THESIS

TECHNO-ECONOMIC AND LIFE CYCLE ASSESSMENT OF A NOVEL OFFSHORE MACROALGAE BIOREFINERY

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2019

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ABSTRACT

TECHNO-ECONOMIC AND LIFE CYCLE ASSESSMENT OF A NOVEL OFFSHORE MACROALGAE BIOREFINERY

Innovative and effective solutions to providing renewable fuels represent a critical need. The cultivation and conversion of salt water macroalgae into liquid transportation fuels may offer a viable alternative to petroleum-based diesel, but the potential of this technology in terms of economic feasibility and environmental impact has not been thoroughly investigated. This work evaluates the sustainability of a free-floating macroalgae cultivation to fuel concept. While free-floating biomass cultivation structures may offer solutions for reducing infrastructure requirements and expenses, extreme ocean conditions pose great risks and unknowns. This study focuses on emerging technologies for large scale cultivation and harvesting of macroalgae biomass including drone assisted seeding and harvesting operations, recycled carbon fiber long-lines with sensor equipped buoys, and adhesive spore seeding methods. The harvested biomass is then converted to fuels through hydrothermal liquefaction. Three different system pathways have been explored to determine the impacts of the various emerging technologies on the sustainability of the system and provide direction for future research and development. Results from the techno-economic analysis show a baseline minimum fuel selling price of \$6.38 per Gallon of Gasoline Equivalent (GGE) with a range from \$5.10 GGE^{-1} to \$11.00 GGE^{-1} based on optimistic and conservative assumptions regarding biomass yield, length of the growing season, and technology readiness level. The 90% confidence interval from the Monte Carlo Analysis performed by varying the top 10 high-impact parameters, suggests a range of \$6.02 GGE^{-1} to \$11.17 GGE^{-1} for the baseline pathway. The well-to-wheel life cycle assessment (LCA) shows net greenhouse gas emissions of 22 gCO_2-eq MJ^{-1} for the baseline pathway and a range of 18 to 32 gCO_2-eq MJ^{-1} for the optimistic and conservative pathways, respectively. The Monte Carlo LCA results show a range of 19 to 27 g CO2-eq MJ^{-1} based on the 90% confidence interval. Discussion focuses on the feasibility of the various technologies and utilizes results from the analysis to weigh the risks and rewards associated with the proposed concept, in an effort to guide research and development for macroalgal cultivation and conversion systems.

ACKNOWLEDGEMENTS

The author would like to acknowledge Colorado State University and Dr. Jason Quinn for providing the tools and motivation for this work. In addition, the United States Department of Energy, ARPA-e, and the MARINER Project for funding this work (Award # DE-AR0000913). Furthermore, the author would like to thank Michael Huesemann and Jonathan Whiting with Pacific Northwest National Labs, Jascha Gulden from Reliance Laboratories, Geoffrey Wood with the Composite Recycling Technology Center, Thomas Mumford with Marine Agronomics LLC, and Solomon Yim with Oregon State University for their expertise and input. The author would like to thank Jesse Cruce for his assistance and expertise regarding the construction of the HTL model. Finally, the author would like to thank David, Donna, and Josh Greene for their endless support.

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CHAPTER 1. INTRODUCTION

While traditional terrestrial biomass crops like corn, soybeans, and sugarcane represent current viable feedstocks for renewable fuel, the associated cultivation and conversion processes are energy and resource intensive. Additional issues arise when considering the need to save arable land, fresh water, and fertilizer for food production to sustain a rising population. Macroalgae, also known as seaweeds, provide a promising alternative to existing bio-based fuel feedstocks as their cultivation doesn't require fresh water, arable land, or added fertilizer. Additionally, macroalgae are highly photosynthetic (three to four times as photosynthetic as terrestrial biomass crops) and are capable of surviving and thriving in harsh oceanic conditions [1]. Macroalgae-based fuel and food systems utilize the open ocean for cultivation, providing significant potential for scalability as oceans cover 70% of the Earth's surface. Furthermore, existing processes to convert the biomass into useable fuels include fermentation [2], anaerobic digestion (AD) [3], and hydrothermal liquefaction (HTL) [4]. Due to their high water content (10% solids), macroalgae are particularly compatible with the HTL process which typically requires a feedstock with under 20% solids [5]. While the concept of cultivating and converting kelp into fuel seems to address many of the major concerns associated with biofuel production, the development and implementation of these systems is heavily dependent on a successful proof of concept in both research and development and pilot plant operation. While near shore macroalgae cultivation is well established and understood for the production of food and high value products in different parts of the world, it is imperative to illustrate a clear path towards economic and environmental viability for large scale offshore cultivation before macroalgae is seriously considered as a feedstock for fuel production. Achieving parity with fuels will certainly require innovative solutions that decrease cultivation complexities and increase production volumes [6].

Several attempts have been made in the past to cultivate kelp with off-shore structures. Perhaps the most referenced attempt was the Marine Biomass Program, which came about in the 1970's with the intent of creating biogas from *Macrocystis pyrifera* to provide a renewable source of natural gas [6]. The

Marine Biomass Program focused on the development and testing of off-shore free-floating structures aimed at upwelling and distributing nutrients to horizontal polypropylene cultivation lines. The deployed systems were ultimately unsuccessful, largely due to an inability to meet the structural requirements necessary to withstand wave action and ocean currents [6]. Destruction of these systems quickly rendered off-shore cultivation as an unpredictable and expensive concept. However, advancements in carbon fiber reinforced plastics and the reduction in manufacturing costs from composite recycling technology enable new investigation into free-floating offshore structures for macroalgae cultivation. From corrosion resistant properties to high tensile and compressive strengths, recycled carbon fiber (rCF) may succeed where polypropylene rope has failed in the past. While great achievements have been made in material science since the 1970's, it will be difficult to gain momentum in the development and deployment of free-floating structures without illustrating their economic and environmental sustainability. Many studies have been published to explore the feasibility of a seaweed to energy concept, including a techno-economic analysis (TEA) from Konda et al. [1] predicting a minimum ethanol selling price from \$2.90 - \$3.50 gal^{-1}, and Dave et al. [7] predicting a breakeven electricity price of \$134.20 MWh^{-1} from evaluating the potential of biogas production from AD. These studies provide valuable metrics yet fail to carry the analysis through the entire process from spore production in a hatchery to energy conversion in a biorefinery. The studies above focus only on the processing of the biomass and assume a biomass purchasing price, rather than determining biomass production cost to explore the economic implications of different system pathways on the minimum fuel or biogas selling price. Failure to quantify the biomass cost results in unrealistic estimates on the performance from a systems level. In addition, there is limited work investigating the environmental impacts of macroalgal fuel systems, which is critical considering the economic implications of meeting the renewable fuels standard.

This work specifically investigates the sustainability of a free-floating macroalgae cultivation system coupled with HTL for fuel production. Foundational engineering process modeling is used to accurately capture system performance as a function of individual sub-process performance. Modularity in the model supports the evaluation of alternative technologies at the sub-process level and multiple scenarios within any given system pathway. The five sub-processes included in the model are spore production, line deployment and inoculation, growth, harvesting, and conversion into fuel via HTL. This foundation is coupled with TEA and Life Cycle Assessment (LCA) to understand the economic viability and environmental impact of the pathways modeled. Two particular kelp species were explored in this study, *Saccharina latissima* and *Nereocystis luetkeana,* with the system designed to simultaneously grow both species on a pultruded carbon fiber line. Seaweed biomass is converted into biocrude through the application of heat and pressure in an HTL reactor, which after refining yields a renewable diesel product that is chemically identical to petroleum diesel and can be used in existing diesel engines for transportation or power generation [8]. In total, three pathways (conservative, baseline, and optimistic) are evaluated to quantify the impact of different hatchery, seeding, and biomass transport technologies. In addition, the three pathways assume different biomass yields and growing season lengths to capture the true range of system performance. Discussion focuses on technology readiness, research direction driving towards sustainability, and a direct comparison with other biofuel based systems.

CHAPTER 2. MATERIALS AND METHODS

The proposed system design is focused on successfully implementing a free-floating carbon fiber cultivation line attached to sensor equipped buoys for data transmission and communication with surrounding maritime traffic. The modeled system would be deployed off the coast of Seattle, WA in the form of a daily line release from large seeding vessels or alternatively, with autonomous drone tug technology. Following ocean currents and natural nutrient upwell areas, the system is designed to float down the west coast of the United States of America where the lines will be collected and stripped of their biomass off the coast of California after drifting for 90-120 days. Due to uncontrollable biological parameters, such as water temperature, thermohaline circulation, and nutrient availability, the system cannot function year round and is limited to roughly 100 operational days per year in which lines are seeded and harvested (March 15^{th} - June 25^{th}). The system has been separated into 5 sub-processes including process 100: On-Shore Nursery Facility, 200: Open Ocean Seeding Process, 300: Open Ocean Drift, 400: Open Ocean Harvesting, and 500: Fuels and Co-Products Generation, figure 1.

Various technologies have been modeled in order to compare system configurations and draw conclusions regarding economic and environmental impacts. Within process 100, a traditional kelp spore hatchery has been modeled based on the work of Flavin et al. [9] as well as an adhesive slurry production facility based on a binder based seeding method presented by Kerrison et al. [10]. For process 200, both a traditional seeding approach using large vessels has been modeled as well as an approach which would utilize autonomous drone tug vessels. For process 400, both an Aframax tender vessel and autonomous drone tugs have been modeled for biomass transport. For process 500, an HTL process model has been developed to cost and scale the HTL reactor based on the work of Cruce and Quinn [5]. Figure 1 illustrates the various possible pathways within the system. The baseline pathway has been defined as the most realistic system configuration for implementation in the near future and has been modeled to reflect current design potential (baseline pathway follows the blue arrows in figure 1). The conservative pathway assumes a lower biomass yield (20 kg wet/m), shorter operational season (90 days per year), and does not depend on successful implementation of any emerging technology (conservative pathway follows the red arrows in figure 1). In comparison, the ideal pathway assumes an optimal yield (30 kg m^{-1}), an extended cultivation season (120 days per year), and incorporates the use of bio-adhesive seeding, drone deployment, and drone tug transport (ideal pathway follows the green arrows in figure 1).

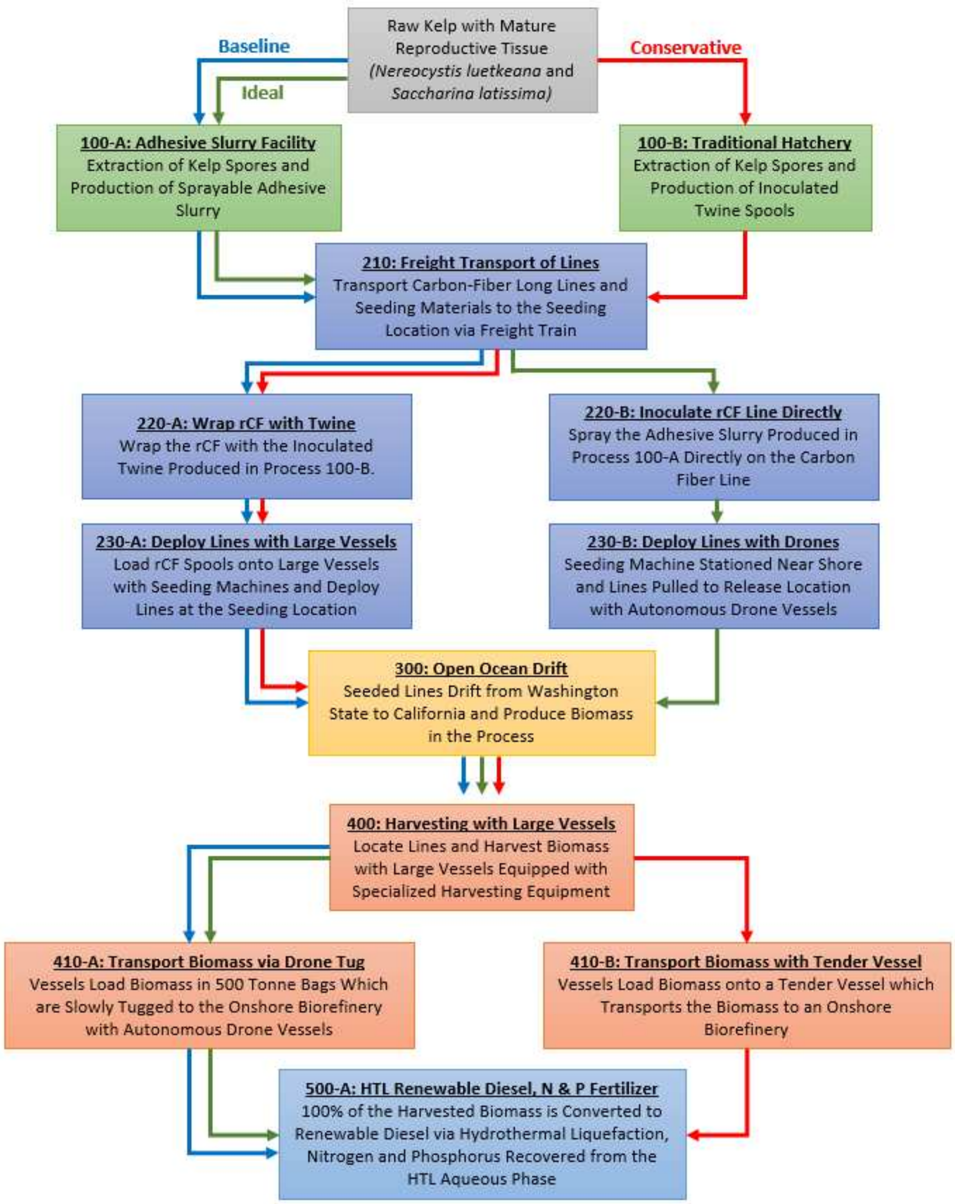

Figure 1. System process flow diagram illustrating the three different system pathways evaluated and the technological configuration of each pathway. The baseline, ideal, and conservative pathways are illustrated with the blue, green, and red arrows respectively.

A modular high fidelity engineering process model was constructed which served as the foundation for evaluating the sustainability of each pathway. Modularity supports the evaluation of various scenarios within a given pathway. Sustainability is evaluated through economic and environmental indicators.

2.1 Engineering process model

2.1.1 Nursery

The onshore spore production facility has been modeled as an indoor hatchery with robust infrastructure, laboratory-grade facilities, and an HVAC system. In all cases, the model assumes that this facility will be built on undeveloped land and located less than 50 km from the seeding vessel loading dock. Land costs were estimated using 12 property listings in Washington State. Distance from the ocean, total acreage, and the cost of the 12 land plots were used to determine an average cost per hectare which was scaled up by a contingency factor of 1.25. Construction costs for the facility were estimated to be $4,181.92 per square meter ($388.50 sf^{-1}) based on values for a greenhouse, biological research facility (RF), chemistry RF, and an animal RF [11].

For sub process 100-A: Adhesive Slurry Facility (baseline and ideal pathways), the engineering process model was constructed using the assumptions and values presented by Kerrison et al. [10]. The adhesive seeding method presented by Kerrison et al. [10] requires the addition of a binder to the sorus solution, allowing direct application onto a textile substrate (porous cloth or twine). The production of this adhesive solution eliminates the need to submerge and inoculate PVC spools wrapped in seed string, greatly reducing the cost of this sub-process and significantly scaling down the facility in terms of energy consumption and water volume requirements. Calculations for the amount of spore solution required are based on the use of 2.75 mL of spore solution per 30 cm of nylon twine [10]. Additionally, it's assumed that the spore solution can be transported to the seeding vessel in a tanker truck and sprayed on the large PVC spools (wrapped in twine) in a separate staging area on the vessel prior to being wrapped around the carbon fiber, eliminating the need to ship submerged spools. This technology was modeled as it represents a realistic low input seeding process.

The nursery design for process 100-B: Traditional Hatchery (conservative pathway) is based on the work of Flavin et al. [9] and Redmond et al. [9]. The model assumes the fabrication of large nesting PVC spools (the largest spool is 0.9 m tall with a 0.9 m diameter) that become inoculated in 1.1 m diameter drums (591.5 L) and are compatible with a high volume seeding machine [9]. The model incorporates detailed calculations for the energy and equipment requirements for the processes needed to support the growth of the spores including UV sea water purification, nutrient addition, artificial lighting, water chilling, air pumping, cold storage, seawater pumping to and from the facility, HVAC, and manual labor. For equipment energy calculations see Appendix A: Supplementary Information. Aquaria water is assumed to be changed (50% volume replaced) every 8 days [10] and spore stocking densities have been back-calculated from experimentally successful stocking densities used at the Ocean Approved facility [9]. The model includes the energy and equipment requirements needed to keep the spores alive during transport from the facility to the seeding vessel (transportation of the fully submerged PVC spools in refrigerated trucks).

All of the nursery configurations outlined above are scaled to meet the annual demand of sorus solution, which is dictated by the number of harvesting vessels, harvesting speed, and number of operational days per year. For all pathways, a period of 40 days is assumed to grow from an extracted spore to a useable gametophyte [9].

2.1.2 Seeding

Sub-processes 220-A and 220-B (shown in figure 1) represent the two possible methods of attaching the kelp spore to the carbon fiber line. The baseline and conservative pathways are assumed to follow the procedure modeled in sub-process 220-A: Wrap rCF with Twine. A wrapping factor of 1.5 is assumed for the nylon twine, thus 1.5 km of twine is required for each km of carbon fiber [10]. While the baseline pathway assumes the use of twine, it still assumes that water, energy, and labor will be saved in process 100-A by spraying the spore solution onto the twine using a binder, and that this process can be carried out on the seeding vessel prior to line deployment. 220-B: Inoculate rCF Line Directly (ideal pathway) refers to the scenario where a carbon-fiber-compatible adhesive is successfully developed, allowing the carbon fiber to be sprayed directly with the spore solution, eliminating the cost of PVC spools and nylon twine.

Sub-processes 230-A and 230-B deal with the physical line deployment mechanism. All pathways assume the use of a custom seeding machine. The seeding machine is predicted to consume 7.5 kW with a 10 km h^{-1} line deployment speed, \$160,000 capital cost, and \$8,000 of annual maintenance costs. The seeding machines utilize hydraulic mechanisms and draw power from the seeding vessels' diesel engines. Sub-process 230-A: Deploy Lines with Large Vessels (baseline and conservative pathways) assumes the use of two large 38 m vessels, each with a cruising speed of 16.7 km h^{-1}, 80 metric ton capacity, 4 crew per boat with an annual salary of \$20,205 per season, \$60K per year for maintenance, 132 L h^{-1} fuel consumption rate, and 24 hours per day operation during the growing season [12]. Additionally, annual maintenance and insurance are assumed to be 5% and 3%, respectively, of the \$2M capital cost [13], with annual slip fees at \$36 m^{-1} $month^{-1}$ [14]. All pathways assume a daily commute of 100 km from the loading dock to the line deployment location off the coast of Northern Washington.

In an attempt to reduce process emissions and the cost of labor, an alternative seeding method has been modeled and included in the ideal pathway, sub-process 230-B: Deploy Lines with Drones. Recent developments in unmanned surface vehicles (USV's) have been used to inform the model for specifications regarding an autonomous drone tug specifically designed for seaweed biomass transport. The drone design utilizes two large slow turning propellers to maximize efficiency and transport loads over long distances with minimum fuel consumption. The model assumes a capital cost of \$150,000, power supplied from a 12 kW diesel generator, a cruising speed of 8 km h^{-1}, fuel consumption rate of 4.54 L h^{-1} (1.2 GPH), and a towing capacity of 500 tonnes. These parameters have been used within the model to estimate the economic feasibility of utilizing drone tugs to transport the deployed carbon fiber lines from a near shore barge to the drift start location 100 km off shore. While the drone seeding model accounts for the purchase cost of seeding machines, cranes, drones, a large barge, and all the associated maintenance costs, it should be noted that the model excludes unforeseen costs associated with autonomous control system integration, testing, and refinement. Further analysis is necessary to fully define drag forces imposed on the bare line, as the model simply scales the total weight of the lines by a factor of 1.5 to account for drag forces imposed on the line as it is pulled across the surface of the ocean.

For all pathways, the seeding sub process includes the cost of shipping the carbon fiber long-lines from California to Washington (1609 km distance) annually. Based on a bending radius of 1.83 m, each 5 km long-line coils into a spool with a 3.18 m diameter and 1.27 m width, each weighing roughly 1.5 tonnes. The carbon fiber is assumed to be in the form of a twisted fiber rope with a 1.52 cm diameter and a density of 1.52 g cc^{-1}. Shipping cost calculations are based on loading plain gondola train cars (19.8 m by 2.7 m with a 90.7 tonne capacity) [15], and a shipping cost of 4 cents per tonne-km [16]. For train emissions, the model assumes that an average cargo train diesel engine consumes 8.8 L km^{-1} [17].

2.1.3 Ocean Drift

The open ocean drift process is identical across the various system pathways. Based on buoyancy calculations using the properties of the carbon fiber, the two kelp species, and commercially available buoy specifications [18] the carbon fiber line will require 21 flotation buoys per km of long-line. For navigational and data transmission purposes, each 30 km carbon fiber line will have a smart buoy on either end. The line is submerged at a depth of 5 m below the ocean surface, thus it is assumed that each flotation buoy will be equipped with a vertical supporting line and a weight disk, and that each buoy/support-line/weight assembly can be manufactured for $95. The model assumes a smart buoy manufacturing cost of $10,000 per buoy, and a total buoy maintenance cost of 1% of the total buoy capital expenditure, spent annually. The drift process assumes 4 data transmissions per day per smart buoy, each costing $0.08, and a logistical staff member monitoring the lines for 40 hours per week at $20 h^{-1} during the growing season. The drift process also assumes a biomass loss of 2% due to grazing from marine life and other potential complications.

2.1.4 Harvesting

For the harvesting process, all pathways assume the use of 38 m vessels equipped with custom built harvesting machines. The harvester is expected to pull in the long-line at 8-10 km h^{-1} and strip the biomass off of the carbon fiber with water jet cutting streams. The harvesting machines consume 75 kW and utilize hydraulics pulling power from the vessels' diesel engines. Since the vessels are stationary during the harvesting process, vessel engines are assumed to operate at 30% of their full capacity while harvesting. The model assumes a capital cost of $500,000 per harvester and annual maintenance costs of $25,000 yr^{-1}. The assumptions regarding vessel capital costs, cruising speed, fuel consumption, crew size and salary, maintenance, insurance, fuel capacity, and hull capacity match the assumptions for the vessels used in process 230-A: Open Ocean Seeding. Once stripped from the line, the biomass will fall into a trough where it will be partially ground, dewatered down to 20% solids, and placed in a floating biomass transport bag (500 tonne capacity). The carbon fiber line is then steam cleaned and spooled before being shipped up the coast for the next growing season. During the off season, the nursery facility is assumed to provide storage space for the carbon fiber spools. The offshore distance of the harvesting location along with additional distance the vessels must travel to account for potential line dispersion dictate how many vessels are required for continuous operation during the 90-120 day harvesting season. The impact of increasing both of these distance parameters on the biomass production price and fuel selling price has been explored. The model includes the cost of vessels, harvesting machines, seaweed bags, deck cranes, forklifts, slip fees, and the associated maintenance costs for all equipment.

Two different methods of biomass transportation have been modeled in order to compare technologies. The first method represented in the baseline and conservative pathways is 410-A: Transport Biomass via Drone Tug. The drones used for sub-process 410-A are identical to those used in sub-process 230-B. The drones are assumed to travel back and forth between the shore and the harvesting location, carrying 500 tonnes of seaweed (at 20% solids) with each trip. Within the model, the number of drones required is a function of the distance to the harvesting location, the drone cruising speed, and the amount of biomass harvested daily. The second method, 410-B: Transport Biomass with Tender Vessel (conservative pathway), involves purchasing and using an Aframax tender vessel to collect the harvested biomass from the vessels then transporting the biomass to shore. In the event that the drone tug technology is unavailable, a large tender vessel eliminates the need for vessels to travel to and from the harvesting location one load a time, greatly improving system efficiency. Parameters for the large Aframax vessel include a capital cost of $43M, a cruising speed of 26.85 km/h, residual fuel oil consumption of 35.2 tonnes per day at max power, 27,800 nm range, 3000 tonne biomass capacity, and insurance at 2% and maintenance at 5% of the capital cost annually [19]. Additionally, the model assumes a 6 member crew with an average seasonal salary of $17,808.

2.1.5 Conversion to Fuel and Fertilizer Products

For the conversion of the macroalgae biomass into useful energy and co-products, an HTL sub-process model has been constructed. Sub-process 500-A is incorporated in all pathways and assumes that the biomass will be converted into bio-crude via HTL. Once converted through the addition of heat and pressure, the bio-crude is upgraded to renewable diesel (R100), Naptha, and Butanol. The process model constructed for this pathway follows the HTL process outlined by Cruce and Quinn [5]. The HTL reactor and required equipment has been sized based on the flow-rate of the macroalgae feedstock, which is a function of the total amount of biomass cultivated on the rCF lines. All of the capital and operational costs associated with constructing and operating the HTL plant have been included in the model. As the HTL model was originally constructed for microalgae, the bio-crude yield and amount of process chemicals and catalysts has been adjusted based on the modeled biomass composition. Assuming an equal biomass yield (wet weight) from both *S. latissima* and *N. leutkeanna* on the carbon fiber long-line, the average composition of the harvested biomass was determined using values found in literature for both the nutritional and elemental composition of each individual species. Results show that ash will make up 36% of the harvested biomass, and the biomass also consists of proteins (10%), carbohydrates (49%), lipids (2%), and residue (3%) [4], [20]–[23]. For detailed compositional calculations, see Appendix A: Supplementary Information 6.5. High ash content is assumed to not impact bio-crude yield but does impact the HTL reactor size. Based on the HTL feedstock composition, the model assumes a bio-crude yield of 34% on an Ash Free Dry Weight (AFDW) basis [5]. The HTL process yields an aqueous phase rich in nitrogen and phosphorus, and the model assumes that the valuable nitrogen and phosphorus can successfully be extracted from the aqueous stream and sold as fertilizer to be used on terrestrial crops. The model includes a high level stoichiometric calculation, assuming an aqueous phase yield of 26 wt% of the input feedstock [16]. The aqueous phase is assumed to contain 36% of the nitrogen present in the original feedstock, and a phosphorus yield of 0.017 kg phosphorus per kg aqueous phase [8]. Using a selling price of \$12.17 kg^{-1} for nitrogen fertilizer [24] and \$8.93 kg^{-1} for superphosphate fertilizer [25], the model determines the revenue from these nitrogen and phosphorus fertilizer co-products. It should be noted that the model excludes the costs related to the extraction and detoxification processes, and is meant to serve as a preliminary high level overview of the potential co-product revenue. Currently there is large uncertainty surrounding HTL aqueous phase toxicity. Some studies show the successful recycling of nutrients from the aqueous phase into the algal growth process, while other studies suggest a range of existing complications for this recycling process.

2.2 TEA methodology

The TEA utilizes a 30 year discounted cash flow rate of return (DCFROR) model in order to determine the minimum fuel selling price (MFSP). The model assumes a 7 year MACRS depreciation, a 10% internal rate of return (IRR), a 3 year construction period, and a start-up period of 0.5 years where facility production is assumed to be at 50% of full capacity. A tax rate of 35% is assumed over the 30 year facility life. The TEA assumes 40% equity, a loan term of 10 years, and an interest rate of 8%. The working capital was assumed to be 5% of the total system capital expenditure. The TEA model receives capital and operational costs from each of the sub-processes (100-500) implemented during the production and conversion of the biomass, and uses the revenue generated from the products (fuel and co-products) to determine a MFSP such that a net present value of zero is achieved based on an internal rate of return of 10%. Results are expressed with the metric USD per Gallon of Gasoline Equivalent (GGE).

2.2.1 Sensitivity Analysis

In order to determine high-impact model parameters, a sensitivity analysis was performed including all input parameters within the engineering systems model. Each parameter was individually adjusted by ±20% subsequently re-solving the DCFROR model to determine the change in minimum biomass selling price. The data was compiled and organized from largest to smallest change in biomass price. The 38 parameters which inflicted the largest change in biomass selling price from a 20% increase or decrease were assumed to be high-impact parameters and were carried through to the statistical analysis. A student t-test was performed on the data to determine the critical t ratio to identify the cut-off for parameters with significant influence on model results based on a 95% confidence interval. Once the high-impact parameters were identified, the most important were subject to further analyses.

For the high-impact variables identified, a range was defined for each using values from literature. High-impact variables were tested across their realistic ranges to determine impacts on the MFSP in order to provide bounds on the results. The major parameters tested in this study were biomass yield (kg wet weight per m long-line), total distance to the harvesting location, and the distance between 30 km line segments (each unit is 30 km in length) to capture the impact of line dispersion. The independent distributions defined for each high-impact parameter were subsequently used for the Monte Carlo analysis.

2.3 LCA methodology

The mass and energy flows quantified in the engineering process model were used in combination with life-cycle inventory (LCI) data to quantify the environmental impacts of the system in its various configurations. LCI data were compiled using Open LCA with the Ecoinvent database [26], the NREL LCI database [27], and the Argonne National Lab GREET model [28]. Global warming potential (GWP) for the various system pathways were calculated by combining emissions from carbon dioxide, methane, and dinitrogen monoxide with their respective equivalency factors of 1, 34, and 298, specified by the International Panel on Climate Change (IPCC) based on 100 year impact [29]. For all transportation methods within the model (trucks, trains, and vessels), emissions are calculated for both the production and combustion of the diesel. Emissions related to electricity (nursery facility utilities) are based on emissions data from the state of Washington [30] and from the U.S. Energy Information Administration [31]. Emissions associated with electricity demand in the HTL process are calculated using the California grid mix, as the conversion process is assumed to occur near the harvesting location [26]. For nutrients used in the hatchery, nutrient formulas were acquired from Flavin et al. [9], Kerrison et al. [10], and Redmond et al. [10] and LCI data regarding the production of the various chemicals were utilized to determine GWP. For the catalysts and buffer agents used in the HTL process, GWP data was taken from Nie and Bi [33], and the model assumes an emission of 6.54 gCO_2-eq MJ^{-1} for the production and use of the buffer agent, and 1.14 gCO_2-eq MJ^{-1} for the production and use of the HTL catalyst. Emissions were allocated to the combined fuel output of naptha and renewable diesel, and the system is credited for atmospheric carbon uptake during the cultivation of the macroalgae and the displacement of fertilizer recovered from the HTL aqueous phase. The system boundary for the work is well to wheel and includes combustion assumed to be 72.6 gCO_2-eq MJ^{-1} [34].

2.4 Monte Carlo Analysis (TEA and LCA)

A Monte Carlo error analysis was used to reduce the uncertainty in the results for the MFSP, as well as the net system GHG emissions. Ten of the most impactful model parameters determined from the sensitivity analysis (Sugar Kelp Yield (kg wet per m of line), Bull Kelp Yield (kg wet per m of line), Harvesting Rate (km h^{-1}), Operational Days per Year, Biomass Solids Content (% Solids), Distance to the Seeding Location (km), Dispersion Distance (km), Carbon Fiber Rope Diameter (in), Cost of a Flotation Buoy ($), and Harvesting Hours of Operation (hours per 24 hour day)) were all assigned triangular distributions using a low, mean, and high value for each parameter found in literature. Assumptions and sources regarding min, mean, and max values for the Monte Carlo inputs can be found in Appendix A: Supplementary Information 6.6. For each iteration of the analysis, each of the ten variables were assigned a random value within their respective distributions. A total of 5000 iterations were performed in the analysis, from which a probability distribution and 90% confidence interval were determined for both the MFSP ($ GGE^{-1}) and the net system GHG emissions (gCO_2-eq MJ^{-1}).

CHAPTER 3. RESULTS

3.1 TEA Results

An engineering process model was developed and used to understand the economic viability of three different pathways (outlined in figure 1). Modularity in the model is used to produce intermediate economic results such as the minimum biomass selling price prior to fuel and co-product conversion, as well as systems level results which incorporate all process from spore production through fuel production.

3.1.1 Bounding the Minimum Biomass/Fuel Selling Price

Following the Nth plant economic assumptions and the system configuration consistent with the baseline pathway shown in figure 1, the minimum biomass selling price to achieve a 10% IRR over a 30 year facility life is \$278.13 per Dry Metric Ton (DMT). This result is based upon a 30 kg m^{-1} combined polyculture biomass yield and 100 days per year to release/harvest lines. Furthermore, this baseline cost assumes a 10 km dispersion distance (between incoming 30 km sections of line) and a total distance of 100 km from the harvesting location to the shore. For the conservative pathway (see figure 1), the minimum biomass selling price increases to a maximum of \$565.14/DMT. This increase in cost is the result of decreasing the polyculture biomass yield to 25 kg m^{-1}, increasing the dispersion distance to 50 km, increasing the distance to the harvesting location to 200 km, and decreasing the total operational days per year to 90. Following the ideal pathway outlined in figure 1, the minimum biomass selling price decreases to \$210.18/DMT. This minimized cost is the result of assuming short travel distances (100 km to the harvesting location and no dispersion), high biomass yield (35 kg m^{-1}), and a longer cultivation season (120 operational days per year).

Including the HTL process in the model, and using the feedstock flow rates and compositions determined from engineering process model, the MFSP was determined for the baseline, conservative, and ideal pathways, figure 2. The same assumptions used to determine the minimum biomass selling price for each of the pathways were used to generate figure 2, with the capital and operational expenses related to fuel conversion incorporated. Additionally, figure 2 includes the revenue generated by extracting and selling nitrogen fertilizer (urea) and phosphorous fertilizer (super phosphate). Additionally, the contribution from each of the individual sub-processes, capital expenses, taxes, and land are shown for each pathway. Based on the results, the MFSP for the baseline, conservative, and ideal pathways is \$6.38 GGE^{-1}, \$11.00 GGE^{-1}, and \$5.10 GGE^{-1} respectively. These minimum fuel selling prices each include the co-product revenue from fertilizers, valued at \$1.42 GGE^{-1} for all pathways due to fixed nitrogen and phosphorus yields from the aqueous phase. Conservative estimates are higher due to increased travel distances, lower yields, traditional hatchery methods that are less efficient, and fewer operational days per year to produce, harvest, and convert biomass. Furthermore, the conservative pathway assumes the use of a large Aframax tender vessel rather than drone tug biomass transport, significantly increasing the capital and operational expenses associated with process 400. Ideal estimates are lower due to minimized energy consumption, technology with lower capital and operational costs, and maximized biomass yield and growing season length.

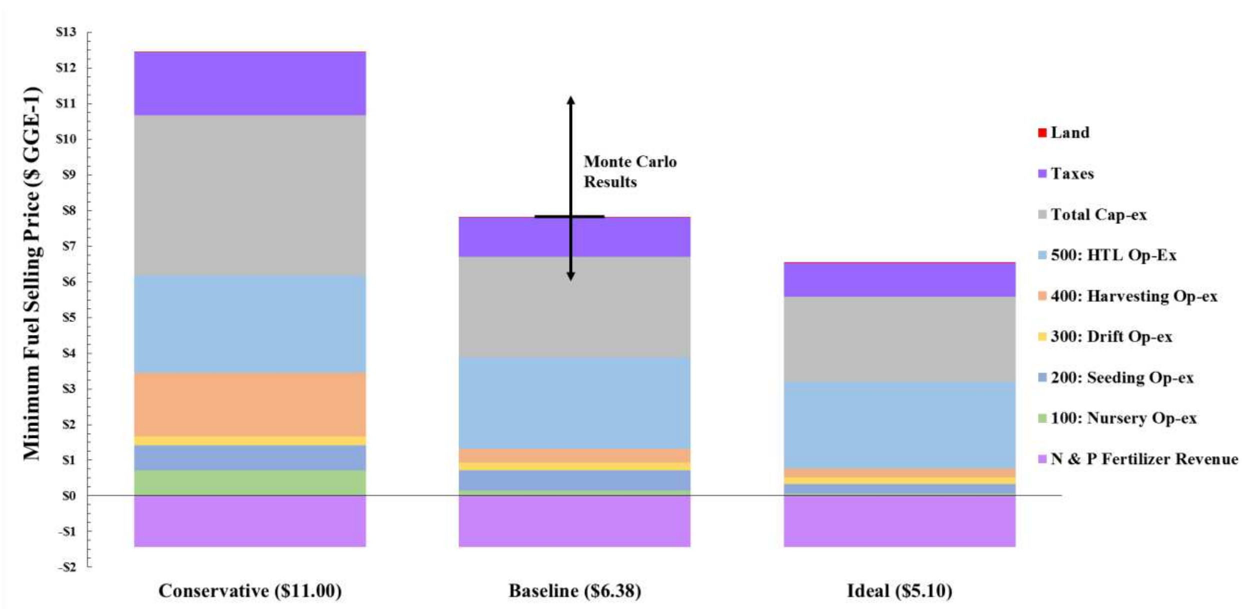

Figure 2. Minimum fuel selling price for the baseline, conservative and ideal pathways. Differences between pathways are based on technology readiness level and biological parameters. Monte Carlo median and 90% confidence interval are shown with the black line and arrows on the baseline results.

It should be noted that the capital investment for the baseline system is rather large, contributing 36% of the MFSP. The total capital expenditure for the baseline system is just under $375M and this is mainly due to the large investment in sensor equipped and flotation buoys ($95.8M) and carbon fiber long-line ($44M). HTL operational costs contribute the second largest portion at 33% of the MFSP. Taxes contribute 14% of the MFSP. In addition, operational expenses from sub-processes 100, 200, 300, and 400 contribute 2%, 7%, 3%, and 5% respectively to the MFSP for the baseline pathway. A breakdown of all the capital expenses can be found in Appendix A: Supplementary Information.

3.1.2 Sensitivity Analysis of Baseline System

The foundational engineering process model was combined with a sensitivity analysis to understand the high-impact variables. Results from the statistical analysis performed on the model sensitivity data are presented in figure 3.

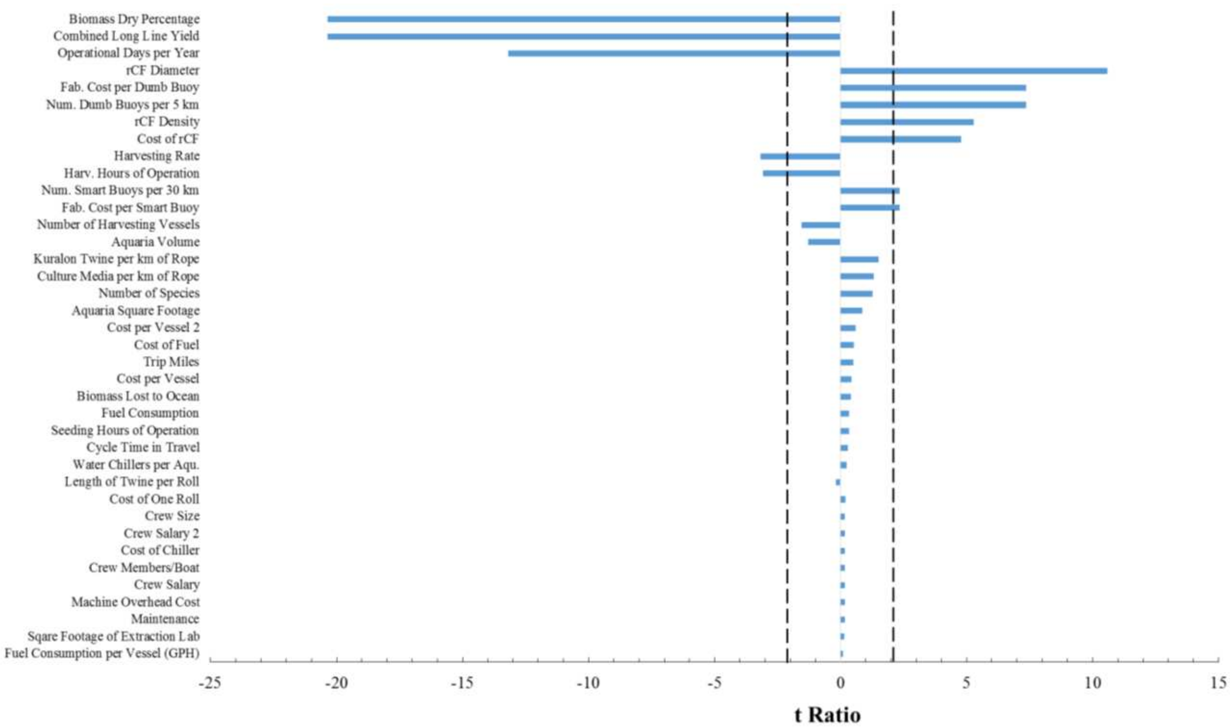

Figure 3. Statistical analysis on sensitivity data for biomass production cost of the baseline system (38 of 518 model inputs shown and $\pm t_{critical}$ shown by the dotted vertical lines).

Results were sorted to show the most impactful variables, and the data for the top 38 of 518 inputs were fit to a least squares model using JMP statistical software. Results from the analysis showed a high F ratio of 34.65 and 12 different independent variables with a t ratio greater than $t_{critical} = \pm 2.0273$ (shown in figure 3 with the two black dotted vertical lines). The variables with the largest impact on the model are closely related to biomass productivity and include Biomass Dry Percentage (amount of water in the harvested biomass), Combined Long-line Yield, and Operational Days per Year. With more operational days per year, the system produces more biomass, thus the price of the biomass can be lowered, while still achieving a 10% internal rate of return over 30 years. The next group of high-impact variables deal with capital expenses for the large amount of equipment required by the system. As the system requires nearly 240 km of carbon fiber line to be seeded and released on each day of the growing season, and each carbon fiber line requires smart buoys for GPS location tracking and maritime communication, factors such as the rCF Diameter, Fabrication Cost per Buoy, Number of Buoys per 30 km, rCF Density, and Cost of rCF, all have a significant impact on the minimum biomass selling price. As the equipment parameters are more or less determined by the loading scenarios, material costs, and manufacturing processes, focus was not placed on minimizing material costs, but rather on addressing the more unpredictable high-impact parameters.

3.1.3 Monte Carlo Results

For the Monte Carlo analysis, 5000 iterations were performed. Within each iteration, each of the top ten high-impact variables (determined in the sensitivity analysis) were assigned random values within their assigned triangular distributions based on minimum, mean, and maximum values either found in literature or estimated. Results from the Monte Carlo analysis show a minimum fuel selling price 90% confidence interval from \$6.02 GGE^{-1} to \$11.17 GGE^{-1}. Outside the 90% confidence interval the results show a maximum fuel selling price of \$16.94 GGE^{-1} and a minimum of \$4.91 GGE^{-1}. Additionally, the analysis suggests a standard deviation of \$1.62 GGE^{-1} and a median value of \$7.89 GGE^{-1}. All Monte Carlo results include the co-product revenue of \$1.43 GGE^{-1} and the consistency across pathways is due to fixed nitrogen and phosphorus yields from the HTL aqueous phase. The results suggest 23% percent error between the baseline system cost estimate (\$6.38 GGE^{-1}) and the median value from the Monte Carlo analysis. These results are also incorporated into figure 2 on the baseline results.

3.1.4 Scenarios and Improvements

The potential reduction in minimum fuel selling price from technological advancements is very significant, and the modularity of the model was used to quantify the economic and environmental impacts of each technology explored in this study. The ideal pathway assumes the use of all the emerging technologies, and without the associated savings in capital and operational expenses the ideal pathway MFSP would increase from \$5.10 GGE^{-1} to \$10.79 GGE^{-1}. Modifying the on-shore nursery facility to produce an adhesive spore solution (100-A) rather than the traditional method of producing inoculated spools described by Flavin et al. [9] (100-B), reduces the baseline MFSP by 11% or \$0.71 GGE^{-1}. This technology greatly reduces the energy, water, and labor requirements for sub-process 100 and thus improves the sustainability of the system. The second technology is an alternative seeding method, which involves spraying the adhesive slurry directly on the carbon fiber line and allowing it to cure in the cool ocean water (220-B), rather than wrapping the carbon fiber with inoculated twine during the seeding process (220-A). As nylon twine and PVC are relatively inexpensive, this variation in process execution only reduces the baseline pathway MFSP by 0.6% or \$0.04 GGE^{-1}. It should also be noted that there are a large number of unknowns associated with the direct application process, including the need to identify a binder that is compatible with both the carbon fiber and both species of kelp. Drone Tug Seeding represents moving away from large vessels equipped with seeding machines to deploy lines, and instead using autonomous drone vessels to pull seeded lines to their release location. While this technology reduces the baseline MFSP by 4% (\$0.28 GGE^{-1}), it may pose more risk than reward as the complex autonomous programming required for line transport in unpredictable open ocean environments certainly carries a list of unforeseen complications. Using Drone Tug technology for biomass transport as opposed to using an Aframax tender vessel is currently being researched. While the drone tug technology may be difficult to develop for process 200, the long distance transport of 500 tonne floating seaweed bags can be achieved with minimal energy/fuel inputs and results in a baseline pathway cost reduction of 29% (\$1.84 GGE^{-1}). This technology has been identified as a necessity to reduce system capital cost, operational costs, and emissions. The cost advantage of using recycled carbon fiber (\$2 lb^{-1} instead of \$8 lb^{-1}) is very significant and increasing the cost of the rCF to \$8 lb^{-1} results in a 44% (\$2.82 GGE^{-1}) increase to the baseline pathway MFSP.

The metric of minimum biomass selling price has been chosen for the following scenario analysis to allow for the evaluation of alternative system configurations that pair the proposed cultivation system with alternative fuel conversion pathways in future studies. Shown in the sensitivity analysis, the parameter with the largest impact (and highest likelihood to vary based on a number of environmental conditions) is the combined long-line biomass yield. Using the baseline, conservative, and ideal system assumptions a scenario analysis was performed to determine the biomass production cost as a function of the combined long-line yield, figure 4.

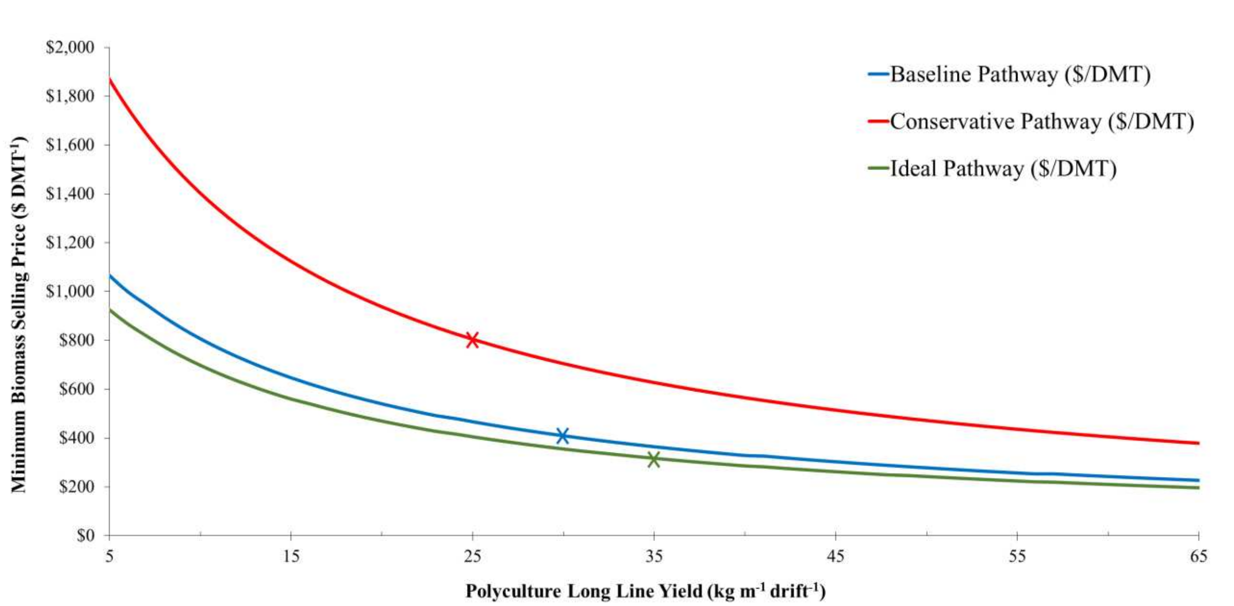

Figure 4. Impact of long-line yield on minimum biomass selling price for the baseline, conservative, and ideal system pathways. The X on each line identifies the assumed yield for each pathway.

The impact of the combined long-line yield on the minimum biomass selling price is shown in figure 4 for the baseline, conservative, and ideal pathways. Low yields have a dramatic effect on system performance, however, past the knee of the curve (around 20-25 kg m^{-1}) the impact of increased yield on the biomass cost begins to plateau. The baseline pathway assumes a combined yield of 30 kg m^{-1}, or 15 kg m^{-1} from each species. This assumption is based on several reported yields for the two different species, with values exceeding 15 kg m^{-1} for both species. A study from Broch et al. [35] suggests a yield of 31.25 kg wet m^{-1} from *S. latissima* alone. Peteiro and Freire [36] indicate a yield of 16.1 kg m^{-1} for *S. latissima* alone, and Merrill and Gillingham [37] report *N. luetkeana* yields as high as 22 kg m^{-1}. It is possible to convert between linear yield (kg wet per m) and hectares using values from Skjermo et al. [38], who predicted *S. latissima* yield ranges of 170 – 340 wet weight tons per ha. Using the assumption of 10% solids, this equates to 17-34 dry tons per ha. While increasing the yield above the realistic baseline assumption of 30 kg m^{-1} does positively impact the sustainability of the system, the non-linear impacts seen in the lower yields do not continue past this assumed value.

One of the high risk items associated with the proposed system, is the potential for the released lines to drift away from one another, resulting in a dispersion distance between the released lines relative to the harvesting location. Lines are expected to be released in 30 km increments, and a parameter for dispersion distance has been incorporated in the model. When this parameter is increased, the minimum biomass selling price also increases, figure 5.

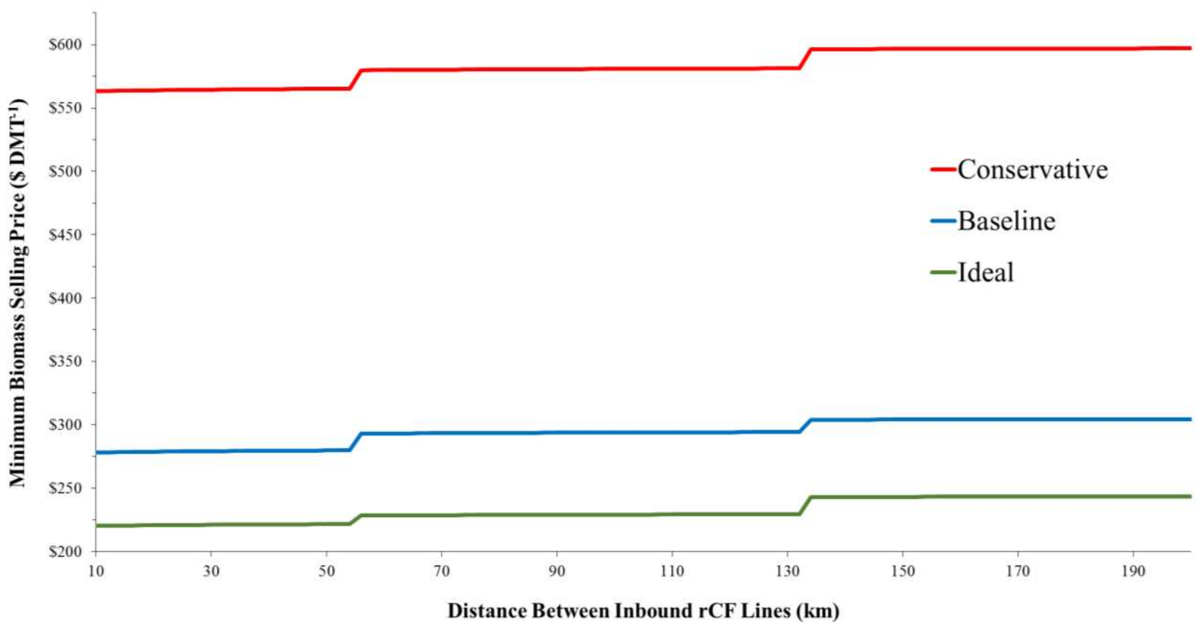

Figure 5. Impact of increasing the dispersion distance between inbound carbon fiber lines on the minimum biomass selling price. Conservative, baseline, and ideal pathways are shown with the red, blue, and green lines, respectively.

If the carbon fiber lines do not follow their predicted trajectory and end up further dispersed in the open ocean, this results in an increased travel distance to and from each line at harvest. When the distance between lines is increased, the harvesting vessels must spend more time traveling between the lines, increasing the amount of fuel consumed and number of vessels/drones required for continuous harvesting operations. All of these factors result in a gradual increase in the minimum biomass selling price. For the baseline pathway, at 56 km of distance between lines the price increases by 5% ($13.21 DMT^{-1}). This jump represents the threshold where the travel time between lines is so large that there is not enough time in the day for the two harvesting vessels to reach and harvest all the incoming lines, and a third vessel must be added to the system. A similar trend can be seen at 134 km dispersion distance with the baseline price increasing by 3.5% ($9.68 DMT^{-1}). The sudden increase in price can be attributed to the increased system capital and operational expenses associated with adding another vessel, while the biomass output of the system is constant. While the dispersion distance has an impact on the minimum biomass selling price, figure 5 suggests that dispersion is not a high risk item, as the system can handle dispersion of up to 200 km between inbound lines with a maximum increase of 9.23% or \$26.36 DMT^{-1} for the baseline pathway. Similar trends are observed for the conservative and ideal pathways.

3.2 LCA Results

3.2.1 Emissions for the Baseline, Conservative, and Ideal Pathways

The same three pathways used for economic evaluation are used to investigate the GHG emissions associated with fuel production from the proposed macroalgae to fuels concept. Emissions are expressed in grams of CO_2 equivalent per MJ of fuel produced by each system. The different sources of emissions from the sub-processes within the baseline pathway are explored in figure 6.

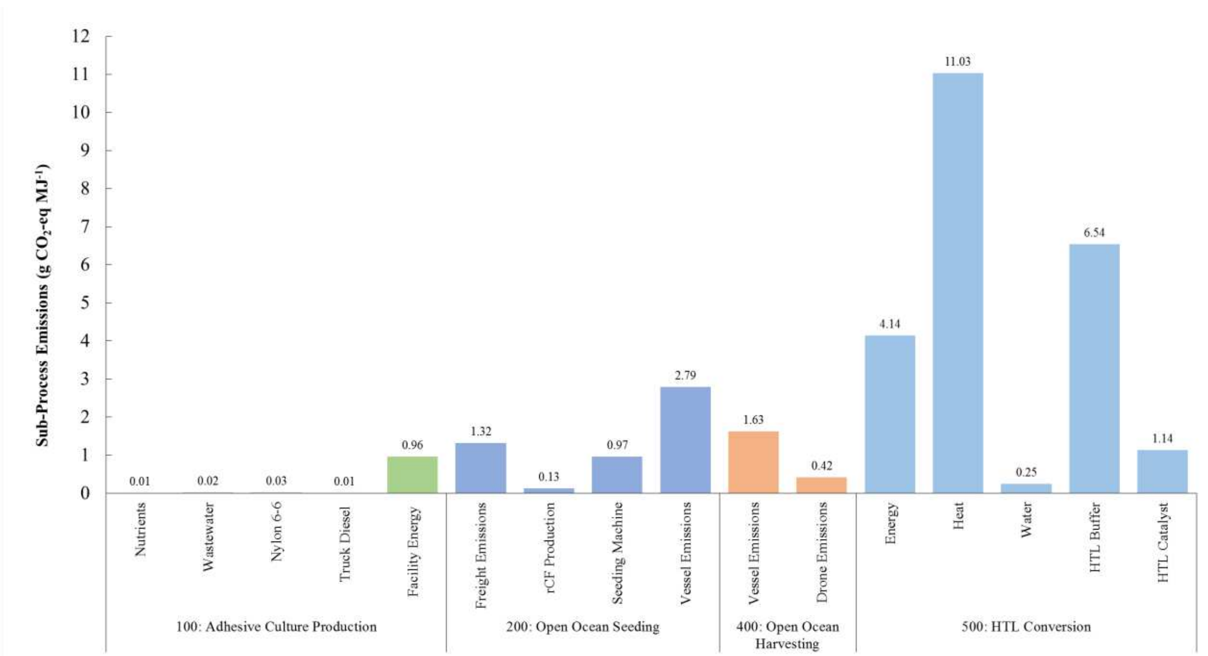

Figure 6. Baseline pathway system emissions categorized by sub-process. Carbon uptake credits (negative emissions) associated with macroalgal growth, biochar production during HTL, and nitrogen/phosphorus displacement are not included in figure 6.

The conversion process of HTL has the highest GHG emissions across the baseline pathway as this process is energy intensive and requires large amounts of natural gas, electricity, and catalysts associated with high GHG emissions for production. The lowest emissions within the baseline pathway occur in process 100: Nursery, with facility energy being the only significant contributor to the total emissions for sub-process 100. It should be noted that vessel emissions associated with the seeding process are higher than vessel emissions associated with the harvesting process. This result is due to the seeding vessels traveling between the seeding location and loading dock on a daily basis, and must use their full engine capacity for the seeding process, while the harvesting vessels can remain on the water near the harvesting location for weeks and are able to run engines at 30% capacity during the harvesting process. Utilizing drone tugs for biomass transport allows the vessels to remain at the harvesting location for weeks, greatly reducing vessel emissions. The drones represent very efficient transport devices as they can operate at very low speeds. Sub-process 300: Drift, is not included in figure 6 as any energy consumed in process 300 is produced by the system itself through solar PV arrays on the smart buoys. In order to capture the net emissions associated with the three system pathways, the operational emissions, carbon credits, and end use emissions have been determined. Rather than producing GHG emissions in process 300, the system actually captures carbon from the atmosphere/ocean through uptake during macroalgae growth, and this carbon credit is illustrated in figure 7 with the negative yellow bars. Of the carbon captured during macroalgal growth, about 85% (68.8 g CO_2-eq MJ^{-1}) ends up in the fuel and the remaining 15% (11.79 g CO_2-eq $MJ^{-}1$) ends up in the biochar generated during the HTL process. The system receives another carbon credit from displacing urea and superphosphate through the recovery of nitrogen and phosphorus in the HTL aqueous stream. The analysis follows a well-to-wheel methodology, incorporating the end use or combustion of the produced diesel fuel (assumed to be 72.6 g CO_2-eq MJ^{-1} [34]). With both emissions and credits considered, the system net emissions are shown for each system configuration with the grey bars in figure 7.

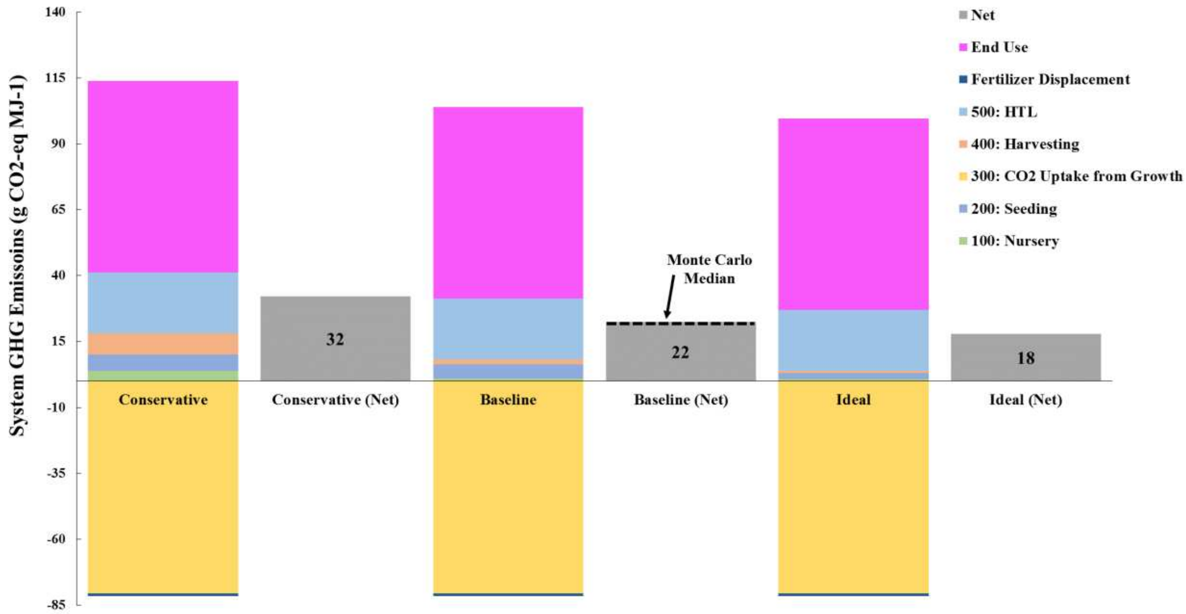

Figure 7. Life cycle analysis results for the baseline, conservative, and ideal pathways with results broken down into the main process with totals presented in grey. The Monte Caro median value is shown with the black dotted line on the baseline results.

There are several major differences between the conservative, baseline, and ideal pathways, which cause the GHG emissions to vary between pathways. The most impactful parameters are related to the nursery. For the conservative system, the LCA assumptions follow the TEA assumptions, in that a traditional hatchery setup will be used to submerge spools of PVC in sorus solution and produce inoculated twine, to be wrapped around the carbon fiber line. This assumption results in increased energy demands for the nursery facility in terms of water pumping, chilling, and aerating. Furthermore, the emissions associated with transporting the spools are much higher, as the spools must remain submerged in water during transport. Incorporating the traditional hatchery assumptions into the conservative system results in an increase of 12.7% (2.86 g CO_2-eq MJ^{-1}) relative to the baseline pathway. Furthermore, the ideal system assumes that the sorus solution can be sprayed directly on the carbon fiber line. This assumption results in a 1.3% decrease (0.3 g CO_2-eq MJ^{-1}) in GHG emissions relative to the baseline pathway net emissions. The configuration of the nursery is directly related to the seeding method (wrapping twine or spraying spores directly on the carbon fiber) and these assumptions impact the emissions related to sub-process 200: Open Ocean Seeding. The conservative pathway sees a 4.6% increase (1.04 g CO_2-eq MJ^{-1}) relative to the baseline pathway. The ideal pathway also assumes the use of drones for line deployment. This drone seeding technology in combination with direct application of the spores to the rCF results in a 13.3% decrease (2.97 g CO_2-eq MJ^{-1}) within process 200 relative to the baseline pathway net emissions from removing the burdens associated with Nylon 6-6 twine production and vessel diesel combustion emissions. The last major difference is related to the harvesting process. The distance to the harvesting location and the dispersion distances vary for the three pathways, impacting the amount of fuel consumed for both the manned vessels and autonomous drones used in the harvesting process. Furthermore, the conservative pathway assumes the use of an Aframax tender vessel for biomass transport. The conservative pathway sees a 26.5% increase (5.93 g CO_2-eq MJ^{-1}) relative to the baseline system, and the ideal pathway sees a 5% decrease (1.13 g CO_2-eq MJ^{-1}) within sub-process 400: Harvesting relative to the baseline pathway. Sub-processes 300, 500, fertilizer displacement, and end use are identical across the three pathways.

3.2.2 Monte Carlo Results for LCA

For the Monte Carlo analysis, 5000 iterations were performed, and the top ten high-impact variables (determined in the sensitivity analysis) were assigned triangular distributions based on minimum, mean, and maximum values either found in literature or estimated. Results from the Monte Carlo analysis suggest the 90% confidence interval for system net emissions ranges from 18.90 g CO_2-eq MJ^{-1} to 27.02 g CO_2-eq MJ^{-1}. Outside the 90% confidence interval the results show a maximum net emissions value of 37.85 g CO_2-eq MJ^{-1} and a minimum of 17.67 g CO_2-eq MJ^{-1}. Additionally, the analysis suggests a standard deviation of 2.61 g CO_2-eq MJ^{-1} and a median value of 21.66 g CO_2-eq MJ^{-1}. The results suggest 1.55% percent error between the baseline system net emissions estimate (22 g CO_2-eq MJ^{-1}) and the median value from the Monte Carlo analysis. The median value from the Monte Carlo distribution is shown in figure 7.

3.2.3 Scenario/Improvements

The adhesive seeding method where twine is sprayed with spore solution prior to line deployment (consistent with the baseline pathway) results in an 8.7% (1.95 g CO_2-eq MJ^{-1}) reduction to the net system emissions due to decreased nursery facility size, decreased seawater volume requirements (as spools need not be submerged during inoculation), and significantly less facility energy requirements due to minimized water chilling, filtration, and pumping energy. When spraying the carbon fiber directly with the spore solution (assuming a carbon fiber compatible adhesive is developed) further reduces emissions by 0.1% (0.03 g CO_2-eq MJ^{-1}). Drone seeding (sub-process 230-B) reduces system emissions by 11.6% (2.60 g CO_2-eq MJ^{-1}) due to decreased fuel consumption and higher fuel efficiency. Drone tug transport (410-A) has a significant impact on baseline pathway emissions, reducing them by 15.2% (3.41 g CO_2-eq MJ^{-1}). Again, this improvement is due to increased fuel efficiency from large diameter slow turning propellers on the drone tug vessels. Using recycled carbon fiber as opposed to virgin carbon fiber has the largest impact on system emissions, as the embodied energy of the recycled carbon fiber is nearly 2 orders of magnitude lower than the virgin fiber. Utilizing this composite recycling technology results in a 32% (7.18 g CO_2-eq MJ^{-1}) reduction to the baseline pathway net emissions.

CHAPTER 4. DISCUSSION AND RECOMMENDATIONS

4.1 Limitations, Error, and Uncertainty

While there are many limitations, this study is the first successful attempt at modeling a macroalgae fuel system through the entire process of producing spores, inoculating line, cultivating, harvesting, and converting into fuel. The modularity in the model has successfully quantified the economic and environmental impacts of the evaluated technologies. The results have identified the critical technologies to be the recycled and pultruded carbon fiber, the production of an adhesive culture rather than submerging twine in the inoculation tanks, and the successful integration of autonomous drone tugs for biomass transport. The results suggest that spraying the spore solution on the carbon fiber directly will have a negligible impact on system costs and emissions, and the investment to develop this technology may outweigh the benefits of its use. Furthermore, the implementation of drone tug vessels for the seeding process may pose more risks than rewards due to the difficulty of autonomous programing. However, if the technology is successfully developed, this technology can significantly reduce system costs and emissions.

There are a number of limitations to discuss regarding the assumptions and procedures used for this study. Perhaps the largest limitation or source of error is a lack of data regarding the specific cultivation and conversion system modeled. While macroalgae hatcheries and cultivation lines are used throughout the world, no one has attempted to scale up a hatchery facility to a bio-fuel feedstock production volume. Further, the successful integration of carbon fiber in a free-floating macroalgae cultivation system has yet to be demonstrated. Several of the pathways explored in this study assume the successful development of a bio-adhesive to adhere the kelp spores directly to the carbon fiber line, and currently no such adhesive exists. While eliminating the nylon twine from the system has a negligible effect on system costs and emissions, spraying the twine with the spore solution rather than submerging the spools in the solution results in significant reductions for both system costs and emissions (-$0.71

GGE^{-1} and -2.86 g CO_2-eq MJ^{-1}) and this process requires an adhesive compound similar to that used by Kerrison et al. [10]. While adhesive compounds clearly exist, they are not commercially available and costs associated with the development of this technology are not included in this model. There are large unknowns regarding the behavior of the carbon fiber long-line in the open ocean. Drift trajectories and hydrodynamic modeling provide insight (see Appendix A: Supplementary Information 6.7), however field tests are necessary for model validation. For parameters related to nautical distances, vessel engine specifications, crew sizes, and operational speeds (seeding and harvesting speed), approximations have been made based on discussions with industry professionals and research, however, accurately predicting values for these parameters can be difficult. Additional unknowns exist related to the seeding and harvesting technology incorporated in this work. Perhaps the most important unknown related to this study is the success of using macroalgae as a feedstock for high volume HTL conversion. While HTL is well-understood for microalgae, the compositional differences and high ash content of macroalgae significantly lower the effectiveness of the conversion process. A maximum conversion efficiency of 34% is assumed in the HTL model, when in reality this conversion efficiency will need to be much higher to yield economically favorable results. Increasing the yield to similar upper end yields assumed in the microalgae industry of 50% decreases the baseline pathway MFSP by 63% to \$3.99 GGE^{-1}. In addition, reducing the ash content of the feedstock would dramatically impact the end results. In summary, there are a variety of aspects for the proposed technology that need to be vetted.

For these reasons, the sensitivity, scenario, and Monte Carlo analyses have been carried out to address this error and to understand how it may propagate throughout the model. After performing the model sensitivity analysis with over 500 model parameters, the 10 most impactful parameters were assigned triangular distributions based on minimum, maximum, and mean values which were either estimated or obtained from literature. While many of the variables, such as biomass yield, would most likely follow a lognormal distribution, triangular distributions were used in the Monte Carlo analysis due to limited data availability. While the assigned triangular distribution may not match the natural distribution for each variable, the Monte Carlo method still ensures that values across the reported range are randomly tested throughout the model. Since the median values for the Monte Carlo output distributions are close in value to the baseline approximations (23% error for fuel selling price, and 1.55% error for GHG emissions), the impact of error propagation throughout the model is relatively insignificant despite testing a wide range of high-impact parameters.

4.2 Recommendations and Comparison to Existing Bio-Fuel Systems

A common trend throughout the results is the inefficiency of HTL conversion. HTL contributes between \$2.44 GGE^{-1} (ideal) and \$2.74 GGE^{-1} (conservative) to the total minimum fuel selling price and represents more than 30% of the MFSP. In terms of environmental impact, the HTL process contributes 23.1 g CO_2-eq MJ^{-1} (22% of the positive emissions) to the net emissions of the proposed baseline pathway. Modularity in the model has demonstrated the high cost and low output of HTL conversion, and the results strongly suggest that more efficient fuel conversion pathways should be explored for macroalgae. Some potential pathways that should be explored in future studies include fermentation of the macroalgae to produce bio-ethanol or anaerobic digestion to produce bio-gas.

In terms of production cost, the proposed system yields positive results. Based on the work of Hoffman et al. [39], microalgae cultivation systems range from \$510 DMT^{-1} for algal turf scrubbers to \$673 DMT^{-1} for open raceway ponds. The proposed baseline pathway yields a minimum biomass selling price of \$286 DMT^{-1}, which represents a 44 - 58% decrease in cost compared to microalgae cultivation systems. Furthermore, the results suggest that the cultivation of macroalgae on free-floating carbon fiber long-lines can produce biomass without the use of fresh water, nutrients (once the spores are out of the nursery facility), and arable land. This is another advantage of free-floating offshore cultivation systems when compared to terrestrial and algae biomass sources.

In terms of global warming potential, the modeled system yields extremely favorable results. The conservative system estimate yields net emissions of only 32 g CO_2-eq MJ^{-1}, successfully meeting the renewable fuels standard. Thus, no matter the system configuration or technology used, the results suggest that macroalgae fuel systems are environmentally favorable over petroleum based fuel systems, and have lower life cycle emissions than biodiesel from canola oil (45.6 g CO_2-eq MJ^{-1}) and biodiesel from soybean oil (51.5 g CO_2-eq MJ^{-1}) [40].

CHAPTER 5. CONCLUSION

This study focused on taking a modular approach to modeling mass and energy flows for a macroalgae biorefinery. The proposed system cultivates two different species of kelp on free-floating horizontal carbon fiber cultivation lines that drift from North to South off the west coast of the United States. The model accounts for costs and emissions associated with a nursery facility, seeding, drifting, and harvesting operations, and assumes the production of renewable diesel through HTL and recovery of nitrogen and phosphorus in the aqueous phase. This study examined the impacts of several emerging technologies on cultivation and conversion costs and emissions, and results conclude that the evaluated technologies in combination with co-product revenue may reduce the minimum fuel selling price to a potential low of \$5.10 GGE^{-1}, and may reduce well-to-wheel emissions to a potential low of 18 g CO_2-eq MJ^{-1}. Furthermore, this work concludes that line dispersion in a free-floating cultivation system is not a major economic risk if maintained below 200 km of distance between incoming lines. The results suggest that the development of a carbon fiber/kelp compatible adhesive may cost more to develop than the economic benefits it would provide to the system (\$0.04 GGE^{-1}). Results from this study strongly suggest that cultivation of macroalgae is economically feasible, and that major losses occur in the conversion process. These findings represent a critical need to develop high volume HTL processes aimed at improving conversion efficiency based on macroalgae feedstock composition, or the development of alternate fuel conversion methods specifically for macroalgae. If the technology evaluated in this study can successfully be integrated in macroalgae to fuel systems, there is great potential to reduce environmental impacts while providing fuel and energy around the globe.

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APPENDIX A. SUPPLEMENTARY INFORMATION

6.1 100: Nursery Facility Modeling

Table 1 – Nursery Facility Energy Consumption Modeling Inputs and Outputs

100: Nursery Facility Energy Requirements and Equipment Costs				
Inputs	Value for 100-A: Adhesive Slurry Facility	Value for 100-B: Traditional Hatchery	Units	Reference & Notes
Air Pumping Energy and Costs				
Cost Air Pump	$200.00	$100.00	$/pump	100-A: Assumes a $100 sale price (includes pipes, air stones, installation) 100-B: Assumes a $200 sale price (includes pipes, air stones, installation)
Pumps per Aquaria	1	1	pumps/aquaria	Assuming the 8 W pump is sufficient for 1000 L, a 4 W pump should be sufficient for a 591 L aquarium
Wattage	8	4	Watts	8 W - Ali Express [41], scaled by 0.5 for 100-A.
Aquaria Volume	1000	591	L	Based on Engineering System Model
Total aquaria	280	3840	aquaria	Based on Engineering System Model
Hours of operation	24	24	hours/day	Assumption
Total Pumps	280	3840	pumps	Calculation
Total Cost	**$56,000.00**	**$384,000.00**	**USD**	Calculation
Daily Energy	**53.76**	**368.64**	**kWh/day**	Calculation
Annual Energy	**5376**	**36864**	**kWh/yr**	Calculation
Artificial Lighting Energy and Costs				
Bulbs per Aquaria	10	4	lights/aquaria	[9]
Bulb Type	4' LED's	4' LED's	N/A	[9]
Cost per bulb	$8.99	$8.99	$/bulb	1000bulbs.com, scaled by factor of 0.6 for bulk pricing
Number of Aquaria	280	3840	Aquaria	Based on Engineering System Model
Bulb Energy Rate	22	22	Watts	1000bulbs.com
Photo period	12	12	hours/day	[9]
Total Bulbs	2800	15360	bulbs	Calculation
Energy/bulb	0.264	0.264	kWh/bulb/day	Calculation
Total Cost	**$25,183.20**	**$138,147.84**	**USD**	Calculation
Daily Energy	**739.2**	**4055.04**	**kWh/day**	Calculation
Annual Energy	**73920**	**405504**	**kWh/yr**	Calculation
HVAC Energy Consumption				
Square footage Facility	11038.4	47176	ft^2	Based on Engineering System Model
Building Electric	100.1	77	kWh/sf/yr	[42]
Building Gas	431	215.5	kBTU/sf/yr	[42]
Total (Electric and Gas)	673	673	kBTU/sf/yr	Calculation

Daily Gas Energy (kBTU)	13034.4	27853.2	kBTU/day	Calculation
Daily Gas Energy (kWh)	3820.0	8163.0	kWh/day	Calculation
Daily Elec. Energy (kWh)	3027.2	9952.2	kWh/day	Calculation
Annual Gas Energy (kBTU)	4757550.4	10166428.0	kBTU/yr	Calculation
Annual Gas Energy (kWh)	**1394301.1**	**2979487.4**	**kWh/yr**	Calculation
Annual Elec. Energy (kWh)	**1104943.8**	**3632552.0**	**kWh/yr**	Calculation
Annual Gas Energy	**5019501.1**	**10726191.5**	**MJ/yr**	Calculation
Total Cost at $0.05/kWh	**$124,962.24**	**$330,601.97**	**USD**	Calculation
Refrigerator Energy Consumption				
Industrial Fridge Vol.	72	72	ft^3	[43]
Capital Cost	2995	2995	$/fridge	[43]
Fridge Amps	10.4	10.4	Amps	[43]
Fridge Volts	120	120	Volts	[43]
Hours of operation	24	24	hours/day	Assumption
Volume Sorus Solution per Day	2.84	24.45	ft^3	Based on Engineering System Model
Fridge Efficiency	0.1	0.1	percent on	Assumption
Refrig. Wattage	1.248	1.248	kW	Calculation
Daily Energy	2.9952	2.9952	kWh/day	Calculation
Number of Refrigerators	1	1	Refrigerators	Calculation
Total Capx	**2995**	**2995**	**$**	**Calculation**
Annual Energy	**299.52**	**299.52**	**kWh/yr**	**Calculation**
Seawater Filtration Energy (Via UV Filtration)				
Seawater Volume	42080.48	1314561.00	L/day	Based on Engineering System Model
Operating Time/day	12	12	hours	Assumption
Seawater Volume	3506.71	109546.75	L/h	Based on Engineering System Model
Seawater Volume	926.47	28942.25	GPH	Based on Engineering System Model
Sanitron S17A	180	360	GPH	[44]
Wattage	18	25	Watts	[44]
Percent on	1	0.95	percentage	Assumption
Cost	875	975	$/unit	[44]
Maintenance kit	100	100	$/yr	[44]
Number of Units Req.	6	81	Units	Calculation
Capx for Units	**$5,250.00**	**$78,975.00**	**$**	Calculation
Maintenance Cost	**$600.00**	**$8,100.00**	**$/yr**	Calculation
Daily Energy	**1.296**	**24.3**	**kWh/day**	Calculation
Annual Energy	**129.6**	**2430**	**kWh/yr**	Calculation
Water Chilling Energy				
Water per Day	280000	2271360	L	Based on Engineering System Model
Water per Day m3	280	2271.36	m3	Based on Engineering System Model
Water per Day kg	287000	2328144	kg	Based on Engineering System Model

Specific Heat	3850	3850	J / kg°C	Conversion
Delta T	10	10	°C	Assumption
Heat Requirement	11049500000	89633544000	J	Calculation
Heat Requirement BTU	10472903	84956196	BTU	Calculation
Volume Flow	11666.67	94640.00	L/h	Calculation
Volume Flow m3/s	0.00	0.03	m3/s	Calculation
Cooling Power	127887.73	1037425.28	Watts	Calculation
Cooling Power kW	127.89	1037.43	kW	Calculation
Refrigerator Tons	36.36	294.97	RT	Calculation
Total Active Aquaria	280	3840	aquaria	Based on Engineering System Model
Desired Temp	18	18	°F	[9]
BTU per Aquaria	NA	22124.01	BTU	[9]
NCS 0402 BTU Rating	335755	335755	BTU	[45]
Wattage	51.7	51.7	kW	[45]
Hours of Operation	24	24	hours/day	Assumption
Cost of Chiller	$48,067.00	$48,067.00	USD	[45]
Chiller Rated Tons	104.6	104.6	ref. tons	[45]
Chiller Run Time/Day	1	1	percent on	Assumption
Adjusted Wattage	51.7	51.7	kW	Calculation
Load (Tons)	36.36	294.97	Refrig. Tons	Based on Engineering System Model
Total Ind. Chillers	1	3	Chillers	Calculation
Total Capx	$48,067.00	$144,201.00	USD	Calculation
Daily Energy	**620.4**	**3722.4**	**kWh/day**	Calculation
Daily Energy (kBTU)	**2116.9**	**12701.35**	**kBTU**	Calculation
Annual Energy	**62040**	**372240**	**kWh/yr**	Calculation
Cost at $0.05/kWh	**$3,102.00**	**$18,612.00**	**$/yr**	Calculation
Seawater Pumping To/From Facility Energy				
Calculated Water Usage	294563.37	3067309.00	L/week	Based on Engineering System Model
Contingency Factor	2.00	3.00	multiplier	Assumption
Actual Water	589126.75	9201927.00	L/week	Based on Engineering System Model
Daily Water Usage	84160.96	1314561.00	L/day	Based on Engineering System Model
Hourly Water Usage	3506.71	54773.38	L/h	24 h/day
Volume Flow Rate	0.00	0.02	m^3/s	Calculation
Distance from Ocean	2500.00	2500.00	m	Assumption (max distance)
Differential head	50.00	50.00	m	Assumption
Fluid Density	1027.00	1027.00	kg/m^3	[46]
Pipe Diameter	0.08	0.25	m	Assumption, 10 in
Pipe Cross-sec. Area	0.01	0.05	m^2	Calculation
Gravity	9.81	9.81	m/s^2	Known Constant
Dynamic Viscosity	0.00	0.00	Ns/m^2	[46]
Water Temp	10.00	10.00	°C	[46]

Velocity	0.17	0.30	m/s	Calculation
Rough Cost Pump	$300.00	$600.00	$/unit	Assumption
Re	10669.55	55551.36	unitless	[47]
Friction factor	0.04	0.04	unitless	[47]
Head loss from friction	6.31	6.33	m	[47]
Pressure Drop from Height	503743.50	503743.50	Pa	[47]
Pressure Drop from Height	503.74	503.74	kPa	[47]
Pressure Drop from Friction	63541.92	63796.10	Pa	[47]
Pressure Drop from Friction	63.54	63.80	kPa	[47]
Total Pressure Drop	567.29	567.54	kPa	[47]
Required Power	0.55	8.64	kW	[47]
Pump Efficiency	0.60	0.60	unitless	[47]
Pumping Power	920.97	14.39	Watts	[47]
Daily Energy	**22.10**	**345.40**	**kWh/day**	Calculation
Annual Energy	**4420.67**	**69080.13**	**kWh/yr**	*2 for both directions
Cost at $0.05/kWh	**$221.03**	**$3,454.01**	**$/yr**	Calculation

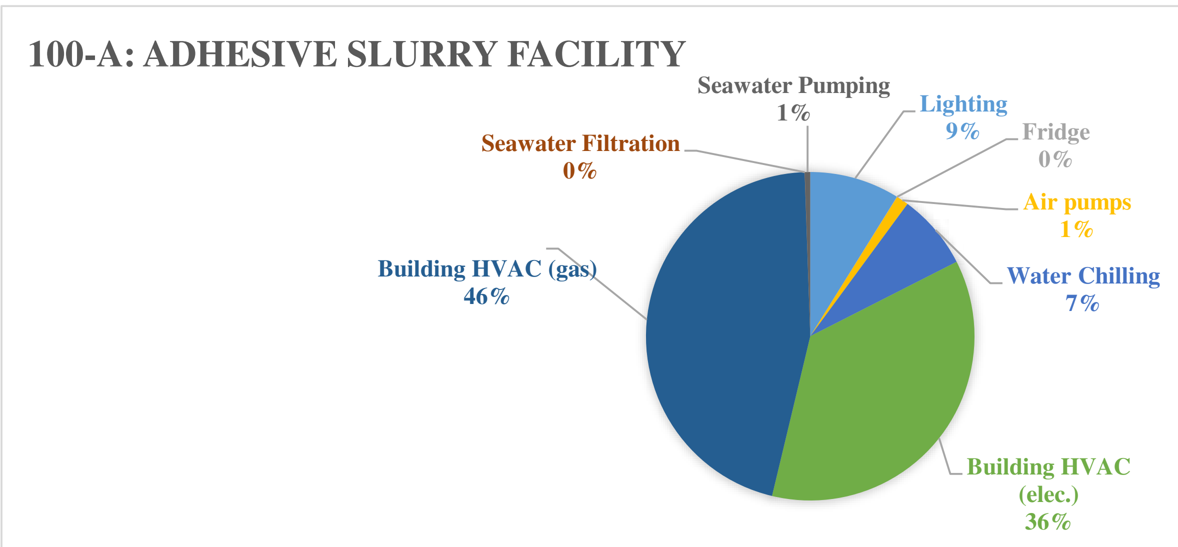

Figure 8. Nursery Facility (Sub-Process 100-A) Energy Consumption Pie Chart

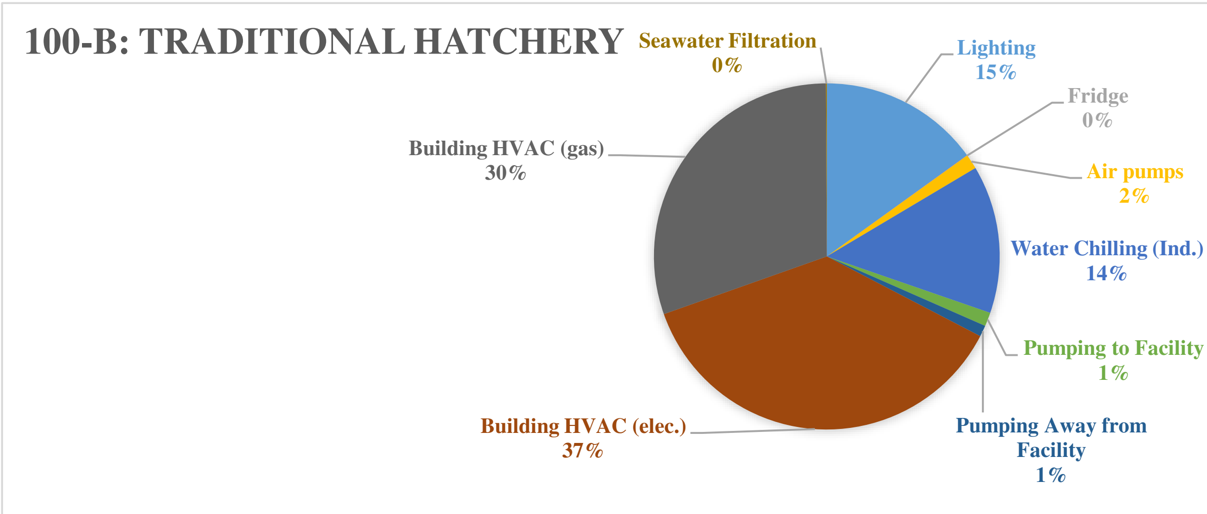

Figure 9. Nursery Facility (Sub-Process 100-B) Energy Consumption Pie Chart

Table 2 – Capital and Operational Costs for Sub-Processes 100-A and 100-B

Capital Costs		
Source	100-A Amount	100-B Amount
Equipment	$530,704	$1,490,622
Land, Const., Infrastructure	$4,450,628.73	$18,486,948.88
Total	**$4,981,333**	**$19,977,571**
Operational Costs		
Source	100-A Amount	100-B Amount
Facility Labor	$139,041.10	$700,000.00
Facility Maintenance	$14,040.26	$115,292.15
Facility Energy	$74,431.43	$374,607.78
Trucks/Transportation	$17,070.82	$35,380.86
Nutrients	$4,819.10	$213,310.93
Kuralon Twine	$180,000.00	$180,000.00
PVC Spools	$959.77	$959.77
Total	**$429,402.70**	**$1,438,591.73**

6.2 200: Open Ocean Seeding Sub-Process Model

Table 3 – Capital and Operational Costs for Sub-Processes 230-A and 230-B

230-A: Vessel Seeding Cap-ex and Op-ex					
Capital Costs			Operational Costs		
Source	$ Amount	Notes	Source	$ Amount	Notes
Seeding Vessels Capx	$4,000,000.00	Assumption (2 Vessels)	Vessel Maintenance	$200,000.00	All vessels, Cost/yr
Seeding Machine	$320,000.00	Assumption (1 per Vessel)	Seeding Machine Maintenance	$8,000.00	All vessels, Cost/yr
Vessel Equipment	$80,000.00	Installation, customization, etc.	Carbon Line Shipping	$472,529.78	Continually shipping
Deck Crane	$25,000.00	[Marine Deck Crane]	Vessel Diesel Cost	$384,345.75	Changes for vessel/drone seeding
Forklift	$15,000.00	[Forklift]	Annual Labor	$161,643.84	All vessels, Cost/yr
Carbon Fiber Lines	$29,372,539.68		Annual Insurance	$120,000.00	All vessels, Cost/yr
Total	**$33,812,539.68**		rCF Line Replacement	$293,725.40	1% lost
			Annual Slip Fees	$33,000.00	
			Total	**$1,673,244.77**	
230-B: Drone Seeding Cap-ex and Op-ex					
Capital Costs			Operational Costs		
Source	$ Amount	Notes	Source	$ Amount	Notes
Seeding Machine	$320,000.00	Assumption	Seeding Machine Maintenance	$8,000.00	All vessels, Cost/yr
Cranes and Machines	$80,000.00	Installation, customization, etc.	Carbon Line Shipping	$472,529.78	Continually shipping
Carbon Fiber Lines	$29,372,539.68		rCF Line Replacement	$293,725.40	1% lost
Drones	$450,000.00	All drones	Drone/Seeding Machine Fuel	$22,118.40	Drone fuel + 20% of vessel diesel for seeding machine
Offshore Anchored Barge	$2,000,000.00	Assumption	Drone Maintenance	$30,000.00	All drones
Total	**$32,222,539.68**		**Total**	**$826,373.58**	

6.3 300: Open Ocean Drift Sub-Process Model

Table 4 – Capital and Operational Costs for Sub-Process 300

300: Open Ocean Drift Cap-ex and Op-ex					
Capital Costs			Operational Costs		
Source	$ Amount	Notes	Source	$ Amount	Notes
Buoys	$63,880,000.00	Smart Buoys and Flotation Buoys	Monitoring Labor	$11,428.57	$20/h, 40 h/week during growing season
Total	**$63,880,000.00**		Buoy Opx	$638,800.00	1% of total capital
			Transmission Cost	$2,880.00	4 transmissions per day per Smart Buoy at $0.08 per
			Total	**$653,108.57**	

6.4 400: Open Ocean Harvesting Sub-Process Model

Table 5 – Capital and Operational Costs for Sub-Processes 410-A and 410-B

400: Open Ocean Harvesting Cap-ex and Op-ex					
Capital Costs			Operational Costs		
Source	$ Amount	Notes	Source	$ Amount	Notes
Vessels Capx	$4,000,000.00	All vessels	Vessel Fuel	$214,500.10	
Harvesting Machine	$1,000,000.00	All vessels	Vessel Insurance	$120,000.00	
Aframax Tender Vessel	$43,000,000.00	Only included for 410-B	Vessel Maintenance	$200,000.00	
Drone Tug Capx	$1,050,000.00	Only included for 410-A	Harv. Machine Maintenance	$25,000.00	
Seaweed Bags	$193,000.00		Annual Labor	$161,643.84	
Deck Crane	$50,000.00		Drone Tug Diesel	$401,882.35	Only included for 410-A
Forklift	$30,000.00		Drone Maintenance	$1,500.00	Only included for 410-A
Total	**$49,323,000.00**		Aframax Fuel	$6,891.24	Only included for 410-B
			Aframax Insurance	$860,000.00	Only included for 410-B
			Aframax Maintenance	$2,150,000.00	Only included for 410-B
			Aframax Labor	$106,849.32	Only included for 410-B
			Annual Slip Fees	$33,000.00	
			Total	**$1,157,526.29**	

6.5 500: Conversion to Fuel and Fertilizer via HTL Sub-Process Model

Table 6 – Kelp Compositional Analysis Data for S. Latissima and N. Leutkeanna

Saccharina latissima		
Average Values from All Sources (% Dry Weight)		
Parameter	Value	Source
C Content	14.10	[4]
N Content	2.99	[4]
P Content	N/A	[4]
% Solids	13.84	[22]
Ash	28.26	[22]
Proteins	9.60	[22]
Carbohydrates	60.24	[22]
Lipids	1.94	[22]
Residue	0.00	[22]
Nereocystis luetkeana		
Average Values from All Sources (% Dry Weight)		
Parameter	Value	Source
C Content	N/A	
N Content	2.05	[20]
P Content	0.33	[20]
Moisture Content	7.14	[20], [23], [37]
Ash	44.23	[20], [21]
Proteins	9.86	[20], [21]
Carbohydrates	38.80	[21]
Lipids	1.90	[21]
Residue	5.21	Calculation
Polyculture Average (Assuming Even Weight of Both Species)		
Average Values from All Sources (% Dry Weight)		
C Content	14.10	Average from above values
N Content	2.52	Average from above values
P Content	0.33	Average from above values
Moisture Content	10.49	Average from above values
Ash	36.24	Average from above values
Proteins	9.73	Average from above values
Carbohydrates	49.52	Average from above values
Lipids	1.92	Average from above values
Residue	2.61	Average from above values

Table 7 – Capital and Operational Costs for Sub-Process 500

Yield: mm GGE per year	4.661487009
Total Cap-Ex	$69,893,370.06
Variable OPX	
Chemicals	$1,537,363.60
Electricity	$347,856.97
Heat	$429,282.11
Total	$2,314,502.68
Fixed OPX	$2,926,650.50
Macroalgae U.S. Tons per Year	77779.06381

6.6 Monte Carlo Analysis

Table 8 – Monte Carlo High-impact Parameter Distributions

Monte Carlo Distributions for High-impact Parameters				
Parameter	Distribution	Max	Mean	Min
Sugar Kelp Yield (kg wet/m longline)	Triangular	62.5	27.93	8
Bull Kelp Yield (kg wet/m longline)	Triangular	22	11	6
Harvesting Rate (km/h)	Triangular	12	8	5
Operational Days per Year (days/year)	Triangular	150	100	70
Biomass Dry Percentage (% solids)	Triangular	13	10	8
Distance to Seeding Location (km)	Triangular	200	100	80
Dispersion Distance (km between 30 km sections of line)	Triangular	200	30	10
Diameter of rCF (inches)	Triangular	0.8	0.6	0.4
Cost of Dumb Buoy ($ USD)	Triangular	150	95	50
Harvesting Hours of Operation (hours/day)	Triangular	24	22	18

Table 9 – Data and Sources Used to Inform Monte Carlo Distributions

Data		
Biomass Yield - Sugar Kelp		
Value	Units	Source
62.5	kg/m	[35]
41.67	kg/m	[35]
31.25	kg/m	[35]
8	kg/m	[48]
29	kg/m	[48]
16.1	kg/m	[36]
10	kg/m	[10]
28.36	kg/m	Mean
19.38	kg/m	Standard Deviation
Biomass Yield - Bull Kelp		

Value	Units	Source
5	kg/m	[37]
22	kg/m	[37]
6	kg/m	Oregon State University Modeling
11.00	kg/m	Mean
9.54	kg/m	Standard Deviation

6.7 Hydrodynamic and Trajectory Modeling

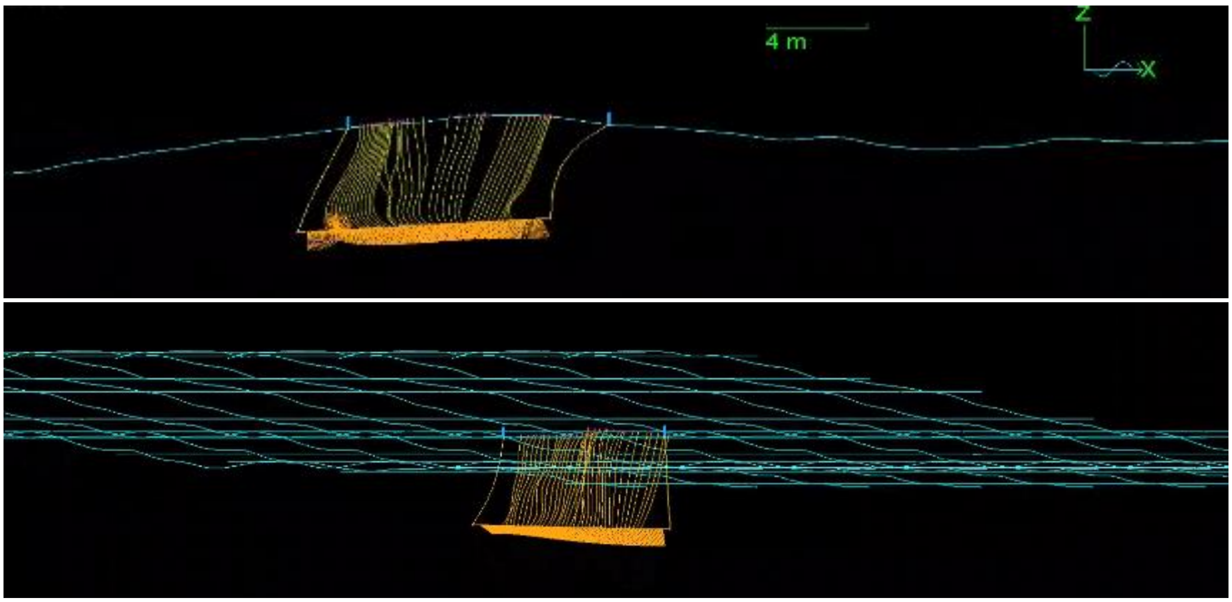

Figure 10. Hydrodynamic Modeling Snap-shots from Oregon State University

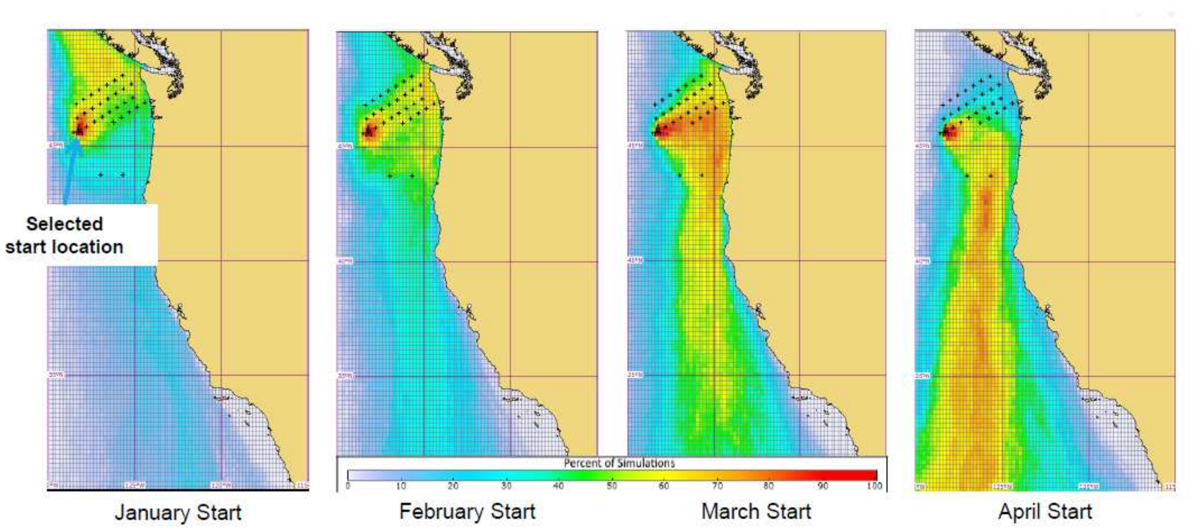

Figure 11. Trajectory Modeling Snap-shots from Pacific Northwest National Laboratory