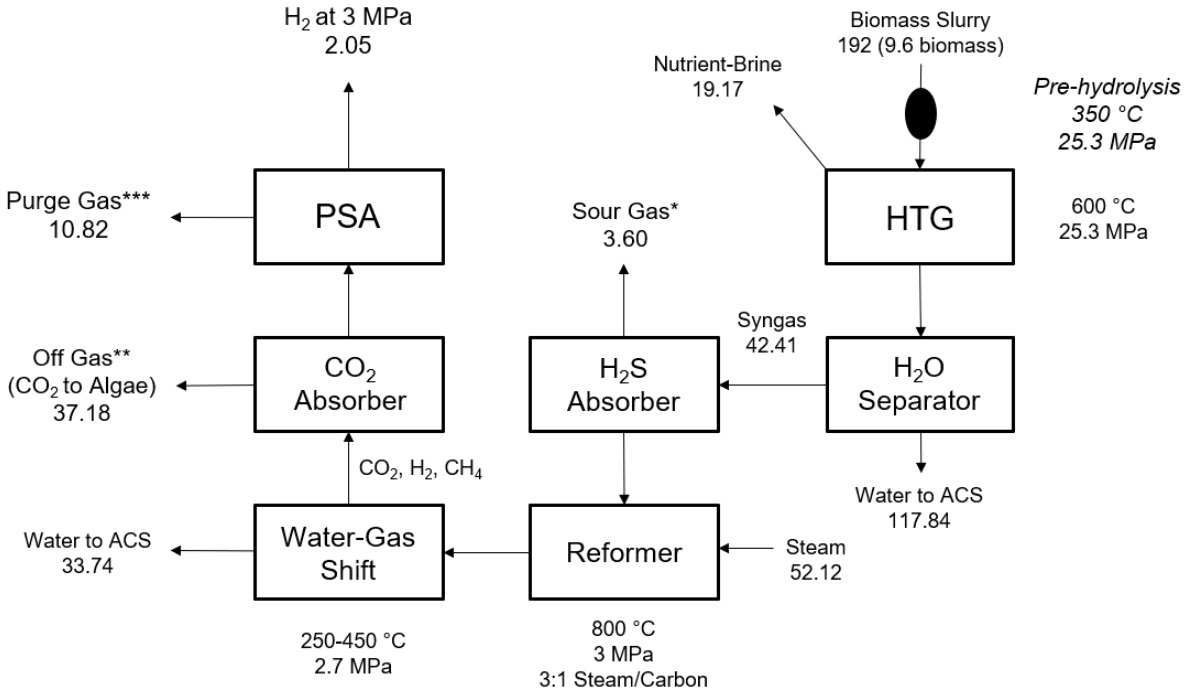
This HTG process is a thermodynamic equilibrium model based on Gibbs free energy minimization, which means it does not consider the complex kinetics involved in algae biomass decomposition, gasification, and syngas reforming. Extending from the Ideal Gas Law, the model utilizes the Peng Robinson (PR) and Soave Redlick-Kwong (SRK) Equation of State property methods for predicting reactions under supercritical and subcritical processes, respectively (Kumar, 2018). Using a thermodynamic approach under the PR and SRK methods does not allow for any prediction of reaction times, and it may result in an over-prediction of product yields as the calculations are based on ideal gas behaviour. Despite its limitations, the original model was verified to predict yields within a 3.5% margin of error compared to experimental results of similar nature (Kumar, 2018; Chakinala et al., 2009; Tiong & Komiyama, 2019). It should be noted that after verification, the replication of the model was scaled from 2000 to 192 tonne per day capacity; this decrease in scale may contribute to an increased margin of error compared to experimental results.

As shown in Figure 7, the biomass slurry (5% dry wt.) is fed into an HTG reactor at 600 °C and 25.3 MPa. These supercritical conditions were pre-determined by Kumar (2018) to be optimal for hydrogen production under continuous processes. The HTG reactor process is modelled after the MODAR reactor, initially proposed by Hong et al. (1989), which utilizes a multi-zone design to effectively separate minerals in a sub-critical aqueous stream that may otherwise clog the subsequent processes. This “nutrient-brine” produced from the reactor is assumed to be diluted with other recycle streams and used to feed the ACS. The pre-feed is decomposed in RYIELD to simulate hydrolysis of the biomass into its constituents and the HTG reactor uses the RGIBBS unit operation to simulate the gasification of the feed under

supercritical conditions (Appendix C). As pressure is released post-gasification, a turboexpander and a heat exchanger are included in the outlet stream to recover energy as electricity produced from the turbine and feedstock pre-heating, respectively (Kumar, 2018).

Figure 7

Daily Mass Flow Rates of the Algae Biomass Hydrothermal Gasification System Process Model



Note: Adapted from Kumar et al. (2019).

Calculated from the Aspen Plus Simulation Stream Results.

All product values are shown in tonnes per day mass flow rates at 95% capacity (Appendix C).

HTG = Hydrothermal Gasification ; PSA = Pressure Swing Adsorption.

*Sour Gas (% wt.) = 92.80% CO_2, 3.46% H_2S, 2.63% CH_4, 1.09% H_2O, 0.02% CO.

**Off Gas (% wt.) = 97.09% CO_2, 2.82% CH_4, 0.07% H_2, 0.02% H_2S.

*** Purge Gas (% wt.) = 68.51% CO_2, 28.05% CH_4, 3.34% H_2, 0.09% CO.

After gasification, the water is separated and passed through a two-stage absorption process, steam reforming, and a gas purification stage. The H_2S and CO_2 absorber columns are

both modelled using the RADFRAC unit operation with Selexol as a physical solvent; this absorption approach can avoid energy penalties for regeneration when operated under high pressures (Burr & Lydon, 2008). The first absorber releases sour gas that is assumed to be sent to an out-of-scope process for desulphurization and the second absorber releases CO_2-rich gas that is recycled to the ACS. The sweetened gas is sent to the steam reformer, which is assumed to utilize steam purchased from the adjacent NGCC facility that is superheated by the CHP engine. Reformed gas is passed through the water-gas shift process under relieved pressure and descending temperatures to produce mainly H_2 and CO_2; the resulting stream is then passed through the second Selexol column to capture the CO_2. The H_2-rich product stream following CO_2 absorption is purified with an adsorption-based Pressure Swing Adsorption (PSA) system that produces a pure (>99%) H_2 stream and an energy-rich purge gas (Moon et al. 2018). All purge gas is assumed to be utilized in an adjacent (out-of-scope) CHP system to power the process (Kumar, 2018). The following sections will address the energy, environmental, and economic performance of this model based on the simulation results and related studies.

6.3 Energy

The HTG of biomass requires an immense amount of energy to maintain sub-critical and supercritical conditions. The simulation provided a general estimate of power requirements for the HTG process based on Gibbs free energy minimization at chemical equilibrium (Appendix C); this was used to predict the daily energy flows (Figure 8). Most of the energy input is used to heat and pressurize the biomass slurry to around 253 times atmospheric pressure (25.3 MPa) and 350 °C. These sub-critical conditions allow the slurry to liquefy in a “pre-hydrolysis” stage that was simulated by RYIELD, which estimates the energy required to break down the biomass into its constituents without considering the intermediate reactions (Figure 7; Kumar, 2018). The pre-hydrolysis stage is the most energy-intensive part of the process, requiring an estimated 11.1

MWh of energy to process 400 kg/hr of biomass (Appendix C). It should be noted that because the simulation does not consider hydrodynamics or the kinetics of the intermediate reactions involved in biomass decomposition, the true energy requirement may differ significantly. This model provides only a preliminary estimate of how demanding this process can be to operate and how valuable energy optimization is for the HTG process.

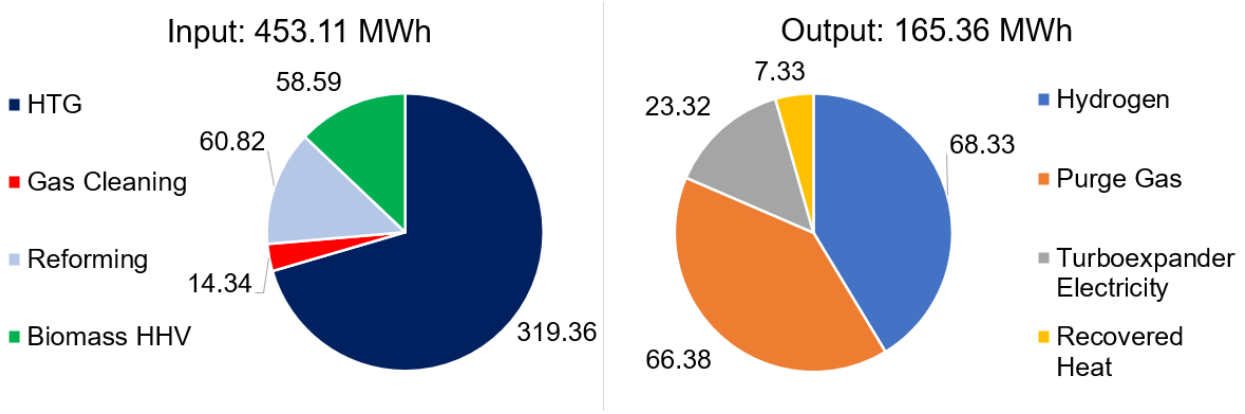
The next most energy-intensive component is the high-pressure steam required for reforming, which uses around 2.2 MWh at 192 tpd. Steam is a significant energy input and source of GHG emissions when generated with natural gas, as assumed in this model (Appendix D). Ideally, the process should minimize steam requirements using alternative reforming methods, such as tri-reforming (Minh et al., 2018). Tri-reforming uses a mixture of steam, oxygen, and CO_2 to convert methane into hydrogen and carbon monoxide; substituting this process could substantially reduce the energy consumption of the process and the associated emissions of steam generation while also utilizing carbon dioxide as a reactant. However, alternative simulations of the HTG process indicated that tri-reforming in place of steam reforming would result in a lower hydrogen yield and higher residual methane, a finding consistent with related literature (Minh et al., 2018; Zhang et al., 2014). Despite its energy-intensity, steam reforming proved to be the most effective reforming method for HTG-based hydrogen production.

Based on the power requirements estimated by the simulation, the daily energy flows of the system were calculated at full capacity, as shown in Figure 8. The daily hydrogen production was found to be 2.05 tonnes per day at 68.33 MWh, while the higher heating value (HHV) of the purge gas from the pressure swing adsorption (PSA) purification system supplies an additional 66.38 MWh per day (Figure 7; Figure 8). Including the biomass HHV as an input of 58.59 MWh

for 9.6 tonnes per day, the overall efficiency of the HTG process was calculated at 36.5% (Appendix D). This efficiency is relatively low compared hydrogen production methods such as steam methane reforming, which can range from 60-80% with carbon capture capabilities (Yan et al., 2020). Most of the inefficiency in the HTG model can be attributed to unrecovered heat (~30%), the energy required to break down the biomass (~65%), and the relatively low hydrogen production of 2050 kg H_2 per day (68.33 MWh). For this process to be energetically feasible, the system should be optimized to recover waste heat for process heating and catalysts should be integrated to improve hydrogen yields and reduce reaction temperatures (Okolie et al., 2021b).

Figure 8

Daily Energy Inputs and Outputs for the Hydrothermal Gasification (HTG) Process.



Note: Calculated from the Net Power Requirements of the Unit Operations and the Higher Heating Value (HHV) of the Fixed Composition Algae Biomass in the Aspen Plus Simulation (Appendix D).

6.4 Environment

Land footprint, GHG emissions, and water footprint were considered as environmental performance indicators of the HTG system. The land footprint for HTG was assumed make up around 300 m^2 with its added processing equipment, considering that existing HTG reactors of 1000 kg hr^{-1} have been designed to fit into shipping containers (Treatech, n.d.; IEA Bioenergy, 2020). The results of the simulation provided an estimate of the gaseous emissions released into

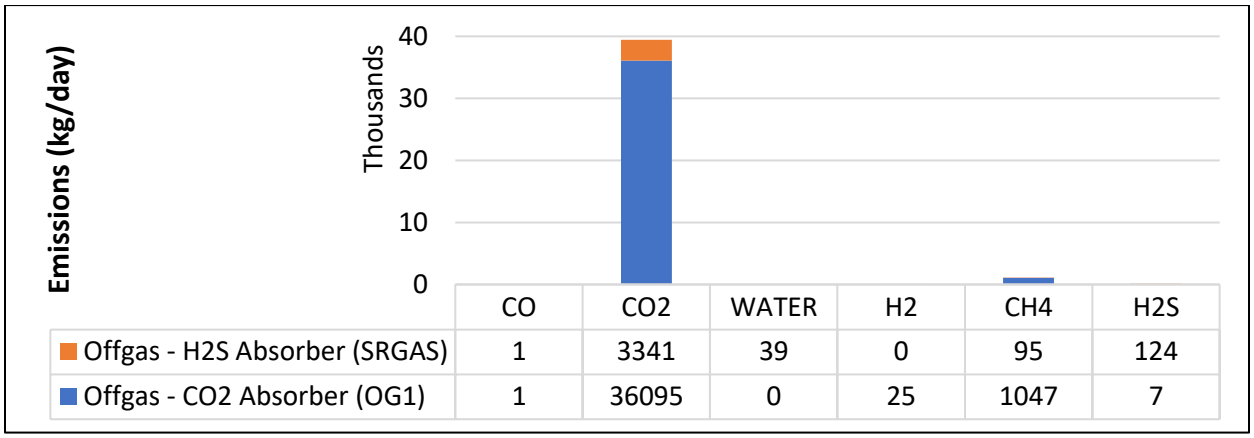
the atmosphere (Figure 9) and the water discharged from the process (Figure 10). Since the HTG process converts most of the carbon in the system to carbon dioxide through water-gas shift reactors, the carbon emissions released from the process are significantly higher than other production methods (Ewing, 2020). There are 39.44 tonnes of CO_2 and 1.14 tonnes of CH_4 generated from the process every day, equating to around 68 CO_2 equivalent tonnes of total daily emissions at a CH_4 global warming potential of 25 (GoC, 2021c). In addition, there are 0.13 tonnes of H_2S released daily within the first off-gas streams that must be addressed with desulphurization technology. However, the sour gas formation is dependent on the algae biomass composition and may be insignificant depending on the sulfate in the wastewater treated by the algae. The treatment of the sour gas was assumed to be dealt with by an adjacent facility that was not included in this study's scope, but it should be recognized as a significant added investment and potential safety risk (Kumar, 2018).

Considering all the unabated CO_2 equivalent emissions released from the process and the hydrogen production rate, the carbon intensity of the fuel is roughly 282 g CO_2 MJ^{-1}; this is nearly three times that of steam methane reforming without carbon capture (Ewing, 2020). The high carbon intensity can be partially attributed to the small scale of this model compared to industrial steam methane reforming operations, as the economies of scale at higher capacity would increase the hydrogen production and likely reduce carbon intensity. Unrecovered methane also makes up around 63% of the residual GHG emissions. For this process to be considered low-carbon, methane emissions either need to be flared or separated and recovered for energy, likely through solid adsorption technology that can isolate methane from the off-gas (Abdullah et al., 2019). The GHG-intensity of HTG makes a strong case for recycling carbon for

algae cultivation, recovering methane from off-gas, and sequestering residual emissions when possible; these factors must be considered to enable low-carbon hydrogen production.

Figure 9

Daily Gaseous Emissions Released from the Hydrothermal Gasification Process.



	CO	CO2	WATER	H2	CH4	H2S
Offgas - H2S Absorber (SRGAS)	1	3341	39	0	95	124
Offgas - CO2 Absorber (OG1)	1	36095	0	25	1047	7

Note: Calculated from the Stream Results of the Aspen Plus Simulation at (Appendix C).

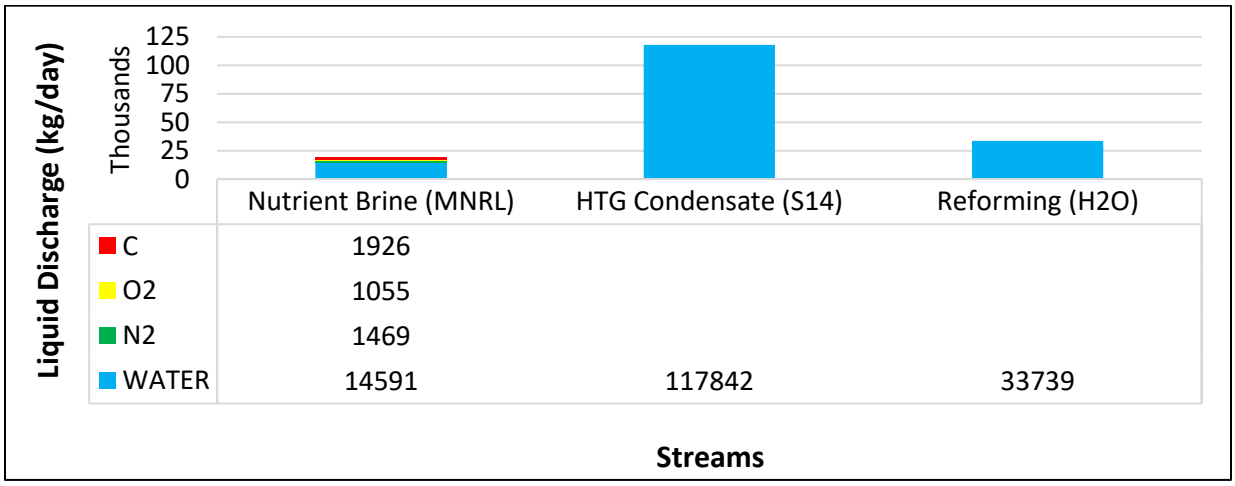
In addition to emissions, the HTG process at 192 tpd requires approximately 182,400 L of water per day for the biomass slurry. After processing, there are three water streams discharged from the process: nutrient brine, HTG condensate, and reforming condensate (Figure 10). Since HTG is a high temperature process that breaks down most contaminants, the condensate discharged from the system can be considered a high-quality diluent similar to distilled water. These higher quality streams would be mixed with the “nutrient brine” containing the nitrogen, phosphorous and inorganic remnants of the algae biomass. In the simulation, the nutrient concentration was represented by the nitrogen and carbon in atomic form, as the process did not include kinetics that could have predicted the specific by-products generated through HTG. The total volume of water discharged from the process for treatment was calculated to be 166,170 L per day and 60.65 ML per year at an 8.8% nutrient brine concentration and a 95% capacity factor (Appendix D). Based on the results shown in Figure 10, the nitrogen and carbon

concentrations of the diluted nutrient brine would be around 11.6 g L^{-1} and 8.8 g L^{-1}, respectively, which suggests that the waste streams may require further dilution for treatment.

It is safe to assume that there would likely be some requirement for additional water treatment if not used in an integrated process since the nutrient brine may contain compounds not safe for discharge into natural water bodies. Given the estimated nutrient concentrations, there is strong potential for this diluted wastewater stream to be used as a nutrient source for algae cultivation; however, there is evidence to suggest that the formation of heterocyclic compounds in HTG nutrient brine may interfere with algae growth (Onwudili et al., 2013). For this study, it is assumed that the microalgae strain *C. vulgaris* can grow in HTG wastewaters, given its proven track record of adapting to harsh waste streams (Daliry et al., 2019). HTG wastewater management would be highly dependent on the location of the facility and local sewer regulations, which is why coupling the HTG system with algae cultivation near a NGCC plant offers an advantage if the ACS is able to utilize the recycled nutrients from HTG.

Figure 10

Daily Liquid Discharge from the Hydrothermal Gasification Process.



Note: Calculated from the Hydrothermal Gasification (HTG) Stream Results of the Aspen Plus Simulation (Appendix C).

6.5 Economics

The initial assessment of the HTG model applied to this study estimated a total capital investment with land and biomass costs at 277.8 million CAD for a 2000 tpd operation (Kumar et al., 2019). This value was obtained using Aspen Icarus Process Evaluator, a process engineering cost estimator that evaluated the individual components of the process model. For this study, I used a ratio estimate with a 0.7 scaling factor to translate the initial fixed cost assessment to my replication of the model at 192 tpd; the estimated costs were converted to 2020 CAD with chemical engineering plant cost indices (Appendix E). The capital cost of the system outlined in this section was estimated at $37,667,666 with a 30% margin of error inherent to the ratio cost assessment method (Green & Southard, 2019). It is important to note that a stand-alone HTG system would likely be on the higher end of the margin of error due to the infancy of the available technologies and their modular designs.

Based on the energy requirements of the HTG processes, the cost of utilities to power the process was calculated to be $17,236 per day, equating to around $5,984,043 every year at a 95% capacity factor. Considering these values with an added 30% in capital costs, an additional 50% in operating costs for biomass and land expenses, and an annual production rate of 748,250 kg^{-1} H_2, the minimum selling price of hydrogen for a 10% return would be roughly $20 kg^{-1} for a stand-alone HTG facility (Appendix E). This cost of production assumes that the lead time has a negligible impact on lifetime hydrogen production, and it does not include any water treatment expenses. Therefore, stand-alone HTG is uncompetitive for hydrogen sales compared to production targets of competing methods set for less than $2 kg^{-1} (Ewing, 2020). The clear lack of economic case for HTG-based hydrogen production was a primary driver of this study to determine if coupling the process with algae cultivation at NGCC facilities may improve the economics of production.

Chapter 7: Results

This section outlines the performance results for the integrated algae cultivation-gasification system (ACGS). The objective of the process integration is to evaluate if, and how, the performance of the system is affected by coupling the two processes and locating them near an NGCC power plant. The following sections outline the performance of the integrated ACGS in terms of energy, environmental, and economic performance.

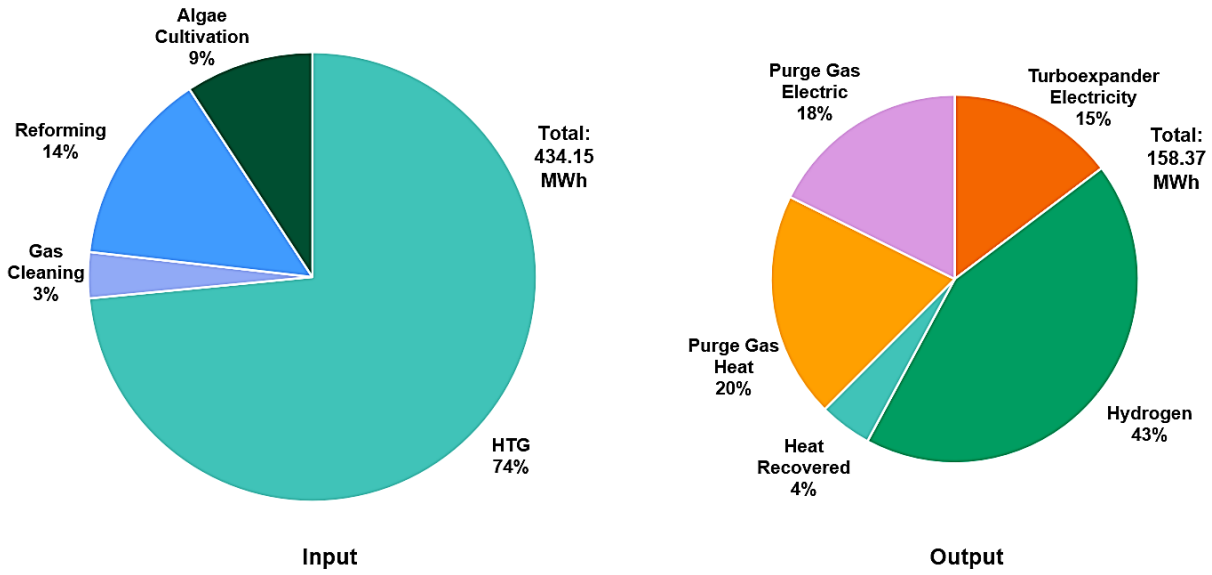
7.1 Energy

Integrating the ACS and HTG has marginal benefits in terms of energy efficiency. By integrating the two systems, energy inputs are decreased through algae cultivation extracting energy from the photo-mediated absorption of wastewater contents. The ACGS powered by the CHP also loses energy output from the purge gas, due to the 85% overall efficiency assumed for the CHP engine with a 90/10 natural gas/purge gas fuel blend (Appendix D).

The counterbalancing gains and losses of the system integration results in a negligible change to the overall efficiency of the ACGS compared to the stand-alone HTG process, which remains around 36.5% (Figure 11). The integration of the systems as an ACGS with CHP results in a negligible change to the energetic performance of the HTG process. However, the true energy yield from the ACS may vary in practical applications as the estimates used in this study are based on equipment design and continuous operations. The energy performance of the ACGS would be highly dependent on operating practices, heat integration with the HTG process, and the local climate in which the system is operating.

Figure 11

Daily Energy Inputs and Outputs of the NGCC-Integrated Algae Cultivation-Gasification System.



Note: Based on the Aspen Plus Simulation and the Estimates by Symbiotic Envirotek (Appendix D).

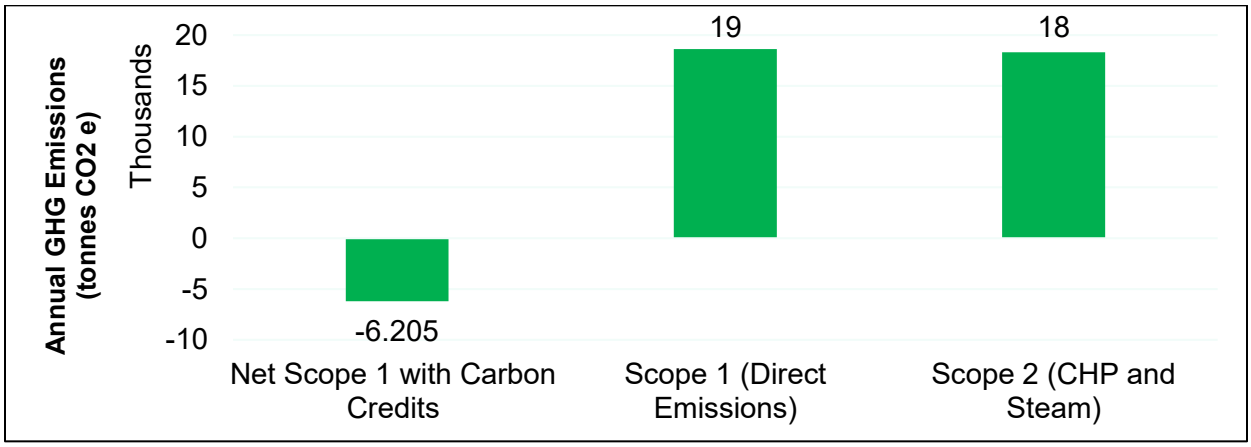
7.2 Environment

The GHG, water, and land footprints of the ACGS were considered as environmental indicators for comparison to the isolated systems' performance. As indicated in Figure 12, the annual net GHG footprint of the ACGS including direct and indirect emissions with the carbon sequestered from algae cultivation is around 11,037 CO_2 equivalent tonnes, which is 6205 tonnes less than the stand-alone HTG system since CO_2 can be recycled for algae cultivation. Around 63% of the direct emissions are due to methane (CH_4) since it has a global warming impact 25 times greater than CO_2 (GoC, 2021c); the remaining emissions are considered carbon neutral CO_2 since they are derived from biomass. For this system to be considered low carbon, the methane released in the off-gas must be recovered or flared to reduce its atmospheric warming effect and excess carbon should be sequestered or utilized for a purpose that would avoid its atmospheric impacts.

The water footprint of the ACGS is the strongest environmental indicator, providing 1,101 ML of treated water every year for NGCC process water. This volume is equivalent to more than 440 Olympic-sized swimming pools, which is enough to provide a complete pre-treatment boiler water supply for an 860 MW NGCC Power Plant, based on this study's findings. Despite the suitable volume, the water quality analysis of the algae-treated water indicated that the high dissolved solids content may diminish its practicality for industrial reuse. Additional treatment mechanisms are likely needed to utilize the algae-treated water in the NGCC process. The ACGS would treat more than 1,168 ML per year, or 3.2 ML per day, including the 166,000 L wastewaters recycled from the HTG process every day. This entire system would operate within a 4 acre footprint, assuming the modular HTG reactors are similar in size to existing technology (IEA Bioenergy, 2020). Overall, the significantly beneficial water footprint, justifiable land use, and abatable GHG emissions of the ACGS can be considered as positive, but there is significant room for optimization of environmental performance.

Figure 12

Annual Greenhouse Gas Emissions as CO_2 equivalents from the Algae Cultivation-Gasification System.



Note: Showing the Net Scope 1 Assuming Carbon Neutrality of the Feedstock, Scope 1 as Direct Emissions from the Hydrothermal Gasification Process, and Scope 2 Resulting from Combined Heat and Power with Off-Site Steam Generation. (Appendix D).

7.3 Economics

The economic performance of the integrated ACGS was assessed by the net present value (NPV) of costs and revenue (Figure 13). The base case outlined in Table 3 assumed competitive product pricing for hydrogen at \$2 kg^{-1} compared with steam methane reforming production costs and the price of the treated water was set at \$2 m^{-3}, the latter of which is a premium for industrial water intake charges (Ewing, 2020; Renzetti, 2017). The costs of electricity and steam were based on prices exhibited by distributed CHP systems and similar studies that purchase external steam for gas reforming, respectively (Doluweera et al., 2020; Okolie et al. 2021b). Credit revenue from recycling CO_2 to the ACS was also assumed for the base case with a carbon price of \$50 with a \$15 annual increase, consistent with the current policy projections outlined by GoC (2021b). This economic model also did not consider land expenses under the assumption that it is co-located with the existing NGCC facility as an integrated system. Labour estimates were based on consultation with industry partners and technology developers.

Table 3

Assumptions for the Base Case Cash Flow Analysis of the Algae Cultivation-Gasification System.

Parameter	Value	Unit	Reference
Rate of Return (Discount, *i*)	10	%	
Project Lifetime (*n*)	20	years	
Operating Costs	7,512,452	\$ per year	Appendix D
Wastewater Tipping Fee	2	$/m^3$	
Water Production Fee	2	$/m^3$	Renzetti (2017)
Competitive Hydrogen Price	2	\$/kg	Ewing (2020)
Cost of Steam	0.022	\$/kWh	Okolie et al. (2021b)

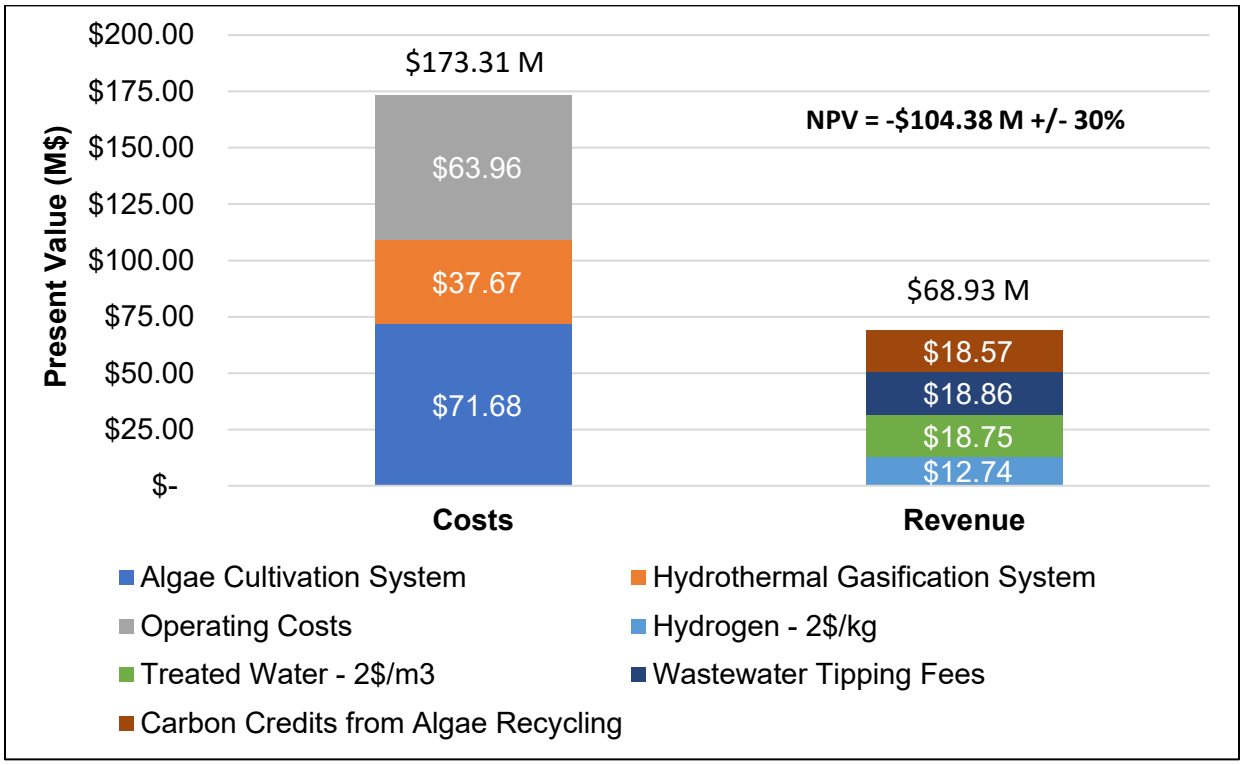
Table 3 (continued)

Parameter	Value	Unit	Reference
Cost of Electricity	60	$/MWh	Doluweera et al. (2020)
Carbon Price ($15/year increase)	50 - 330	$/tonne	GoC (2021b)
Credits from CO_2 Algae Recycling	6205	tonne/year	Appendix D
Credits from FCEV Fuelling	21,010	tonne/year	Appendix E
Labour (13 personnel)	650,000	$/year	

The base case scenario analysis resulted in a negative NPV, which means that the ACGS is not able to produce products at a competitive price and is therefore uneconomic, even with carbon credits from algae CO_2 recycling (Figure 13). For the ACGS to be economic at 10% interest and a 20 year lifetime, the hydrogen must be sold at \$21.23 kg^{-1} hydrogen (Appendix E). This means that the minimum hydrogen selling price of the ACGS will likely increase when compared to stand-alone HTG, mainly due to the high capital costs of the ACS; either way, the costs are prohibitively high for any sensible business case. To improve the economics of production, the system could aggregate biogenic waste feedstocks, such as agricultural residues or sewage sludge that can generate tipping fees for processing (Okolie et al., 2020a; Okolie et al., 2021b). Despite the marginally superior economics of stand-alone HTG with lower cost feed, it is more environmentally sustainable to couple HTG with an ACS as the hydrogen produced has a positive water footprint, which is a unique characteristic for hydrogen production (Mehmeti et al., 2018). Furthermore, the environmental externalities of displacing fossil fuels with hydrogen and reclaiming wastewaters to offset industrial water consumption are not captured in the base case analysis, yet they are the key factors distinguishing the ACGS as a synergistic process for NGCC electricity generation.

Figure 13

Present Value Lifetime Cost and Revenue Breakdown of the Algae Cultivation-Gasification System Base Case Cash Flow Analysis.



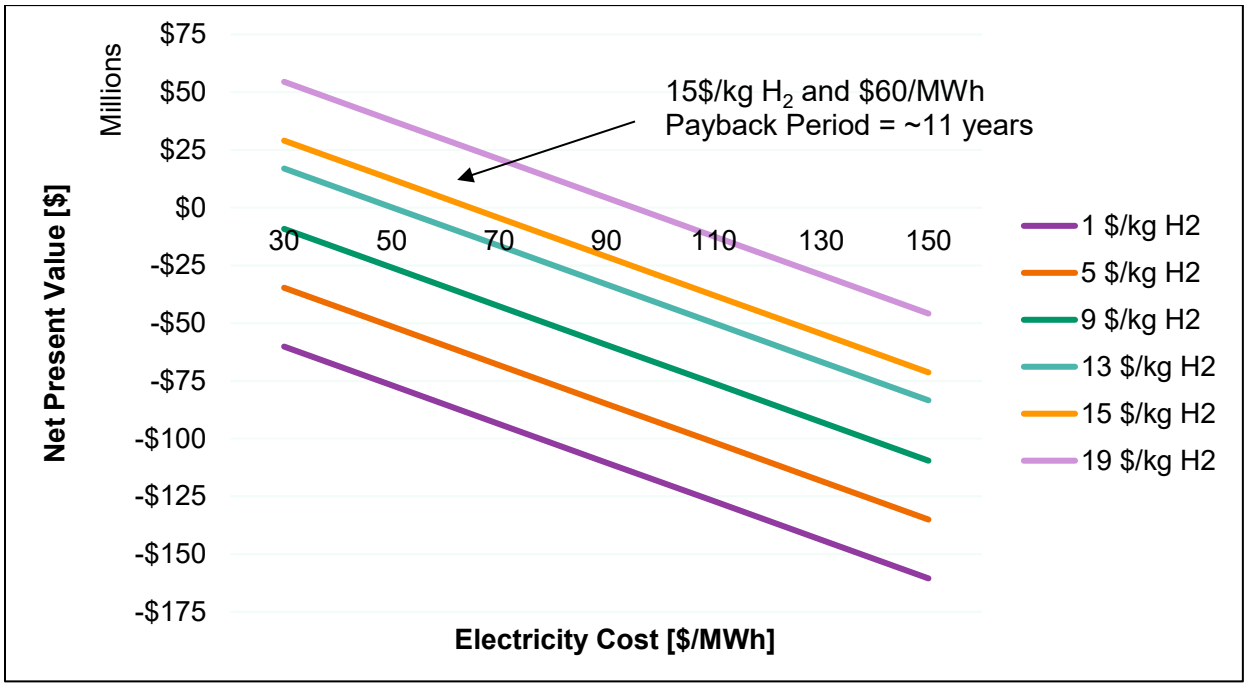
Note: Analysis Included Carbon Credits from Algae Recycling at a $15 per Tonne Annual Increase in Carbon Price Starting at $50 in Year 1 (Appendix E).

In an alternative scenario where the hydrogen is used for fuel cell electric vehicle (FCEV) fuelling, the ACGS has the potential to provide a payback period of 11 years if the hydrogen is sold at $15 kg^{-1} with carbon offsets (Figure 14). The FCEV scenario assumes that the scope 1 emissions from the ACGS are recognized as carbon neutral and that the scope 2 emissions fall below a specified emissions cap (ECCC, 2020; *Greenhouse Gas Pollution Pricing Act*, 2018). The added benefits of FCEV fuelling come from the assumption that 21,010 tonnes of carbon offsets can be sold every year at annual carbon pricing by avoiding the emissions of 149,650 internal combustion engine vehicle tanks of gasoline every year (Appendix E). In comparison,

the hydrogen could be used to displace natural gas emissions and potentially be eligible for around 4,517 tonnes of carbon credits every year, which is less lucrative since natural gas has a lower carbon intensity (Appendix E). These assumptions are consistent with the principles of the *Federal GHG Offset System* and *Clean Fuel Standard* outlined by GoC (2021a) and GoC (2021b), which allow for carbon credits to be reallocated from clean fuel developers to heavy emitters based on the existing carbon price or the market demand for credits. This alternative scenario was used to internalize the environmental benefits and express the holistic business case for the ACGS.

Figure 14

Net Present Value of the Algae Cultivation-Gasification System Considering Different Electricity Costs and Hydrogen Selling Prices.



Note: Analysis Included the Added Revenue of Carbon Credits and Greenhouse Gas Offset Sales from a Hydrogen Fuel Cell Electric Vehicle Fuelling Station at an Increasing Carbon Price of $15 per year Starting from $50 per tonne over the 20-Year Project Lifetime (Appendix E).

Chapter 8: Feasibility Analysis and Discussion

This section discusses the findings while addressing the limitations posed by the time frame available for this study. The results of the study were compiled into a feasibility analysis based on Appendix A and expressed using Figure 15. Indicators for energy, environmental, and economic performance are discussed against the challenges and benefits of the system with consideration to the limitations of the analysis methods.

8.1 Feasibility Analysis

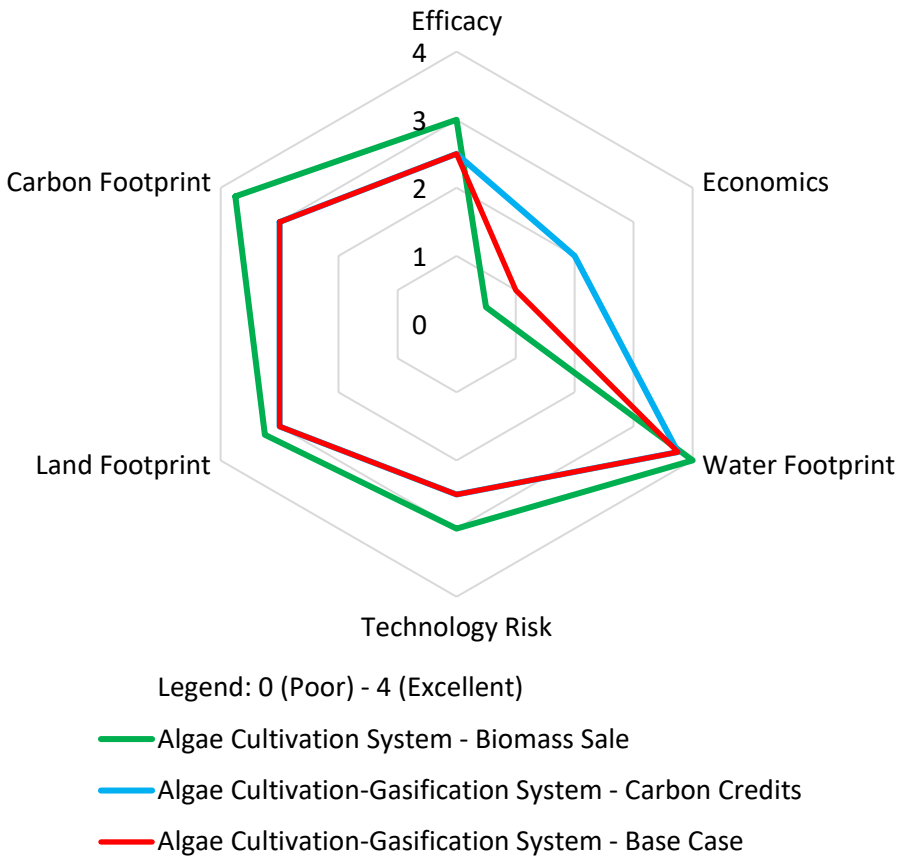
It is evident through the holistic analysis that the technological components of the ACGS require further optimization to increase efficacy, optimize energy efficiency, and reduce capital costs to allow for economic feasibility. The high capital costs of the ACS make the HTG system difficult to integrate as together their costs are economically prohibitive. For integration with NGCC processes, the efficacy of the HTG process must be improved, or it may be more beneficial to identify alternative conversion methods to HTG that can reduce the energy-intensity of operations while still creating economic value from the biomass. The analysis of the algae-treated water found significant improvements in water quality. However, the algae-treated NGCC effluent is likely not a beneficial substitute for high value applications such as pre-treatment boiler water supply due to its high concentration of dissolved solids.

One of the most important factors to make the ACGS feasible is to identify an application for the algae-treated water in the NGCC process that can directly save operations expenses to justify a higher price on the water supply. Based on existing HTG technology, the ACGS would also require eight storage container-sized reactor modules that would have to feed into a central gas reforming system to mimic the conceptual design within a 4 acre land footprint (IEA Bioenergy, 2020). It is important to note that continuous operations at the studied scale for both HTG and ACS technologies is unprecedented; therefore, the technology risks are a significant

burden to the feasibility of the ACGS in commercial settings. Additional studies would also be necessary to process the sour gas emissions and mitigate or recover the methane to enable safe low-carbon hydrogen production via hydrothermal processing.

Figure 15

Results of the Feasibility Analysis.



Note: Based on the Evaluation Matrix Outlined in Appendix A.

8.2 Energy

The energetic performance of the ACGS would need to be optimized through heat recovery and the use of catalysts to reduce HTG reaction temperatures and improve hydrogen yield. The HTG model used for this study only assumed a heat exchanger for syngas cooling. If the system were

to recover heat at every opportunity, there is room to capture around 100 MWh of heat in the waste streams every day to improve the exergy of the conversion process (Appendix C). Studies have also shown that the use of alkali catalysts can reduce HTG operating temperatures and improve hydrogen yields, which could further improve the efficacy of the ACGS (Okolie et al., 2020a; Tiong & Komiyama, 2019). Also, the pre-hydrolysis stage required to establish sub-critical conditions would consume more than 60% of the total energy requirements; if this were to be reduced using catalysts, it could substantially improve the performance of the system. All these factors to reduce energy efficiency would add to the capital costs but the reductions in the operating costs for utilities would likely pay out over the life of the system. It is also likely that the operating estimates for the ACS are underestimated for a cold climate as they are based on design calculations. The integration of a district heating system should be considered to utilize waste heat from the HTG reactors, which would further add to the capital costs of the ACGS.

Another factor to consider for the energy efficiency is that the hydrogen and purge gas production are likely inaccurate due to the reduced scale of the Aspen Plus simulation (Kumar, 2018). Through continued optimization in ACGS operations, it is rational to believe that gas yields would improve over time and that the *C. vulgaris* culture may adapt to its environment to improve biomass yields and supply more feedstock. Any increase in the products energy content would have a significant influence on the feasibility of the ACGS implementation. It is important to recognize the uncertainty around this analysis in its preliminary nature, as commercialized processes being developed around the world are unprecedented at the desired scale. More detailed process simulations and operational data for the HTG and ACS, respectively, are needed to make any reliable conclusions. Based on the data presented for this analysis, the integration of

these processes with NGCC facilities does not offer any substantial benefits with respect to the energy performance indicators.

8.3 Environment

The overall environmental performance of the system encompasses the main benefits of the ACGS for the NGCC processes. In particular, the positive water footprint of 3.02 ML per day (1473 L water per kg H_2) shows potential as a NGCC cooling water supply but it would likely require further treatment or dilution with the existing supply. The four trials indicated that the mineral concentration in the wastewater streams were too high for the algae-based treatment to show any significant reductions; this diminished the effluents' viability as a pre-treatment boiler feed water supply. A more extensive study is needed to verify the results and identify other potential uses for algae-treated water within the NGCC Power Plant. Further research is also required to verify the assumption that both the ACS and HTG can fit within the 4 acre land footprint. The assumed land footprint is equivalent to approximately 3 football fields, which is significantly less than the space required by a 2 MW solar farm (Mancini & Nastasi, 2019); considering the utility of the ACGS, this is a comparatively efficient use of land. The land use estimates were based on SETI's ACS design, and the HTG technology description outlined in IEA Bioenergy (2020), both of which are still in pilot development stages.

The environmental performance of the ACGS was negatively impacted by the scope 1 greenhouse gas emissions (GHGs) from HTG that make up over 19 CO_2 equivalent ktonnes per year. Accounting for the biogenic emissions results in a higher carbon-intensity of hydrogen production than that of steam methane reforming of natural gas (Ewing, 2020). However, the direct GHGs are around 63% methane, which could be near-eliminated through a sequential PSA process that recovers methane for mixing with purge gas (Moon et al., 2018). Recovering methane emissions for the CHP would nearly eliminate scope 1 emissions and improve the

energy efficiency of the ACGS. Also, under the Canadian GHG accounting framework, any CO_2 released directly from the process can be considered carbon neutral since it originates from biomass (ECCC, 2020; GoC, 2021b). For scope 2 derived from utilities, the GHGs would be significantly reduced if the CHP engine assumed to run the process was replaced with non-emitting power. However, this suggested change could eliminate the benefits of the purge gas that helps offset the power demand and offsets emissions as a carbon-neutral fuel through the CHP system. A clear conclusion from this analysis is that despite the benefits from the water, the GHGs released from the HTG conversion restricts the ACGS environmental performance.

The only practical solution to mitigate the GHGs' impact would likely involve geological sequestration of the residual CO_2 emissions. The feasibility of sequestration is restricted by the local geology but has proven to be practical in areas of Western Canada (Layzell et al., 2020). Alternatively, the size of the ACS could be expanded to allow for value-added CO_2 utilization and further enhancement of the system's positive water footprint. To sequester the residual CO_2 emissions with algae, the ACGS would require an additional 166 modules at the 3 g L^{-1} assumed biomass production, which is clearly an impractical addition to the system. Although the system could supply more than 3 ML of treated water for NGCC processes every day in an estimated land footprint of less than 4 acres, the technological risks of the system, both in terms of safety and complexity, are too great to offer practical feasibility at this stage of development. Alternative biomass valorization options discussed in Chapter 2.2 should be explored to replace HTG and mitigate technological risk and improve economic feasibility.

Despite the GHG-intensity of the ACGS operations, the positive environmental benefits of the hydrogen production can be utilized to maximize the systems potential. If the hydrogen is used as a zero emission energy source for fuel cell electric vehicles (FCEVs), the carbon offset

from avoiding the combustion of gasoline can make the entire system nearly carbon neutral, even with the methane emissions. If the methane emissions are abated and the system can be optimized for FCEV fuelling, then the ACGS can be a carbon-negative process and offer offsets to reduce the carbon-intensity of NGCC power generation. Based on the estimated hydrogen production, the ACGS would be able to offset around 21 ktonnes of CO_2 every year by avoiding pollution from 410 passenger cars every day (Appendix E). It is important to note that if the hydrogen were used to fuel heavy duty FCEVs rather than passenger cars, the emissions offset by the system would be even greater as diesel is a more carbon-intensive fuel. The development of a heavy duty FCEV market is also predicted to be more than dominant than passenger cars, especially in colder industrial areas where conventional electric cars would lose capacity (IEA, 2019; Layzell et al., 2020). Overall, the positive water footprint of the ACGS may offer a substantial benefit that can mitigate the impacts of NGCC electricity but the GHGs require mitigation and added investment to enable sustainable, low-carbon operations.

8.4 Economics

The key finding of this analysis is that the integration of these technologies does not significantly improve their economic viability, but strong climate policy has the potential to make it feasible by internalizing the environmental benefits of the system as economic value. Baronas & Achtelik (2019) identified the average hydrogen fuel market value at \$16.51(US) kg^{-1} H_2 in California, which is one of the world's most developed FCEV fuelling markets. The alternative scenario assumed a market value of \$15 (CAD) to account for marginal costs added for storage and the filling station. It is important to note that further investment would be required to establish an FCEV fuelling station, which would likely add \$2-3 per kg of hydrogen and lead to an estimated hydrogen sale price of around \$18 (Layzell et al., 2020). This price is the equivalent of filling up

a 60-L ICE vehicle for $90, which is roughly how much it costs me to fill up my 2006 Hyundai Sonata with Canada's current carbon pricing at $50 per tonne of CO_2.

It is evident that an increasing carbon price can significantly improve the economic viability of clean technology systems like the ACGS. However, the assumptions for the FCEV scenario are based on developing policy that has yet be operationalized and therefore can not provide a reliable basis for economic development. The policy framework supporting the FCEV case comes with political risks that must be mitigated for the ACGS to be economically viable since it depends on an increasing carbon price. One approach to mitigating risks around policy changes is financing the project through government infrastructure banks to establish carbon pricing agreements and reliable subsidization throughout the project life (Owen et al., 2018). Integrated government investment for clean technology development can ensure that policy structures can be agreed to in advance and not be changed by future government administrations.

The ACGS is too expensive to build and operate without government support mostly because of the high-grade materials required to sustain the processes. The ACS is primarily made of steel and most HTG reactors will be made from superalloys, as those are the materials proven to handle the harsh supercritical environments of the continuous process (De Blasio et al., 2021). Identifying low-cost reactor materials and optimization of the energy efficiency to reduce operating costs are critical factors for economic viability. Increased hydrogen yields can also have a significant effect on economic viability by increasing the quantity of the product, allowing for a more competitive price. The use of catalysts, such as alkali metals, should also be explored through kinetics-based simulations to increase hydrogen yields and improve the energy efficiency through decreased HTG reaction temperatures (Norouzi et al., 2016; Okolie et al., 2021b). Despite the benefits of alkali salt catalysts, their use would increase corrosivity risks and

shorten the life of reactor materials (De Blasio et al., 2021). Kinetics-based Aspen simulations are also needed to evaluate the residence times necessary for continuous operations. Current research in HTG modelling suggests that feed residence times may range between 1-60 minutes to obtain the ideal gas yields (Okolie et al., 2021a). If the HTG process proves to require longer than a few minutes of residence time, then the product yields could significantly decrease and diminish hopes of economic feasibility.

8.5 Limitations

The following list outlines the limitations of this study and their effects on the results of the feasibility analysis that should be addressed through future research:

- The algae cultivation trials only had four repetitions based on two samples of NGCC wastewaters. The first sample was a representative 24-hour composite while the second was a grab sample. More trials are necessary to confirm the findings of this study, assess the remediation potential of the ACS, and quantify biomass production rates.
- The Aspen Plus model was a thermodynamic equilibrium-based simulation that did not consider hydrodynamics or the kinetics of the process. Hydrodynamics may significantly impact the energy requirements for pressurization, even at a low (5%) biomass concentration. The kinetics may require residence times that restrict throughput and may also change the energy estimates for the pre-hydrolysis stage where the biomass slurry is liquefied under sub-critical conditions.
- The model was based on chemical equilibrium and assumes infinite time for reaction. In a commercial process, the gas product composition may change to accommodate the dynamic kinetics of the reactions involved in a continuous system. The exclusion of HTG kinetics is a significant limitation of the model. The purpose of the model is not to assess

reaction kinetics, but to provide an estimate of gas yields, by-products, and estimate the heat duty required for process operations. A detailed kinetics-based model should be employed to revaluate the process and validate the findings.

- The evaluation assumed fixed operating costs based on utility demand, which would likely vary significantly throughout the project lifetime based on process adjustments.
- The capital costs assessment was based on industry evaluation and a ratio cost assessment from Kumar et al. (2019) for the ACS and HTG, respectively. Due to the novelty of the process, costs may be 30-50% higher to implement the system when accounting for unforeseen challenges and the available technology (Green et al., 2019; IEA Bioenergy, 2020). The HTG cost assessment methods are acknowledged as preliminary estimates and a more detailed assessment should be conducted to provide more reliable values.
- The model assumes that the ACS can directly recycle the wastewater streams from the HTG process. However, some studies have shown that the HTG wastewaters may contain heterocyclic compounds that can inhibit algae growth mechanisms (Onwudili et al., 2013). The model assumed that a 9% nutrient brine concentration in the "distilled" condensate streams of the HTG process could be remediated in the ACS; this is a critical factor that should be tested in lab-scale experiments with *C. vulgaris*.

Chapter 9: Conclusion

This study has evaluated the integration of algae cultivation and HTG-based hydrogen production with NGCC electricity generation as an ACGS. A holistic analysis of energy, environmental, and economic indicators indicated that the HTG technology requires further development and optimization to improve energy efficiency and economic benefits for the NGCC facility. The environmental performance of the system was positive overall, resulting in a treated water footprint of 1473 L kg^{-1} H_2; this was found to be a unique characteristic for hydrogen production methods. Bench-scale algae cultivation testing with NGCC wastewaters indicated potential for the ACGS to provide supplemental water for NGCC generation but the mineral content of the effluent would restrict its practical use. Further studies pertaining to algae-treated water in the NGCC process are needed to optimize the integration of the ACGS. GHG emissions were also found to be significantly higher than other hydrogen production methods, but the system showed a clear technological path for methane recovery that could enable low-carbon hydrogen production.

Recovering methane from the off-gas and mixing it with the fuel supply used to power the system would have a doubling effect on GHG reductions and efficiency. HTG optimization could set the stage for carbon-negative hydrogen and water production. An alternative scenario analysis also found that policy reflecting the current climate framework of the Government of Canada can make the project economically viable with GHG offsets generated from the fuelling of hydrogen FCEVs. Despite the potential environmental benefits, this study concluded that the ACGS design requires decreased capital costs and energy requirements before it can be considered a feasible process. Further investigation of HTG optimization, additional algae cultivation trials, and valuable applications for algae-treated water in the NGCC process is necessary to identify a sustainable path for ACGS implementation.

9.1 Future Research and Recommendations

The following notes expand on the future research required to improve the feasibility of the ACGS integration with NGCC process. It also provides recommendations on alternative pathways that may provide synergistic effects for NGCC electricity generation.

- The study did not test the algae-treated water as a feedstock for any NGCC power generation process; it only assessed the reuse potential based on the laboratory characterization of the four effluent samples. Additional algae cultivation trials and the use of the effluent in NGCC processes should be investigated to determine the true economic value of the ACGS integrated with NGCC electricity generation.
- The HTG process model applied to this study was a thermodynamic model assuming chemical equilibrium that only provided estimates for the products and energy consumption of unit operations. Future research should incorporate kinetics-based Aspen Plus simulations that can evaluate the residence times of the process and provide more detailed predictions of the HTG products. These simulations should also evaluate the efficacy of nickel, ruthenium, and alkali catalysts to reduce HTG reaction temperatures and increase hydrogen yields (Norouzi et al., 2016; Tiong & Komiyama, 2019).
- This study only considered HTG of algae biomass as a conversion option. Alternative or hybrid valorization options such as hydrothermal carbonization or liquefaction should be considered to improve the performance of biomass conversion operations (Masoumi et al., 2021). Alternative options should also consider aggregating algae biomass with other waste streams, such as sewage sludge, organic waste, agricultural residues or manure that have proven to be suitable feedstocks for hydrothermal conversion into marketable fuel products (Boukis et al., 2017; Kumar et al., 2018; Okolie et al., 2020a).

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Appendix A

Criteria and Evaluation of the Algae Cultivation-Gasification System

Table A1

Criteria and Results of the Algae Cultivation-Gasification System Evaluation.

Category	Criteria	Evaluation
Safety	Evaluate risks of high pressures, temperatures, fire, explosions, toxic substances or by-products.	• Main reactor at 253 bar and 600 °C poses safety risks to critical electricity infrastructure, must be located at a safe distance. • Large-scale demonstrations must prove safety of process before commercial implementation. • Fugitive H_2S and CH_4 emissions are low but require mitigation through gas processing investments not included in the study.
Technology Readiness Level (TRL)	Is the process well-established or emerging technology? (e.g., technology readiness level of major components) Is the process already installed in a commercial operation?	Technology readiness levels: • Algae Cultivation System – TRL 6 (Pilot) • Hydrothermal Gasification – TRL 4 (In development/pilot projects) • No at-scale commercial operations of the integrated system to-date. • Large scale algae cultivation has been proven but not in Canadian climate.

Table A1 (continued)

Category	Criteria	Evaluation
Process Complexity	Does the process require a lot of components? Are the components well understood and easy to operate? Does the process require complex automation?	• The integrated process is complex and requires significant engineering investment. • Algae cultivation is a passive operation with routine cleaning to manage residual algae growth. • Hydrothermal gasification requires skilled workers, sophisticated automation for continuous processes but has well-established components.
Waste Production and Management	What waste streams are produced (solids, liquids, gases)? Are the waste products generated in significant quantities? How can they be managed? Can they be recycled?	• Significant biogenic greenhouse gas emissions that must be mitigated to make system feasible (see Appendix D) – fugitive methane can be extracted for energy recovery via pressure swing adsorption. • ~166,000 L of diluted brine form gasification process is treated via algae cultivation every day – will result in off-site disposal of residual solids/concentrates.
Estimated Capital Cost	Cost of equipment at system level including compressors, pumps, piping, solvents, reactors, boilers, etc.	• Algae Cultivation System: $71.68M • Hydrothermal Gasification System: $37.68M

Table A1 (continued)

Category	Criteria	Evaluation
Estimated Operating Cost	Cost of consumables, power, personnel, etc. Cost of waste disposal (including transportation, if required)	Annual Operating Costs = $7,512,453 • Electricity for HTG = $5,831,952 • Electricity for ACS = $878,409 • Steam at $0.022/kWh = $152,090 • Labour (13 personnel) = $650,000
NGCC CO_2 Emissions Savings	How much CO_2 is consumed and how much does this compare to current emissions?	• 6205 tonnes CO_2 captured, recycled per year from ACGS • 21,010 tonnes of potential offsets per year from FCEV fuelling • Insignificant savings compared to total annual NGCC emissions • Fugitive emissions from HTG must be addressed for life cycle carbon emission reductions
NGCC Wastewater Volume Savings	How much clean water can we prevent from sending to sewer (% of current water disposal)? Can the treated water lead to indirect savings? Can these savings be quantified?	• 1,107,410 m^3 of NGCC wastewater discharge could be avoided every year = $2,214,820 M in sewer charge rates (provided that the algae-treated water can be recycled back to the NGCC facility) • Treated water poses potential as a beneficial substitute for NGCC process water. • Further studies are required to quantify the benefits for the Power Plant.

Table A1 (continued)

Category	Criteria	Evaluation
Ease of Implementation	Infrastructure and building requirements How easy would it be to start small and scale up? Does the process need piloting?	• Existing technologies are modular and require only flat land space. • Modularity makes scaling from small to large feasible. • Process requires a pilot project to verify preliminary study.
Operability	See "complexity" Does the process need frequent operator intervention, or can we turn it on and forget about it? What is the degree of training and experience for operators?	• ACS is essentially autopilot apart from cleaning modules between batches. • HTG would require constant operator attention for safety reasons but is intended as an autonomous process. • Significant training required for operations staff to ensure optimal operations.
Maintainability	How easy are spare parts to secure? Are there expensive components that are difficult to order?	• Spare parts for system may be difficult to find efficiently and expensive due to niche technology in the process components.
Space Requirements	System location, ability to fit within current facility footprint What is the land area that will be occupied (m^2)?	• Approximately 4 acre land footprint – around 3 football fields of space required. • Ideally located directly adjacent to NGCC facility.

Table A1 (continued)

Category	Criteria	Evaluation
Environmental	Net CO_2 Emissions and Water Savings. Potential emissions (Gas/Liquids/Solids)	• 18,608 tonnes CO_2 equivalents released annually from the HTG process, mostly fugitive methane and CO_2 that can be mitigated with pressure swing adsorption and solid adsorption technologies. • 18,310 tonnes CO_2 emitted from ~90/10 natural gas/syngas fueled-CHP operations and purchased steam generation for gas reforming. • 6205 tonnes of carbon credits per year. • Potential for ~4,517 tonnes CO_2 from hydrogen-natural gas offsets • Potential for ~21,010 tonnes CO_2 from hydrogen FCEV-ICE offsets (Appendix D)

Appendix B

Complete Summary of the Bench-Scale Algae Cultivation Trials

Prepared by: Brendan Struthers and Art Deane at Symbiotic Envirotek, March 15th - 28th, 2021.

Background:

This study undertook a series of lab scale experiments to determine to what degree algae will effectively treat wastewater discharged from a natural gas combined cycle power plant that uses reclaimed wastewater effluent for cooling processes. SETI participated in this study as an industry partner to demonstrate their algae cultivation technology's ability to treat wastewater.

Study Objective

The objective of this section of the study is to determine to what degree algae generally and particularly, the *Chlorella vulgaris* (Cv) algae strain, can effectively treat wastewater discharged from a power generation site. Effective treatment would produce algal biomass that is a suitable feedstock for thermochemical conversion technologies and effluent that is of higher quality than the existing boiler water pre-treatment supply used by the NGCC facility.

Scope of Work

Two sets of 20-liter composite samples of the wastewater were collected from the sanitary sewer lift station outside the natural gas power plant and delivered within the hour to SETI's algae testing laboratory where it was immediately used in the studies as follows. The work consisted of two cultivation trials consisting of two runs for each of the collected samples as described in Table B1. A review of the historical NGCC effluent analyses showed that although the wastewater varied widely and contained some excess nutrient elements, there were sufficient levels of carbon, nitrogen, and phosphorous for sustaining algae growth (see Table B2).

Table B1

Description of the Algae Cultivation Trial Runs and Their Inoculant Sources.

Trial-Run	Wastewater Sample Type	Inoculant Source
1-1	24-Hour Composite	Starter Culture
1-2	24-Hour Composite	1-1
2-1	Grab	1-2
2-2	Grab	2-1

Studies Summary

Duplicate experiments were run with each composite sample for a total of four runs. Each experiment was conducted for 96 hours using the methods and conditions in Table B2. The following sections provide a description of the applied methods, handling of the post-cultivation water, and the analysis of the results obtained from the commercial laboratory analysis.

Table B2

Experimental Design Parameters for each Algae Cultivation Trial.

Experimental Design	
Primary treated wastewater	10 liters per study
Chlorella vulgaris algae strain	2 liters per study
Inoculum strength	Approximately 5 x 10^6 cells/mL
Growth cycle	4-days
Lighting spectrum	100% red
Lighting intensity	80 mμ/m^2/s
Lighting duty cycle	24/7 - continuous
Temperature	22°C - 26°C

Table B2 (continued)

Experimental Design	
Media agitation rpm	90
pH set point	6.8 – CO_2 sparging turn-off
CO_2 sparging	Continuous

Inoculum development

A starter culture of the Cv algae strain was cultivated using SETI's inoculum development process with artificial culture media at 22°C, in air over several days prior to the study. After reaching the desired cell density, 4 L of the start culture was mixed with 16 L of the first NGCC wastewater sample in Trial 1. The mature Trial 1 mixture was used as the inoculant for the subsequent trials. It is important to recognize that there were residual nutrients from the starter culture that may have interfered with the first trial results. The nutrient concentrations in the starter culture and the maximum estimated levels in the sample for wastewater trial 1 are outlined in Table 2. The nutrient results for the first trial may be inaccurate due to the residual nutrients from the starter culture and the presence of high dissolved solids interfering with analysis methods. The subsequent trials (Table B1) used 4 L of inoculum from the previous sets and therefore carry any residual nutrients from the starter culture previous cultivation trials.

Table B4

Estimated Nutrient Levels for Starter Culture and Wastewater Trial 1.

Nutrient	Sample	Max Concentration (mg/L)
Total Phosphorous	Starter Culture	8.68
Total Phosphorous	WW Trial 1	6.54

Table B5 (continued)

Nutrient	Sample	Max Concentration (mg/L)
Total Nitrogen	Starter Culture	6.16
Total Nitrogen	WW Trial 1	9.32

Treatment

For each of the four trials, 10 L of the sampled wastewater was inoculated with 2 L of *C. vulgaris* culture and subjected to the conditions outlined in Table 1 for 96 hours. The resulting media was centrifuged, filtered through a 1.1 µm filter, and preserved in samples containers that were sent to a commercial lab for analysis. The treated water was sent for analysis to determine residual levels of N, P, Dissolved Orthophosphate, COD, BOD, pH, conductivity, TSS, TKN, Total Metals, and Anions via IC (NO^{2-}, NO^{3-}, SO_4^{-2}, Cl^-). This process was designed to emulate the commercial-scale algae cultivation system that uses similar equipment with a 1 nanometer filtration system. Due to residual nutrients interfering with the initial trials, Trials 2-1 and 2-2 should be viewed as the most reliable indication of full-scale application.

Figure B1

Run-2, trial-1 Day-0 Septic wastewater filtered to 100 µm.

Figure B2

Run-2, trial-1 Day-0 (left) and the pH is adjusted down from 7.54 to 6.60 by infusing CO_2.

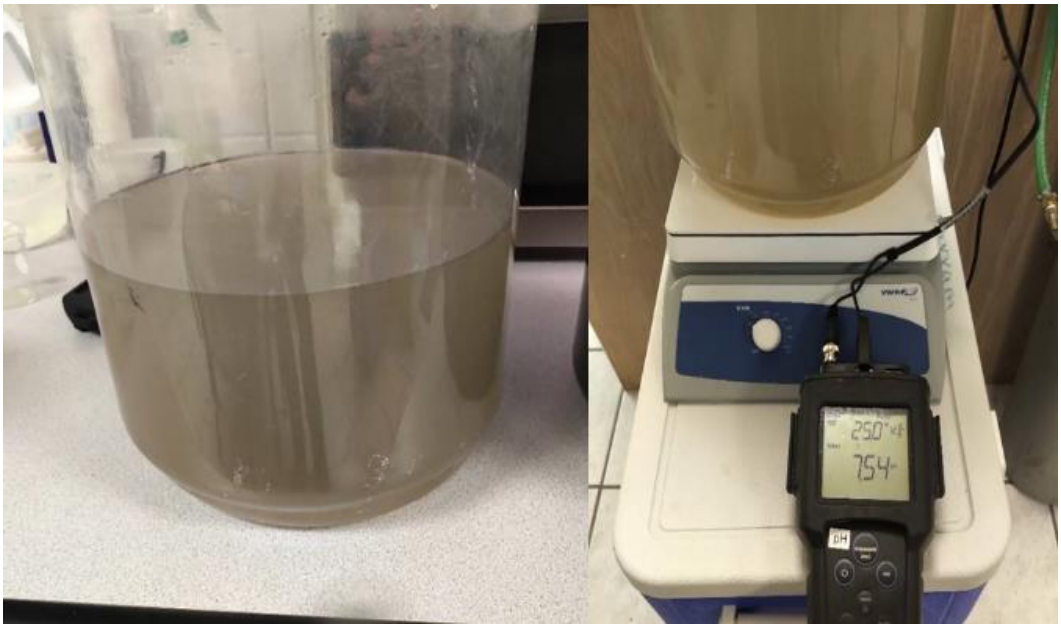


Figure B3

Run-2, trial-1 Day-0. The pH is adjusted to 6.60, then seeded with 2 liters of inoculum at approximately 5^10^6 cells per mL of inoculum.

Figure B4

Run-2, trial-1 Day-0, 0 hours. 10 the liters of septic wastewater is inoculated (seeded) with 2 liters of Chlorella vulgaris with cell density of approximately 5 x10^6 cells per mL of inoculum.

Figure B5

Run-2, trial-1 Day-0, 0 hours. The inoculated wastewater was placed on a shaker table at 90 rpm, under red light set at 80mμ /m^2/s with 24-hour duty cycle (Left). The computerized pH controller was set at a set-point of pH 6.8 sparging CO_2 on demand to maintain pH (Right). Culture was allowed to growth for 96 hours, (4-days).

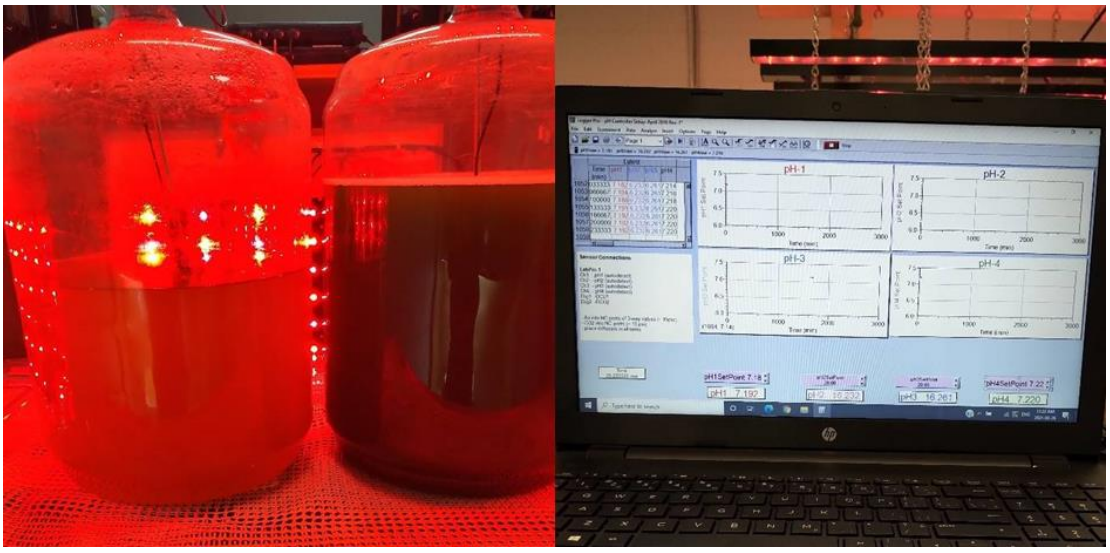


Figure B6

Run-2, trial-1 Day-1, 24 hours (Left). Run-2, trial-1 Day-2, 48 hours (Right).

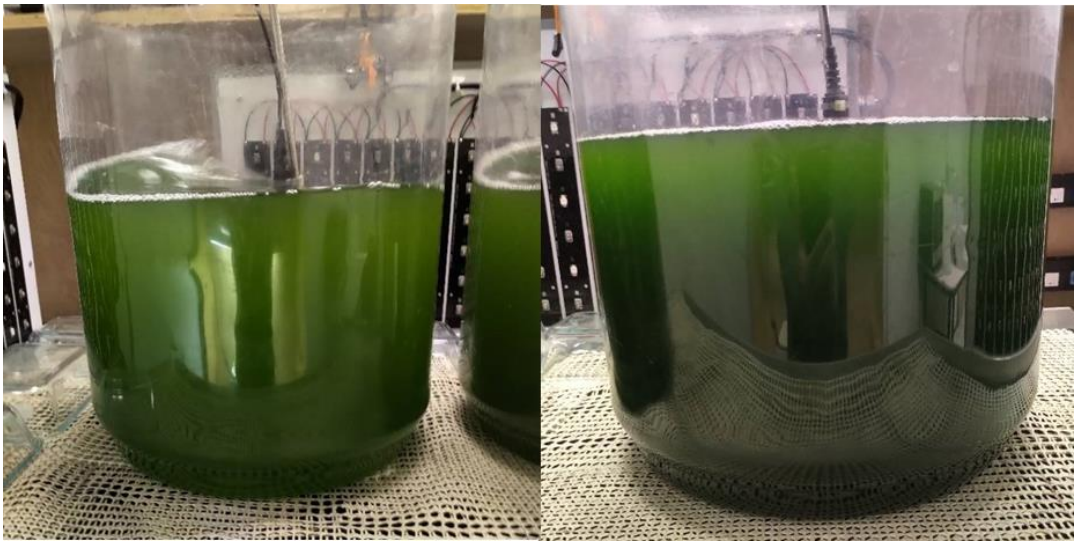


Figure B7

Run-2, trial-1 Day-3, 72 hours (Left). Run-2, trial-1 and 2, Day-4, 96 hours (Right).

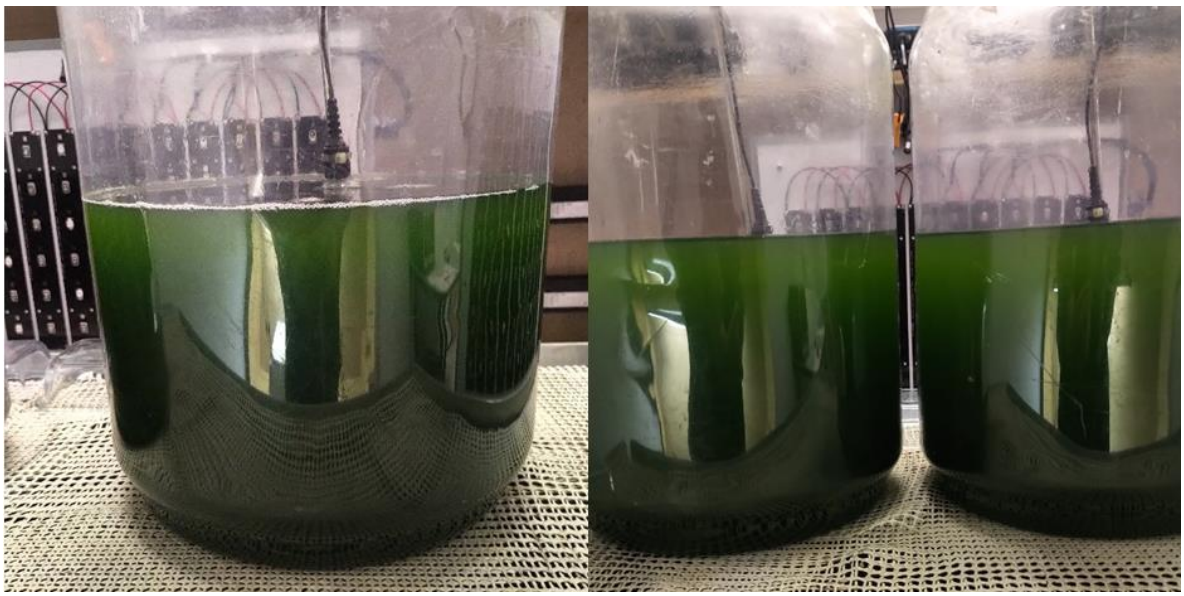


Figure B8

Run-2, trial-1 Day-4 unprocessed (Left). 4 x 250mL samples centrifuged for 7 minutes to concentrate biomass.

Figure B9

Run-2, trial-1 Day-4 after Centrifugation (Left). Permeate liquid poured form concentrated biomass and vacuum filtered via 1.2 µm membrane (Right).

Figure B10

Run-1, trial-1, Day-4 (Left). Run-1, trial-2, Day-4 (Right).

Results

The main effects of *C. vulgaris* cultivation in the wastewater samples compared to the existing Power Plant supply are illustrated in Figures B11 and B12. It is shown that the treatment resulted in significant reductions in most parameters monitored for standard wastewater discharge or reuse regulations, apart from conductivity. The conductivity levels were likely the cause of the high source water concentrations. Since the NGCC process recirculates cooling water, the contents of the reclaimed wastewater are concentrated before discharge. They were also influenced by excess CO_2 diffusion that likely caused the formation of bicarbonate ions, which in turn raised the alkalinity and saturation index of the samples (Table B3).

Conclusion

The main objective of the trials was to determine a valuable application for the process water in the NGCC process. It would be impractical to use the algae-treated water for pre-treatment boiler water supply because it is more concentrated in minerals than the existing supply. The boiler water is demineralized before generating steam in the NGCC process and replacing the supply

with the algae-treated water would require more energy for treatment and likely reduce the life of the existing treatment equipment. The algae-treated water would be most useful as a supplement for cooling water in the NGCC process, an application which has a low product value since reclaimed wastewater is already being purchased at a discounted rate of \$0.62 m^{-3}. It should be noted that the high dissolved solids content interfered with the nutrient analysis methods and that dilution was necessary, leading to increased detection levels for the reported values. This interference may have led to decreased accuracy and higher-than-expected results. Although limited, the trial results indicated that algae-treated wastewater may be a viable candidate for reuse applications such as cooling water for NGCC electricity generation. Additional trials are recommended to validate these findings.

Figure B11

Nutrient Results of Algae-Treated Wastewater compared to Analytical Data from the Existing Water Intake at a Natural Gas Combined Cycle Power Plant using Reclaimed Wastewater as a Pre-Treatment Boiler Water Supply.

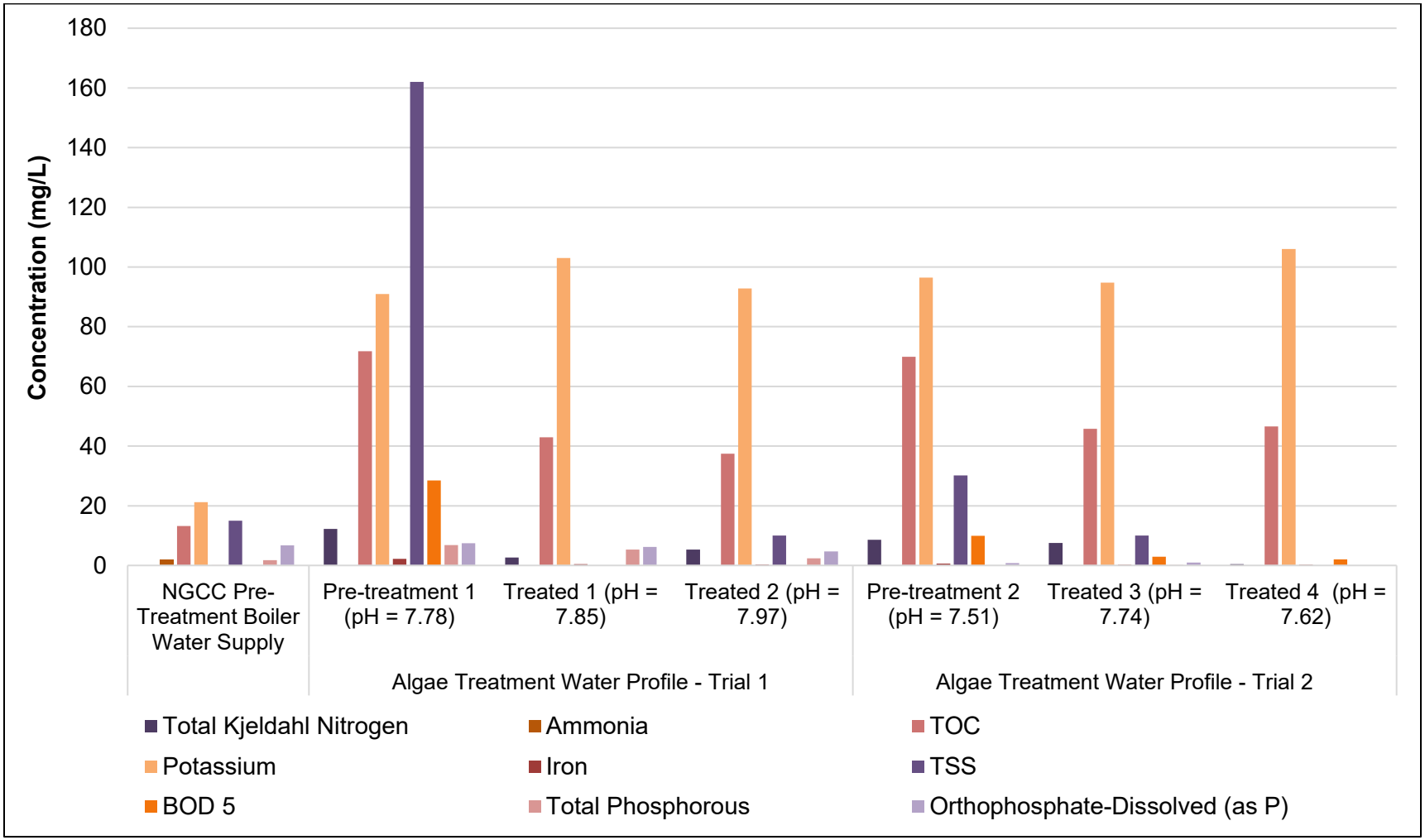


Figure B12

Inorganic and Anion Results of Algae-Treated Wastewater compared to Analytical Data from the Existing Water Intake at a Natural Gas Combined Cycle Power Plant using Reclaimed Wastewater as a Pre-Treatment Boiler Water Supply.

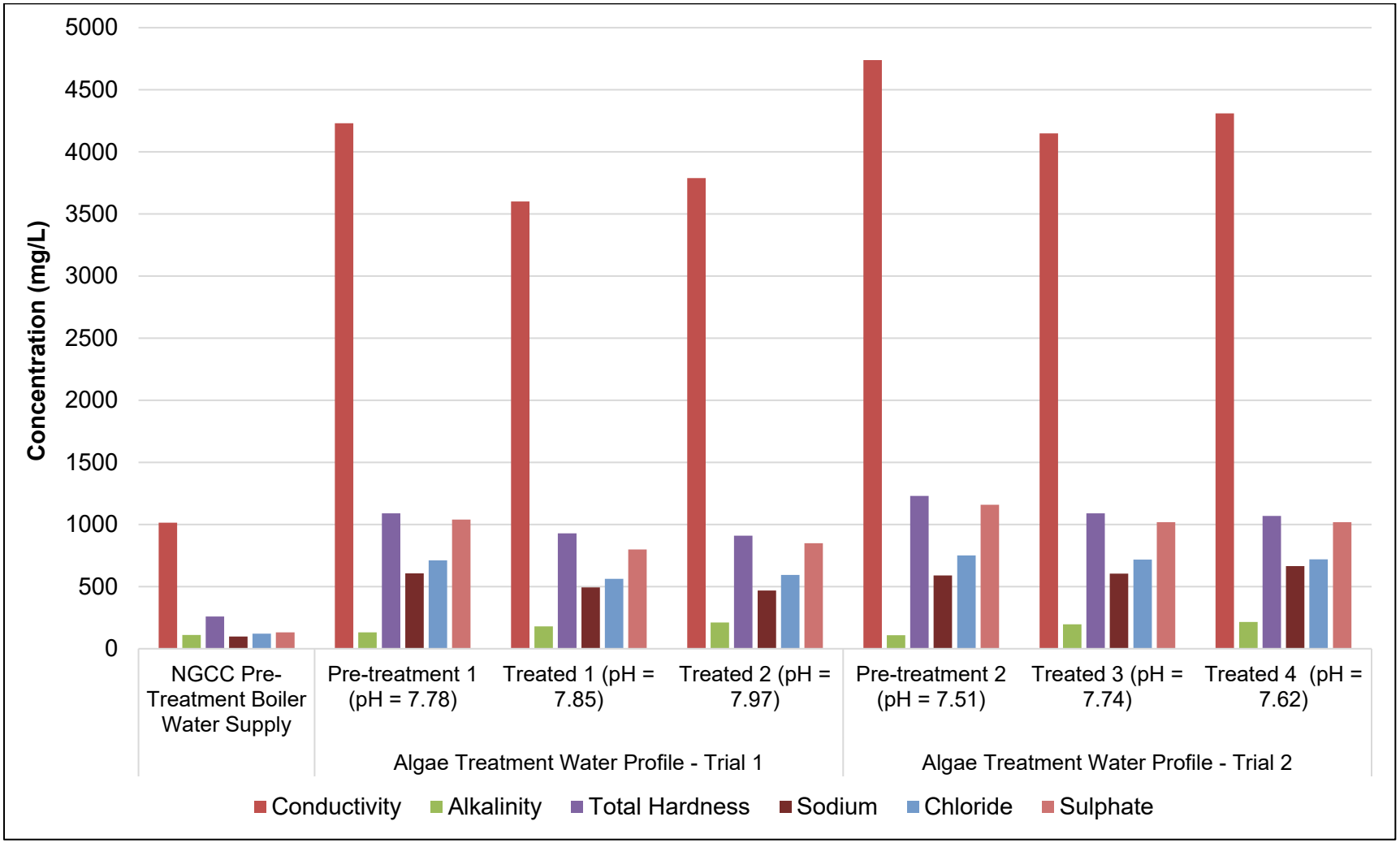


Table B4

Complete Results from Laboratory Analysis of Power Plant Wastewater before and after Algae-Based Treatment

Parameter	Detection Limit	Units	Pre-Treat-1 (Raw)	Treated1	Treated2	Pre-Treat-2 (Raw)	Treated3	Treated4	Mean Treated Results
Total Suspended Solids	3.0	mg/L	162	<3.0	10.0	30.2	<3.0	<3.0	6.5*
Alkalinity, Total (as CaCO3)	2.0	mg/L	132	181	212	109	196	216	201
Bicarbonate (HCO3)	5.0	mg/L	161	220	259	133	239	264	246
Carbonate (CO3)	5.0	mg/L	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
Chloride (Cl)	2.5	mg/L	711	563	594	751	718	719	649
Conductivity (EC)	2.0	uS/cm	4230	3600	3790	4740	4150	4310	3963
Fluoride (F)	0.10	mg/L	0.84	0.38	0.13	<0.20	0.64	0.65	0
Hardness (as CaCO3)		mg/L	1090	929	911	1230	1090	1070	1000
Hydroxide (OH)	5.0	mg/L	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
Ion Balance		%	90.3	103	88.8	99.9	93.9	91	94
Nitrate and Nitrite (as N)	0.11	mg/L	83.9	58.1	52.9	89.1	57.6	59.6	57
Nitrate (as N)	0.10	mg/L	83.9	55.9	49.5	89.1	55.0	57.2	54

Parameter	Detection Limit	Units	Pre-Treat-1 (Raw)	Treated1	Treated2	Pre-Treat-2 (Raw)	Treated3	Treated4	Mean Treated Results
Nitrite (as N)	0.050	mg/L	<0.10	2.19	3.43	<0.10	2.59	2.45	3
Total Kjeldahl Nitrogen	0.050	mg/L	12.2	2.69	5.32	8.56	7.49	0.436	4
pH	0.10	pH	7.78	7.85	7.97	7.51	7.74	7.62	7.80
Orthophosphate-Dissolved (as P)	0.50	mg/L	1.76	6.84	5.34	2.36	0.0531	0.167	3
Phosphorus (P)-Total	0.50	mg/L	6.70	7.48	6.20	4.70	0.800	0.939	4
TDS (Calculated)		mg/L	3150	2620	2600	3500	3090	3090	2850
Sulfate (SO_4^{2-})	1.5	mg/L	1040	800	850	1160	1020	1020	923
Total Organic Carbon	1.0	mg/L	71.8	42.9	37.4	69.9	45.8	46.6	43.2
Aluminum (Al)-Total	0.015	mg/L	5.24	0.276	0.169	1.73	0.355	0.351	0.288
Antimony (Sb)-Total	0.00050	mg/L	0.00257	0.00193	0.00187	0.0023	0.00225	0.00246	0.002
Arsenic (As)-Total	0.00050	mg/L	0.00195	0.00130	0.00122	0.0017	0.00137	0.00153	0.001
Barium (Ba)-Total	0.00050	mg/L	0.142	0.265	0.161	0.0740	0.190	0.222	0.210

Parameter	Detection Limit	Units	Pre-Treat-1 (Raw)	Treated1	Treated2	Pre-Treat-2 (Raw)	Treated3	Treated4	Mean Treated Results
Beryllium (Be)-Total	0.00050	mg/L	<0.00050	<0.00050	<0.00050	<0.0010	<0.00050	<0.00050	<0.00050
Boron (B)-Total	0.050	mg/L	0.631	0.479	0.475	0.65	0.657	0.749	0.590
Cadmium (Cd)-Total	0.000025	mg/L	0.000139	0.000196	0.000125	0.000078	0.000168	0.000216	0.000176
Calcium (Ca)-Total	0.25	mg/L	324	242	247	322	305	346	285.000
Chromium (Cr)-Total	0.00050	mg/L	0.0110	0.00267	0.00188	0.0033	0.00172	0.00220	0.002
Cobalt (Co)-Total	0.00050	mg/L	0.00222	0.00178	0.00165	0.0019	0.00186	0.00203	0.002
Copper (Cu)-Total	0.0025	mg/L	0.0349	0.0692	0.0467	0.0191	0.0407	0.0320	0.047
Iron (Fe)-Total	0.050	mg/L	2.23	0.398	0.339	0.59	0.271	0.295	0.326
Lead (Pb)-Total	0.00025	mg/L	0.00425	0.00292	0.00330	0.00132	0.00200	0.00215	0.00259
Lithium (Li)-Total	0.0050	mg/L	0.0329	0.0318	0.0319	0.040	0.0373	0.0422	0.036
Magnesium (Mg)-Total	0.025	mg/L	115	93.6	91.6	109	108	121	103.550
Manganese (Mn)-Total	0.00050	mg/L	0.197	0.0885	0.0785	0.130	0.0921	0.0849	0.086

Parameter	Detection Limit	Units	Pre-Treat-1 (Raw)	Treated1	Treated 2	Pre-Treat-2 (Raw)	Treated3	Treated4	Mean Treated Results
Mercury (Hg)-Total	0.0000050	mg/L	<0.0000050	<0.0000050	<0.0000050	0.0000067	<0.0000050	<0.0000050	0.000
Molybdenum (Mo)-Total	0.00025	mg/L	0.0401	0.0334	0.0327	0.0391	0.0404	0.0443	0.038
Nickel (Ni)-Total	0.0025	mg/L	0.0154	0.0121	0.0111	0.0117	0.0120	0.0154	0.013
Potassium (K)-Total	0.25	mg/L	90.9	103	92.8	96.4	94.8	106	99.150
Selenium (Se)-Total	0.00025	mg/L	0.00297	0.00245	0.00206	0.00295	0.00282	0.00286	0.003
Silver (Ag)-Total	0.000050	mg/L	0.000512	<0.000050	<0.000050	0.00089	0.000050	0.000058	0.000
Sodium (Na)-Total	0.25	mg/L	607	494	468	590	604	666	558.000
Thallium (Tl)-Total	0.000050	mg/L	<0.000050	<0.000050	<0.000050	<0.00010	<0.000050	<0.000050	0.000
Tin (Sn)-Total	0.00050	mg/L	0.00301	<0.00050	<0.00050	0.0010	0.00051	<0.00050	0.001
Titanium (Ti)-Total	0.0015	mg/L	0.0097	<0.0015	<0.0015	<0.0030	<0.0015	<0.0015	0.000
Uranium (U)-Total	0.000050	mg/L	0.00210	0.000849	0.000927	0.00147	0.00123	0.00139	0.001
Vanadium (V)-Total	0.0025	mg/L	<0.0025	<0.0025	<0.0025	<0.0050	<0.0025	<0.0025	0.000

Parameter	Detection Limit	Units	Pre-Treat-1 (Raw)	Treated 1	Treated2	Pre-Treat-2 (Raw)	Treated3	Treated4	Mean Treated Results
Zinc (Zn)-Total	0.015	mg/L	0.269	0.311	0.285	0.211	0.300	0.332	0.307
Biochemical Oxygen Demand	2.0	mg/L	28.5	<2.0	<2.0	9.9	2.9	2.0	2.2
Chemical Oxygen Demand	10	mg/L	324	122	127	192	141	143	133
Dissolved Metals									
Calcium (Ca)-Dissolved	0.50	mg/L	285	234	241	308	279	271	256
Magnesium (Mg)-Dissolved	0.50	mg/L	91.1	83.6	75.0	113	96.6	95.1	88
Potassium (K)-Dissolved	2.5	mg/L	71.7	99.4	73.5	98.1	82.3	81.0	84
Sodium (Na)-Dissolved	5.0	mg/L	504	469	406	613	518	510	476
Calculated Parameters									
Langelier Saturation Index*				0.361	0.559		0.379	0.356	0.414
Sodium Absorption Ratio									7.98

Parameter	Detection Limit	Units	Pre-Treat-1 (Raw)	Treated1	Treated2	Pre-Treat-2 (Raw)	Treated3	Treated4	Mean Treated Results
Field Paramaters	-								
pH		mg/L	7.88			7.88			
Temperature		mg/L	25.00			25.00			
Total Chlorine		mg/L	3.60			3.96			
Free Chlorine		mg/L	0.11			0.12			
Combined Chlorine		mg/L	3.49			3.84			
Conductivity		µS/cm	4625.00			4934.00			

**Mean result including value of detection limit; **Temperature assumed at 25 °C*

Appendix C

Complete Summary of the Aspen Plus Simulation

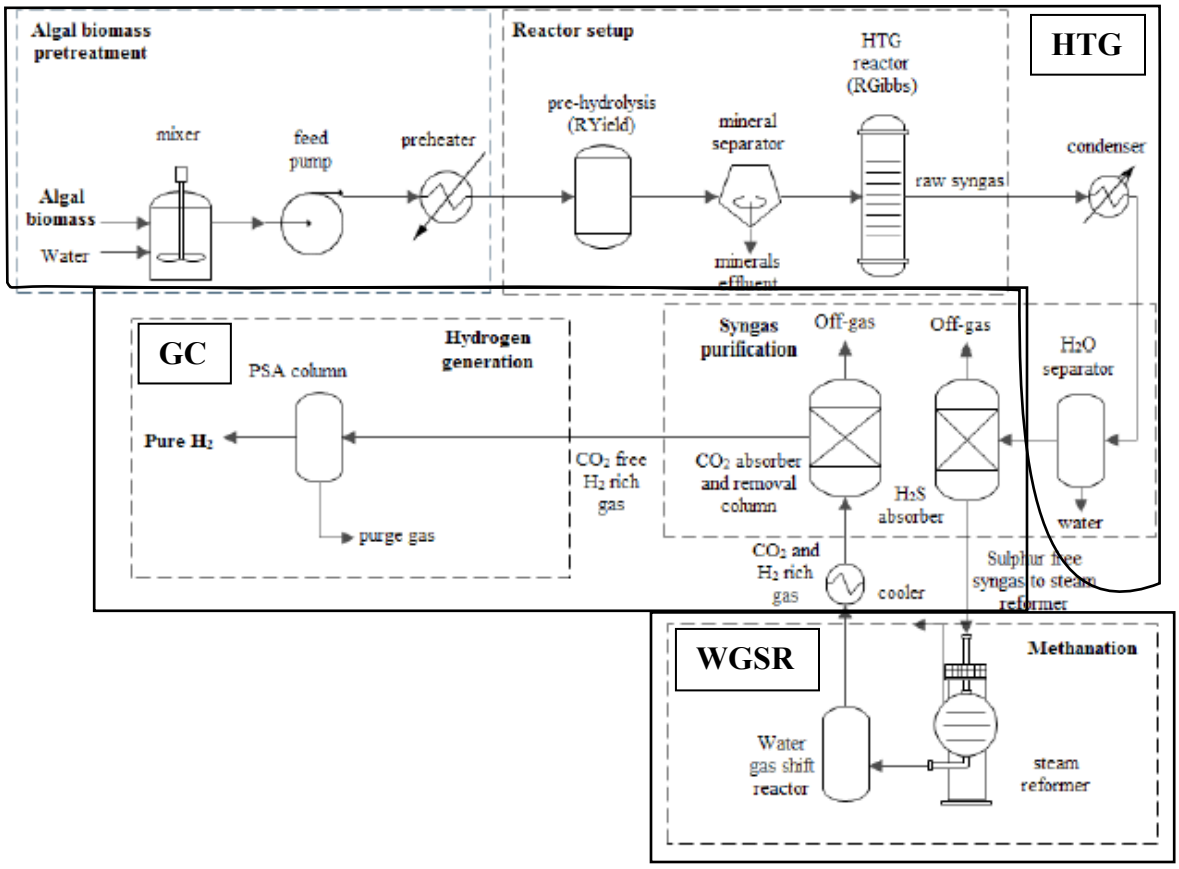
Model Description

The model applied to this study was created by Kumar (2018) and this description is based on the original author's work and relevant literature. This section describes the hydrothermal gasification (HTG) simulation of an algae biomass slurry for hydrogen production. The model assumes chemical equilibrium and generates values based on equation of state property methods and Gibbs free energy minimization. Most simulations and experiments with HTG have focused on glucose, cellulose, and methanol as model wet biomass compounds, while Kumar (2018) simulated the 'real biomass component' with specified parameters as non-conventional coal feed. This model may provide an over-prediction of product yields due to the uncertainty of HTG reactions, but will provide a reliable basis for assessing energy consumption and estimating the products of reaction for feasibility purposes. This model was separated into three main sections: the hydrothermal gasification (HTG) block; the water gas shift reactor (WGSR) block; and the gas cleaning (GC) block.

For the HTG process, Kumar (2018) utilized the Peng-Robinson (PR) and Redlich-Kwong (RK) property methods. These methods allow interactions between molecules and have predicted H_2 mole fractions within a range of 3.5% compared to experimental studies, making them appropriate for use in the sub-critical/supercritical regime. The use of these property methods has been applied to similar supercritical processes (Austegard et al. 2006, Dahl et al. 1992, Lu et al. 2007). Kumar (2018) used the Soave-Redlich-Kwong (SRK) EoS for subcritical processes and the Peng-Robinson (PR) thermodynamic package for supercritical conditions. For this replication, the PR and SRK property methods were used for supercritical and sub-critical processes, respectively.

Figure C1

Process Flow Diagram of the Hydrothermal Gasification Model.



Note: Adapted from Kumar (2018).

The objective of the replication was to verify the accuracy of the model; then, scale it down to meet the algae biomass supply that could be generated from the algae cultivation system (ACS). The results from the scaled-down model at 192 tonnes per day capacity were be used to estimate the mass and energy flows of the system.

HTG Block

The HTG block simulated in this model represents the process from the mixer to the water separation (Figure C1).

- Algae biomass is defined as non-conventional in Aspen; its elemental composition was matched to the assumptions in Kumar (2018) that used composition data from the "ECN Phyliss2 database (Table 2).
- Calculations for the thermodynamic properties are based on correlations for enthalpy and density of coal, referred to as HCOALGEN and DCOALLIGT in Aspen.
- The model assumed homogenous mixing for pre-treatment of feed, 5% dry biomass by weight, and that algae and water enter the mixing block at ambient conditions.
- The pre-hydrolysis stage is required to break down the algae feed into a suitable gasification feed; this is represented by the pre-heating and RYIELD at 350 °C that decomposes the feedstock into its constituents for the RGIBBS reactor.
- The removal of minerals through the pre-hydrolysis stage is designed to minimize clogging of the equipment and maintain a continuous process. The separated MNRL stream contains the ash, nitrogen, and a 10% loss of organics (Kumar, 2018).
- The stream that passes through mineral separation goes to the SCWG reactor, which is simulated by RGIBBS in Aspen. The reactor is set at 600 °C and 25.3 MPa as this was determined to be an optimum temperature for hydrogen production (Kumar 2018).
- Kumar (2018) reactor inputs were modelled to represent the principal designs by NREL, VERENA, and the MODAR reactor (Boukis et al. 2007; Hong et al. 1989).

Table C1

Assumptions for Algae Biomass Feed.

Parameters	Algal Biomass
Moisture Content (%)	5.22
Proximate Analysis, wt% (dry)	
Fixed carbon	15.68
Volatile matter	81.8
Ash	2.52
Ultimate Analysis, wt% (dry)	
C	52.73
H	7.22
N	8.01
S	0.49
O	28.85

Note: Adapted from Kumar (2018).

Water-Gas Shift Reactor Block

For the WGSR block, the H2S-free syngas is passed through a steam reformer, followed by a high-temperature and a low-temperature WGSR phase that yields primarily H_2 and CO_2 dependent on the main reactions shown in Table C2. The product gas of the WGSR is sent to the CO_2 absorption column in the GC block where it is purified into hydrogen and purge gas.

The main assumptions of this process are summarized in Table A3. The WGSR block converts the desulphurized syngas to primarily H_2 and CO_2. The model is based on the steam reforming reactor and high-to-low temperature WGSR processes outlined by Molburg and Doctor (2003) and Chiesa and Consonni (1999), respectively. Steam is used to reform the hydrocarbons in the syngas to CO and H2; the product gas is passed through subsequent water-gas shift reactors with descending temperature and pressure allow conversion of the stream to mainly CO_2 and H_2. The reactors were modelled with REQUIL unit operations and the SRK property method using the reactions outlined in Table C2.

Table C2

Main Equations involved in the Water-Gas Shift Processes.

Reaction(s)	Formula	ΔH *298K* (kJ/kmol)
Steam Methane Reforming	$CH_4 + H_2O \rightleftharpoons CO + 3H_2$	*+206*
Water-Gas-Shift	$CO + H_2O \rightleftharpoons CO_2 + H_2$	*-42*
Methanation	$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O$	*-165*
	$CO + 3H_2 \rightleftharpoons CH_4 + H_2O$	*-206*
Hydrogenation	$CO_2 + 2H_2 \rightleftharpoons C + 2H_2O$	-90
	$CO + 2H2 \rightleftharpoons CH4 + 0.5O2$	-131

Table C3

Summary of Assumptions for WGSR Block.

Items	Values	Sources
Steam Reforming		
Temperature (°C)	800	Molburg & Doctor (2003)
Pressure (MPa)	3	Molburg & Doctor (2003)
Steam/Carbon Ratio	3	Molburg & Doctor (2003)
High Temperature WGSR		
Inlet Temperature (°C)	350	Chiesa & Consonni (1999)
Outlet Temperature (°C)	450	Chiesa & Consonni (1999)
Low Temperature WGSR		
Inlet Temperature (°C)	250	Chiesa & Consonni (1999)
Outlet Temperature (°C)	275	Chiesa & Consonni (1999)

Note: Adapted from Kumar (2018).

Gas Cleaning Block

For the GC block, the syngas feed is the product of the HTG simulation block. Using the PC-SAFT property method, the syngas is first passed through a Selexol absorption system (RADFRAC) to remove H_2S and then through the WGSR. The product gas of WGSR (GAS-

CO2) is passed through an additional absorption system to remove the CO2, and that product gas (TO-PSA) is passed through a pressure swing adsorption (PSA) system to purify the hydrogen. The purge gas from the PSA is discharged to a CHP unit to power the process, which is assumed to superheat the steam for reforming. The CHP unit is out of this study's scope; electrical and thermal efficiency values are assumed at 40% and 45%, respectively (Doluweera et al., 2020).

The GC blocks use the PC-SAFT property method to model the absorption of sour gases using Selexol, represented by Dimethyl Ether of Polyethylene Glycol (DEPG). One main advantage of using Selexol with a high-pressure product gas is that the rich solvent can be stripped by reducing the pressure of the stream, eliminating the need for heat regeneration (Burr & Lyddon, 2008). The first absorber is designed to remove the H_2S from the syngas and assumes 99% removal. At the first absorption stage, a significant amount of CO_2 is also absorbed due to its high concentration in the material stream (Table C6).

A two-stage flash unit is used to separate H_2S-free syngas from the solvent stream. The first unit releases the FGAS stream, which is mixed with the GAS-CO2 product stream of WGSR. The H_2S is stripped from the Selexol through the second flash unit and is assumed to be processed through an out-of-scope desulfurization system. The second absorption column removes the CO_2 from a sweet syngas/recycled gas mixture to maximize CO_2 recovery and H_2 yield. The rich solvent from the CO_2 absorption is then passed through a two-stage flash unit as outlined in Chiesa et al. (2005), where the separated gases are included in the recycled gas to recover valuable gas streams. The product gas (TO-PSA) is purified through the PSA system, modelled by a separator with 85% H_2 selectivity. The PSA produces energy-rich purge gas that is assumed be combusted in the CHP. Figure 3 outlines the main assumptions for the GC block.

Table C4

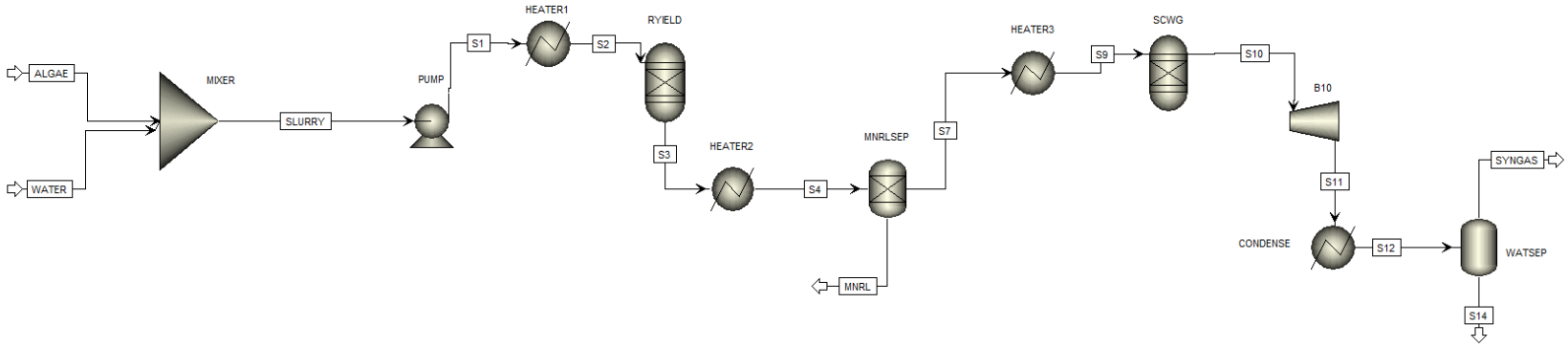
Main Assumptions for the GC Block.

Items	Values	Sources
H_2S Absorption		
H_2S Removal (%)	99	Chiesa & Consonni (1999); Chiesa et al. (2005)
CO_2 Absorption		
Solvent Pump Efficiency (%)	75	Chiesa et al. (2005)
Recycle Compressor		
Mechanical Efficiency (%)	98	Majoumerd et al. (2012)
Isentropic Efficiency (%)	85	Majoumerd et al. (2012)
CO_2 flash separator units		
Pressure in 1st Flash	1.7	Chiesa et al. (2005)
Pressure in 2nd Flash	0.11	Chiesa et al. (2005)

Note: Adapted from Kumar (2018).

Figure C2

Process Flow Diagram for the HTG Block.



Note: Adapted from Kumar (2018).

Table C5

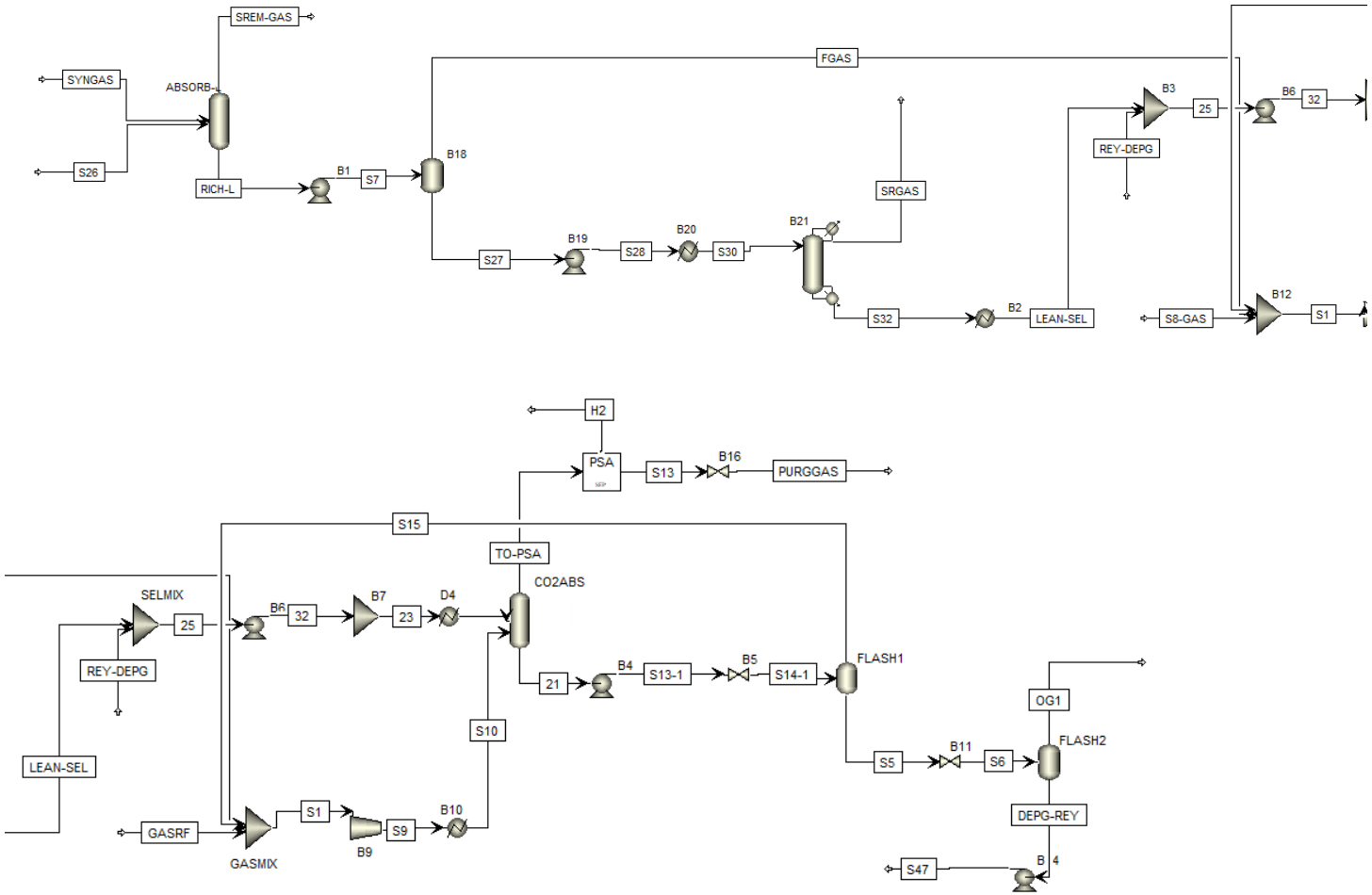
Stream Results for the HTG Block at 192 Tonne per day Capacity.

MoleFlow kmol/hr	Slurry	S1	S2	S3	S4	S7	S9	S10	S11	S12	S14	SYNGAS	ALGAE	MNRL	WATER
CO	0	0	0	0	0	0	0	0.84	0.84	0.84	0	0.84	0	0	0
CO2	0	0	0	0	0	0	0	28.97	28.97	28.97	3.2E-2	28.94	0	0	0
H2O	422.22	422.22	422.22	355.54	355.54	319.98	319.98	287.24	287.24	287.24	287.14	9.6E-	0	35.55	422.22
H2	0	0	0	57.59	57.59	51.83	51.83	17.27	17.27	17.27	0	17.27	0	5.76	0
N2	0	0	0	4.60	4.60	0	0	0	0	0	0	0	0	4.60	0
CH4	0	0	0	0	0	0	0	33.54	33.54	33.54	2.9E-3	33.53	0	0	0
NH3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H2S	0	0	0	0	0	0	0	0.22	0.22	0.22	8.1E-3	0.22	0	0	0
S	0	0	0	0.22	0.22	0.22	0.22	0	0	0	0	0	0	0	0
O2	0	0	0	14.46	14.46	13.02	13.02	0	0	0	0	0	0	1.45	0
C	0	0	0	70.39	70.39	63.35	63.35	0	0	0	0	0	0	7.04	0
C2H4	0	0	0	0	0	0	0	0	0	0	0	6.18	0	0	0
C2H6	0	0	0	0	0	0	0	3.1E-3	3.1E-3	3.1E-3	0	3.1E-3	0	0	0
C3H8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature C	20	21.35	200	350	380	380	475	600	306.67	25	25	25	20	380	20
Pressure bar	1	280	253	253	253	253	253	253	30	30	30	30	1	253	1
Mass Flow kg/hr															
ALGAE	400	400	400	0	0	0	0	0	0	0	0	0	400	0	0
MINERALS	0	0	0	40.83	40.83	0	0	0	0	0	0	0	0	40.83	0
Enthalpy, Gcal/hr	-29.06	-29.40	-27.87	-18.31	-18.04	0	-15.52	-18.27	-19.12	-23.09	-19.73	-3.36	-0.40	-1.89	-29.06

Note: All values below 1 x 10^{-3} were excluded from stream results.

Figure C3

Process Flow Diagrams for the Gas Cleaning Block.



Note: Adapted from Kumar (2018).

Table C6

Stream Results for the Gas Cleaning Block at 192 Tonne per day Capacity.

MoleFlow kmol/hr	S26	SREM-GAS	RICH-L	S7	S27	S28	S30	FGAS	S32	SRGAS	LEAN-SEL	REY-DEPG	25	32	23	15	21
CO	0	0.82	1.7E-2	1.7E-2	1.1E-3	1.1E-3	1.1 E-3	1.6E-2	0	1.1E-3	0	0	0	0	0	0	2.0E-3
CO2	0	22.28	6.66	6.66	3.33	3.33	3.33	3.33	0	3.33	0	0	0	0	0	0	42.55
H2	0	17.18	8.9E-2	8.9E-2	1.4E-3	1.4E-3	1.4 E-3	8.7E-2	0	1.4E-3	0	0	0	0	0	0	2.76
H2O	0	0	9.6E-2	9.6E-2	9.6E-2	9.6E-2	9.6 E-2	0	0	9.6E-2	0	0	0	0	0	0	0
CH4	0	31.86	1.67	1.67	0.26	0.26	0.26	1.40	0	0.26	0	0	0	0	0	0	3.42
H2S	0	3.5E-2	0.18	0.18	0.16	0.16	0.16	0.02	0	0.16	0	0	0	0	0	0	2.0E-3
S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2H4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2H6	0	2.2E-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3H8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DEPG	17.18	0	17.18	17.18	17.18	17.18	17.18	0	16.60	0.58	16.60	180.96	197.56	197.56	197.56	197.56	197.56
Temperature C	1	13	16.19	16.07	12	11.98	6	12	6	6	25	25	25	26.47	26.47	0	7.83
Pressure bar	30	30	30	7	7	1	1	7	1	1	1	1	1	50	50	50	30
Enthalpy, Gcal/hr	-0.45	-2.70	-1.11	-1.11	-0.77	-0.77	-0.77	-0.34	-0.43	-0.34	-0.39	-4.21	-4.60	-4.51	-4.51	-5.23	-9.28

Note: All values below 1 x 10^{-3} were excluded from stream results.

Table C7

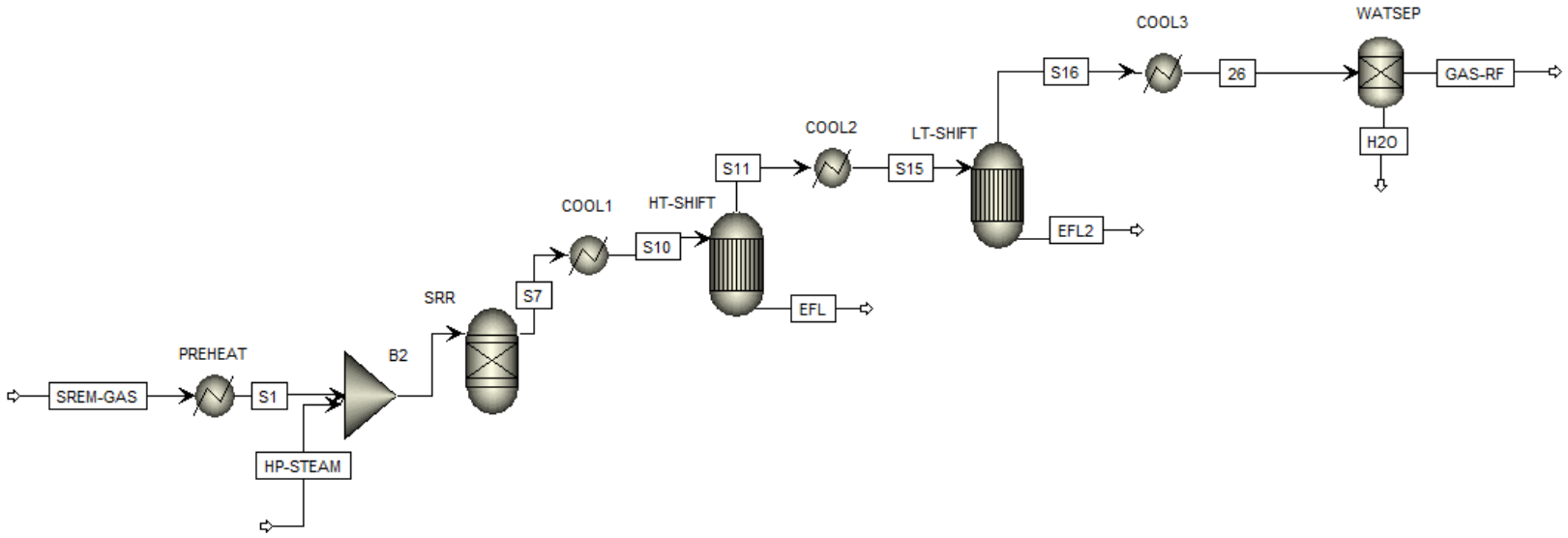
Stream Results for the Gas Cleaning Block at 192 Tonne per day Capacity.

MoleFlow kmol/hr	S1	GASRF	S9	S10	TO-PSA	H2	PURGGAS	S13	S13-1	S14-1	S15	S5	S6	OG1	S47
CO	1.8E-2	1.9E-3	1.8E-3	1.8E-3	1.6E-2	0	1.6E-2	1.6E-2	2.0E-3	2.0E-3	0	1.4E-3	1.4E-3	1.4E-3	0
CO2	49.94	45.08	49.94	49.94	7.39	0	7.39	7.39	42.55	42.55	1.53	41.02	41.02	35.98	5.04
H2	107.68	105.94	107.68	107.69	104.93	89.19	15.74	15.74	2.76	2.76	1.65	1.10	1.10	1.10	3.5E-3
H2O	0	0	0	0	3.30	0	0	0	0	0	0	0	0	0	0
CH4	11.74	9.87	11.74	11.74	8.31	0	8.31	8.311	3.42	3.42	0.46	2.96	2.96	2.87	0.09
H2S	0.02	0	0.02	0.02	0	0	0	0	0.02	0.02	0	0.02	0.02	9.4E-3	1.1E-2
S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2H4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2H6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3H8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DEPG	0	0	0	0	0	0	0	0	197.56	197.56	0	197.56	197.56	0	197.56
Temperature C	22.65	25	243	25	3.37	3.37	-2.45	3.37	7.77	7.92	25	25	20.83	25	26.48
Pressure bar	7	25	50	30	30	30	2	30	23	17	17	17	1	1	50
Enthalpy, Gcal/hr	-4.90	-4.42	-4.61	-4.61	-0.86	-0.01	-0.85	-0.85	-9.28	-9.28	-0.15	-8.64	-8.64	-3.43	-5.01

Note: All values below 1 x 10^{-3} were excluded from stream results.

Figure C4

Process Flow Diagrams for the Water-Gas Shift Reactor Block.



Note: Adapted from Kumar (2018).

Table C8

Stream Results for the Water-Gas Shift Reactor Block at 192 Tonne per day Capacity.

MoleFlow kmol/hr	26	GAS-RF	H2O	HP-STEAM	S1	S6	S7	S10	S11	S15	S16	SREM-GAS
CO	1.9E-3	1.9E-3	0	0	0.82	0.82	19.70	19.70	0.20	0.20	2.0E-3	0.82
CO2	45.08	45.08	0	0	22.28	22.28	25.39	25.39	44.89	44.89	45.08	22.28
H2	105.94	105.94	0	0	17.18	17.18	86.24	86.24	105.74	105.74	105.946	17.18
H2O	82.21	0	82.21	127	0	127	101.91	101.91	82.41	82.41	82.21	0
CH4	9.88	9.88	0	0	31.86	31.86	9.87	9.87	9.87	9.87	9.87	31.86
H2S	0	0	0	0	0	0	0	0	0	0	0	0
S	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
O2	0	0	0	0	0	0	0	0	0	0	0	0
C2H4	0	0	0	0	0	0	0	0	0	0	0	0
C2H6	0	0	0	0	0	0	0	0	0	0	0	0
C3H8	0	0	0	0	0	0	0	0	0	0	0	0
DEPG	0	0	0	0	0	0	0	0	0	0	0	0
Temperature C	25	25	25	510	791	632	800	350	350	250	250	13
Pressure bar	25	25	25	30	30	30	28	28	28	27	27	30
Enthalpy, Gcal/hr	-10.09	-4.42	-5.67	-6.83	-2.06	-8.89	-7.35	-8.34	-8.52	-8.73	-8.73	-2.70

Note: All values below 1 x 10^{-3} were excluded from stream results.

Appendix D

Mass and Energy Calculations

Annual Carbon Emissions

Off-gas: 1583.12 kg/hr CO_2 and 45.92 kg/hr CH_4

SRGAS: 146.52 kg/hr CO_2 and 4.16 kg/hr CH_4 (Appendix C)

Recycled CO_2 Daily for ACS (1.8 t CO_2/t algae x 9.6 tonnes algae biomass) = 17.28 tonnes CO_2

Annual Recycled Emissions = ~17 tonnes per day x 365 days = 6205 tonnes CO_2 per year

*Total HTG Emissions per day (95% capacity) = 39.44 tonnes CO_2 + 28.55 tonnes CO_2 e (CH_4)

Net Emissions per day from HTG = *68 tonnes CO_2 e – 17 tonnes per day = 51 tonnes CO_2 e

Annual Scope 1 Emissions = 18,608 tonnes CO_2 e from biogenic fugitive emissions

Global warming potential for CH_4 = 25 (Government of Canada, 2021c).

Emissions from Combined Heat and Power (CHP) Engine (Scope 2)

Annual Energy Consumption = 95,627 MWh (Table D3)

Annual Purge Gas Electricity Generation via CHP Engine = 9,691.49 MWh (Table D3)

Carbon Neutral Generation = [9,961.49 MWh /95,627 MWh] = 10.13 % of Consumption

Natural Gas-Fueled CHP Generation (89.87% of CHP consumption at 85% efficiency):

= (85,939.98 MWh/0.85) x 3.6 GJ/MWh = 363,981.09 GJ*

Emissions from CHP = 363,981.09 GJ* Natural Gas x 50.3 kg CO_2 / GJ = 18,308 tonnes CO_2

19,359.60 MWh Steam – 11,475.60 MWh (Purge Gas Heat, CHP) = 7,884 MWh (Table D3)

Emissions from 7,884 MWh of Steam from Natural Gas Boiler at 85% Efficiency:

7,884 MWh/0.85 x 3.6 GJ/MWh x 50.3 kg CO_2 / GJ x 1 tonne/1000 kg = 1,680 tonnes CO_2

Estimated Annual Scope 2 Emissions = 18,310 tonnes CO_2 from CHP and Steam Generation

Water Footprint for Hydrothermal Gasification

Nutrient-brine (MNRL): 15.36 m^3/day

HTG Water Separator (S14): 124.04 m^3/day

Water Gas Shift Condensate (H2O): 35.51 m^3/day

Note: 1000 kg/m^3 used for H_2O mass-to-volume conversions (Appendix C, Tables C5-C8)

Total Water Discharge from Hydrothermal Gasification at 192 tonne per day and 95% capacity = 166.17 m^3/day – 8.8% nutrient brine = 60,652.05 m^3 per year HTG discharge treated by ACS

Annual Algae Cultivation System (ACS) Production

16,000 m^3 capacity (128 x 125 m^3 ACS modules) x 25% processed per day – 20% seeding media = 3,200 m^3/day = 3.2 x 10^6 L per day – 192,000 L to HTG = 3.008 x 10^6 L per day treated water

Annual Biomass Production and Hydrothermal Gasification (HTG):

3,200 m^3/day x 3 kg/m^3 dry biomass (Adelodun, 2019) = 9,600 kg per day dry algae biomass

9,600 kg per day x 1 tonne/1000 kg = 9.6 tonne per day

5% biomass (dry wt.) for HTG = 9.6 tonne/0.05 = 192 tonne per day HTG capacity

Integrated Algae Cultivation-Gasification System - Energy Analysis

Efficiency

$\eta = W_t / Q_t$ - Where: η = *System Efficiency;* W_t = *Total Energy Output;* Q_h = *Total Heat Input*

η = 158,370.06 kWh/ 434,152.80 kWh (Table D3) = 36.48%

Biomass Energy Content

Higher heating value (HHV) of algae biomass (kJ/kg) = 337C + 1419(H-0.125O) + 93S + 23N

Biomass (% dry wt.) = C: 52.73%; H: 7.22%; N:8.01%; S: 0.49%; O: 28.85% (Kumar, 2018).

HHV (kJ/kg) = 337 (52.73) + 1419[7.22 – 0.125(28.85)] + 93(0.49) + 23(8.01) = 23,128 kJ/kg

23,128 kJ/kg x 9,600 kg/day x (1 MWh/3.6 x 10^6 kJ) x 95% capacity

= 58.59 MWh per day biomass (HHV) based on average 40.11 MWh per day input (Table D3)

Table D2

Main Assumptions for the Energy Analysis of the Algae Cultivation-Gasification System.

Parameter	Value	Unit	Reference
Capacity Factor	95	%	Doluweera et al. (2020)
CHP Engine Electrical Efficiency	40	%	Doluweera et al. (2020)
CHP Engine Thermal Efficiency	45	%	Doluweera et al. (2020)
Enthalpy of Reformer Steam at 30 bar and 510°C	0.9667	kWh/kg	Okolie et al. (2021c)
HHV of Methane (20 MPa)	50	MJ/kg	Supple (2007)
Electrical Heating Efficiency	99	%	

Table D3

Daily Energy Values of Algae Cultivation-Gasification System.

Process/Product	Net Work (kW)	Consumption (kWh/day)	Generation (kWh/day)
Hydrothermal Gasification	13286.74	31,8881.76	
Gas Cleaning	597.70	14,344.80	
Reforming	4744.01	60,816.24	
Steam	*2210*	*53,040*	
Algae Cultivation	1671.25	40,110	*58,591 (Biomass HHV)*
Turbo-Expander	-971.66		23,319.84
Hydrogen	-2846.94		68,326.68
Heat Recovered	-305.45		73,30.83
Purge Gas Heat	-1310.13		31,443.20
Purge Gas Electric	-1164.56		27,949.51
Total Work		434,152.80	158,370.06

Note: Generated from the Aspen Plus Simulation and the Estimated Energy Consumption of the Algae Biofield™ Provided by Symbiotic Envirotek. Italicized values are subtotals or estimates separate from ACGS efficiency calculations.

Appendix E

Techno-Economic Calculations for the Feasibility Analysis

Cash Flow Analysis

Algae Cultivation System: 128 x 125 m^3 modules - total installed cost = 71.68 million CAD

Estimated at approximately 560,000 CAD per 125 m^3 module by Symbiotic Envirotek.

Hydrothermal Gasification System: 2000 tonne per day (tpd) capital costs = 169.6 million CAD

Estimated by Kumar et al. (2019) using Aspen Icarus Process Evaluator – scaled to 192 tpd.

Rule of seventh for cost estimation (Adelodun, 2019): $Bp = Ap * (Bc/Ac)^{0.7}$

Where: *Ap* = Price of A; *Ac* = Capacity of A; *Bp* = Price of B; *Bc* = Capacity of B

$Bp = 169,600,000*(192/2000)^{0.7} = 32,886,353$ *CAD at 192 tpd capacity.*

Capital Costs = Installation Factor (3.02) x Fixed Capital Investment (Kumar et al. 2019)

*$32,886,353 / 3.02 (*Installation Factor*) = 10,889,521 CAD* = Fixed Capital Investment at 192 tpd

Table E1

Total Direct and Indirect Costs and Fixed Capital Investment (FCI) for the Integrated Hydrothermal Gasification System.

Factor	Value	Unit	Cost (M$)	Reference
Integrated Installation Costs	2	xFCI	21.79	Kumar et al. (2019)
Engineering/Supervision	32	% FCI	3.48	Kumar et al. (2019)
Legal/Contractors	23	% FCI	2.50	Kumar et al. (2019)
Construction	34	% FCI	3.70	Kumar et al. (2019)
Contingency	15	% FCI	1.63	
Total Direct and Indirect Costs		2016 CAD	33,104,143	
Estimated TDIC for 192 tonne per day		2020 CAD*	37,667,666	Ratio Estimate (+ 30%)

Note: CEPCI values 533.9 (2016) and 607.5 (2020) used with Ratio Estimate (Green et al. 2019). Based on the Aspen Icarus Process Evaluation Assessed by Kumar et al. (2019).

Total Capital Costs for Algae Cultivation-Gasification System:

$71,680,000 + $37,667,666 (Table E1) = **109,347,666 CAD (2020)** – Assumed for Year 1

Operating Costs

Present Value (PV)= Annual Value (AV) x [1 - (1 + r)$^{-n}$/r] = AV x 8.514 (Table E2 and E3)

Where: r = interest rate (10%) and n = number of project years (20)

Table E2

Operating Costs for the Algae Cultivation System (ACS) and Hydrothermal Gasification System (HTG).

Process	**Energy Consumption (kWh/day)**	**Cost ($/kWh)**	**Cost ($/day)**	**Cost ($/year)**
HTG	280314.95	0.06	$16,818.90	$5,831,952.44
ACS	40110	0.06	$2,406.60	$878,409.00
Steam	320424.95	0.022	$416.68	$152,090.10
	# of personnel	**Salary ($)**		
HTG Labour	4	50,000		$200,000
ACS Labour	9	50,000		$450,000
			Total ($/year)	7,512,451
		Lifetime Operation Costs (2020 CAD)		**63,957,735**

Table E3

Lifetime Benefits Generated from the Algae Cultivation-Gasification System in Present Value.

Parameter	**Value**	**Unit**
Wastewater Tipping Fee	18,754,087	2020 CAD
Treated Water Rate	18,856,011	2020 CAD
Hydrogen Production at $2/kg	12,739,307	2020 CAD
Carbon Credits at $50-$330/tonne	18,574,742	2020 CAD
Total	**68,924,147**	2020 CAD

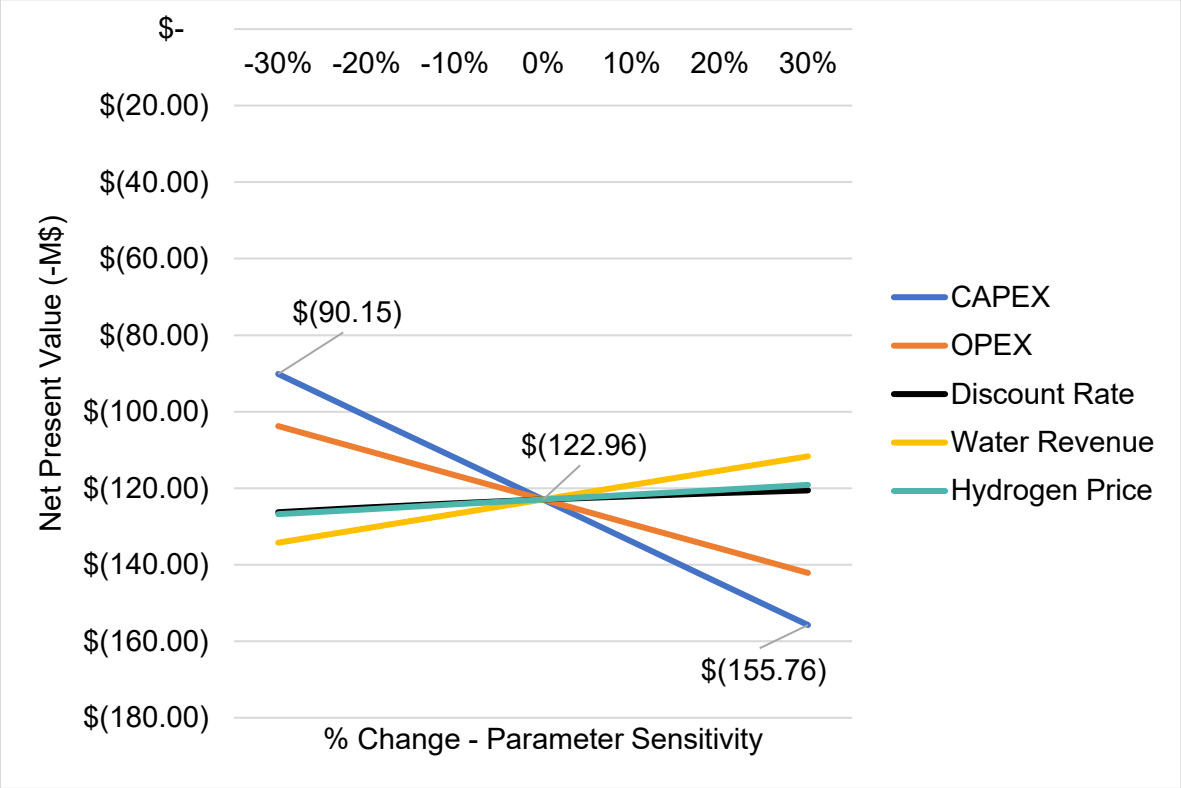
Net Present Value = ∑ Present Value of Lifetime Benefits - ∑ Present Value of Lifetime Costs

Net Present Value of Algae Cultivation-Gasification System

= *$*68,924,147 (Table E3) – [$63,957,735 (Table E2) + $109,347,666] = **-$104,381,254**

Figure E1

Net Present Value Sensitivity Analysis of the Capital Costs, Operating Costs, Discount Rate, and Water Revenue of the Algae Cultivation Gasification System Without Carbon Pricing.



Minimum Biomass Selling Price (MBSP) for Stand-Alone Algae Cultivation System (ACS)

Capital Cost Factor (CCF) = r/ [1 – (1 + r)$^{-n}$]

Where: r = 10% discount rate and n = 20 year project life

Annual Payment for r = CCF x Capital Costs = 0.117 x $71,680,000 = $8,386,560

MBSP = CCF + Annual ACS Operating Costs/ Annual Biomass Production

MBSP = [($8,386,560+ $1,328,409)/ (9.6 tonnes per day (dry wt.) x 365 days per year]

MBSP = $2,772.54 per tonne → $2.77 per kg at 10% interest and 20 year lifetime

Minimum Hydrogen Selling Price (MHSP) for Stand-Alone Hydrothermal Gasification (HTG)

Capital Cost Factor (CCF) = r/ [1 – (1 + r)$^{-n}$]

Where: r = 10% discount rate and n = 20 year project life

Annual Payment for r = CCF x Capital Costs

= 0.117 x (37,667,666 + 30% contingency) = $5,729,252

MHSP = CCF + Annual HTG Operating Costs/ Annual Hydrogen Production

MHSP = [($5,729,252 + ($5,984,043 + 50% for biomass/land expenses))/ (748,250 kg H_2 per year]

MHSP = $19.65 per kg hydrogen at 10% interest and 20 year lifetime

Minimum Hydrogen Selling Price (MHSP) for the Algae Cultivation-Gasification System (ACGS)

Capital Cost Factor (CCF) = r/ [1 – (1 + r)$^{-n}$]; Where: r = 10% discount rate and n = 20 years

*Annual Payment for r = CCF x Capital Costs = 0.117 x $*109,347,666 = $12,793,677

MHSP = CCF + Annual ACGS Operating Costs – Water Revenue/ Annual Hydrogen Production

MHSP = [($12,793,677 + $7,512,451- $4,417,668)/ (748,250 kg H_2 per year]

MHSP = $21.23 per kg hydrogen at 10% interest and 20 year lifetime

Fuel Cell Electric Vehicles (FCEV) Offsets – Replacing ICE Vehicles with FCEVs

Daily hydrogen production = 2050 kg per day/ 5 kg per FCEV = 410 tanks filled per day.

0.1404 tonne CO_2 per Internal Combustion Engine (ICE) vehicle fill avoided

Tonnes of CO_2 Offset per year

= 0.1404 tonnes CO_2 x 410 tanks per day x 365 days = ~21,010 tonnes CO_2 per year

Carbon price at $50 = 21,010 tonnes x $50 per tonne = $1,050,500 potential carbon offset sales

Natural Gas Offsets – Replacing Natural Gas with Hydrogen

0.120 GJ per kg hydrogen / 0.0532 GJ per kg natural gas = 2.26 hydrogen/natural gas

2.676 kg CO_2 per kg natural gas x 2.256 hydrogen/natural gas x 2050 kg hydrogen per day

= 12,376 kg CO_2 avoided per day x 365 days = ~4,517 tonnes CO_2 avoided per year

Carbon price at $50 = 5,517.24 tonnes x $50 per tonne = $275,862 potential carbon offset sales

Carbon Credits from Algae CO_2 Recycling

6205 tonnes CO_2 captured and recycled for cultivation

Carbon price at $50 = 6205 tonnes x $50 per tonne = $310,250 per year in carbon credits

Annualized and converted to 2020 CAD for $15 per tonne annual increase over 20 years.

Payback Period for FCEV Market Value Case and Federal Carbon Price Backstop

Carbon price: Starting at $50 with $15 annual increase (Government of Canada, 2021a).

Capital Investment = $109,347,666; Average Net Annual Income with FCEV Offsets = $9,937,713

Payback Period = Initial Investment/ Net Cash Flow per Period = $109,347,666/ $9,937,713

Payback Period = 11 years*

**When hydrogen price is at $15/kg and offsets are sold at carbon price for FCEV fuelling.*

Table E4

Assumptions for the Carbon Offset and Fuel Equivalency Calculations

Parameter	**Value**	**Unit**	**Reference**
Natural Gas (NG) Energy	0.0532	GJ/kg	Supple (2007)
NG Carbon Intensity	50.3	kg CO_2/GJ	Supple (2007)
Hydrogen Energy	0.120	GJ/kg	Supple (2007)
Hydrogen-Natural Gas Fuel Equivalency	2.26	kg hydrogen/kg NG	
Hydrogen FCEV Tank Fill	5	kg/tank	Toyota (2020)
Gasoline Energy	0.0431	GJ/kg	Supple (2007)
Gasoline ICE Tank Fill	60	L/tank	
Carbon Intensity of ICE Tank	0.1404	tonne CO_2/tank	
Hydrogen-Gasoline Fuel Equivalency	0.083	kg Hydrogen/L Gas	