Flare Gas Recovery for Algal Protein Production

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ABSTRACT

Concern about the sustainable supply of energy and food for future generations has motivated researchers to investigate alternative production pathways. Algal systems represent a promising environmentally favorable production platform for fuel and protein production, however there are many barriers to commercialization, including high energy and intensive fertilizer demands. Meanwhile the volume of flared natural gas around the world has approached 140 billion cubic meters per year. This study investigates the energy return on investment (EROI) of the synergistic integration of flare gas with a microalgae biorefinery. The biorefinery modeled herein includes all sub-processes required for the coincident production of biomass and conversion to biocrude along with a protein-rich feed product. The performance of the biorefinery was estimated by conducting a mass and energy balance for all of the sub-processes. For this design, flare

gas is utilized in a combined heat and power plant to generate heat, electricity, and ammonia for use onsite. Using this method, the baseline EROI is 159, which is higher than conventional energy and food production systems. A life-cycle assessment indicates significant emission reductions with a total well to product emission of $-786 \text{ gCO}_2\text{-eq MJ}^{-1}$. Alternative accounting scenarios and sensitivities are evaluated. Results show the proposed pathway as an opportunity to utilize flare gas for the production of biofuel and protein from algae representing an environmentally beneficial system.

Keywords: Microalgae; Lifecycle Assessment; Feed; EROI; Biofuel; Biorefinery

1. INTRODUCTION

Recent studies demonstrate that global protein demand is projected to increase by more than 100% by 2050 [1, 2]. There are major environmental impacts associated with food production (particularly protein production) and managing these impacts as the population grows is daunting. Research shows that roughly one-third of arable land and up to three-quarters of freshwater is devoted to global food production [3, 4]. Increasing demand from a growing global population highlights the need for the development of alternative protein sources. Agricultural production of algal biomass is a promising candidate to fill the anticipated gap between supply and demand with inherent advantages such as high productivity, suitability for non-arable land, and compatibility with low quality water [5], which are among the largest constraints for traditional crop production [6]. However, despite significant investments from government agencies and private companies [7] energy-efficient, economical, and sustainable production of algal bioproducts has yet to be demonstrated [8].

Primary limitations on algal bioproduct systems are associated with high energy and nutrient consumption in the growth phase, large energy demand for product separation in the harvesting phase, and complications associated with processing and drying wet biomass for end use [8-15]. The barriers to realizing energy efficient production of algal bioproducts include electricity demand (predominantly to supply water and carbon dioxide to the algae facility and to mix the growth volumes), heat requirements (primarily for drying biomass), and energy embedded in nutrient requirements (mainly carbon, nitrogen, and phosphorus) [9].

Meanwhile, significant quantities of natural gas (which is a hydrocarbon co-product of oil extraction) are disposed of every day by flaring (i.e., combustion) at production, distribution, and refining sites. It has been estimated that over 140 billion cubic meters (BCM) per year of natural gas was flared in 2012, representing 3.5% of global production [16]. Flaring occurs when excess gas is produced during oil recovery and economical transportation routes are not available to move the gas to market. In 2014, The United States vented and flared roughly 8.5 BCM (300,000 million cubic feet (mmscf)) of natural gas at oil-and-gas production and processing facilities, which is about 1% of total US extraction [17]. Assuming a heating content of 55 MJ/kg (1033 BTU/cf) and an electricity conversion efficiency of 55%, this amount of gas is sufficient to provide electricity to the entire state of Oregon [18].

Despite the apparent waste, the use of flaring helps manage logistical and safety concerns and reduces the overall environmental impact by converting methane with a global warming potential (GWP) of 29 to carbon dioxide (GWP = 1) [19]. In recent years, up to 30% of produced gas in the Bakken field of North Dakota was flared [20]. Recent studies used satellite instrumentation to observe flare sites around the world [16, 21]. The results revealed thousands of onshore and offshore flare sites associated with production, transportation, refining, and consumption of hydrocarbons. Some of the top flaring countries in the world include Russia, Nigeria, and Iran. As of 2012, the largest flares in the world were located near Punta de Mata, Venezuela with estimated individual flow rates of approximately 1 BCM per year. By comparison, the United States has the largest number of flares of any country, but the vast majority of flare sites burn much less than

0.01 BCM per year (the equivalent of approximately 1 mmscf per day assuming the flare burns continuously throughout the year).

In this study, we propose using flare gas to generate electricity, heat, and nitrogen fertilizer in a novel, integrated pathway to improve the energy efficiency of algal bioproducts (i.e., biocrude and algae meal), increase global protein production, and reduce the negative environmental impacts of oil-and-gas production from flare gas combustion. The integration of algal cultivation systems with flare gas represents a potentially synergistic activity because it would mitigate environmental impacts while producing valuable commodities.

As a proof-of-principle, we use a first-order energy and mass balance approach to evaluate the energetics and life-cycle emissions of the combined system, recognizing that complete techno-economic (TEA) and additional life-cycle analyses (LCA) are needed in future work to fully characterize the feasibility of the proposed system at commercial scale. The energetics of the production system are evaluated with two metrics: 1) the energy return on investment (EROI) [22] and 2) the energy impact of protein-rich algae meal [23]. The life-cycle analysis determines the net greenhouse gas (GHG) carbon dioxide equivalent (CO_2eq) emissions for the proposed system [24]. By utilizing waste flare gas, this study demonstrates the potential to simultaneously improve the EROI for algal biofuels, reduce the energy intensity of protein meal, reduce emissions, and mitigate the deleterious effects of wasted natural gas. Furthermore, this work conducts a direct comparison to previous assessments in the literature, traditional fuels, and traditional crops and livestock products. Discussion includes the potential of the proposed system,

environmental impact of integrating flare gas with algae cultivation, and the impact of energy allocation on results for flare gas and co-product electricity.

2. METHODS

The analysis was completed using an engineering system model that was constructed in a modular fashion with validated sub-process models as shown in Figure 1. Sub-process models – flare gas recovery and conversion, biomass production, and biomass processing – were independently validated and integrated into the engineering system model. A single industrial processing facility is modeled that includes the delivery of flare gas from co-located oil-and-gas operations and used to operate a combined heat and power generation plant (CHP) (i.e., cogeneration), ammonia production system, algae cultivation platform, and algae processing system. This design enables convenient electricity distribution for all sub-systems and facilitates the integration of heat recovery from CHP within one site. Carbon is the limiting resource for most algae systems [9, 25, 26], so the algal cultivation facility was sized to be 10 ha to accommodate all of the carbon dioxide produced from a flare site with a gas flow rate of 2,050 m³/day (72,000 scfd). Volumetric flow rates at individual domestic flare sites can vary widely from less than 3 m³/day (100 scfd) to more than 28,000 m³/day (1,000,000 scfd) [20, 27, 28]. Volumetric flow rates at international flare sites can exceed 270,000 m³/day (9,540,000 scfd) [16]. The flare gas flow rate was chosen to represent a single moderately sized flare site or the combination of multiple smaller flare sources that can provide a dependable supply of flare gas.

A summary of the critical input parameters for the integrated model are presented in Table 1 with details on each of the sub-process models presented in the following

sections. The engineering system model was used in conjunction with life cycle inventory data to evaluate the environmental impact of the proposed process on the metric of greenhouse gas emissions.

Table 1. Primary model parameters.

	Amount	Unit	Reference
<u>Flare Gas Recovery</u>			
Volumetric Flow Rate of Flare Gas	2,050	m ³ /d	[20, 27, 28]
Flare Gas Density	0.70	kg/m ³	[28, 29]
Flare Gas Higher Heating Value	55.0	MJ/kg	[28, 29]
Flare Gas Specific Heat Capacity	2.22	kJ/kg-K	[28, 29]
Compression Ratio	1.67	-	Assumed
Compressor Efficiency	0.85	-	[30]
<u>Combined Heat and Power</u>			
Electricity Production Efficiency	44%	-	[31, 32]
Heat Exchange Fluid Flow Rate	0.90	kg/s	Calculated
Heat Transfer Pumping Energy	81.8	MJ/d	Calculated
Useful Heat Production Efficiency	43%	-	[31, 32]
Heat Recovery Efficiency	90%	-	[31, 32]
(Net) Heat Recovery Efficiency	38%	-	Calculated
Overall Plant Efficiency	82%	-	Calculated
Flue Gas Carbon Dioxide Content	5%	% wt.	[33]
Flue Gas Specific Heat Cap.	0.85	kJ/kg-K	[33]
Compression Ratio	2.50	-	Assumed
Compressor Efficiency	0.85	-	[30]
<u>Ammonia Production</u>			
Electricity Input	0.70	MJ/kg ammonia	[34, 35]
Heat Input	12.6	MJ/kg ammonia	[34, 35]
Water Consumption	1.20	kg/kg ammonia	[34, 35]
Flare Gas Demand	0.45	kg/kg ammonia	[34, 35]
Air Input	1.80	kg/kg ammonia	[34, 35]
Carbon Dioxide Generated	1.18	kg/kg ammonia	[34, 35]
Flue Gas Carbon Dioxide Content	100%	% wt.	[34, 35]
Flue Gas Specific Heat Cap.	0.85	kJ/kg-K	[29]
Compression Ratio	2.50	-	Assumed
Compressor Efficiency	0.85	-	[30]
<u>Algae Cultivation</u>			
Algae Facility Size	10.0	ha	Assumed
Fraction of Facility for Cultivation	0.80	-	[9, 10, 14, 15, 36]

Cultivation Surface Area	8.0	ha	Calculated
Pond Volume	16,000,000	L	Calculated
Mixing Energy Demand	109	kWh/ha-d	Calculated
Daily Harvest Volume	3,200,000	L/d	Calculated
Saline Make-up Water	1,207,00	L/d	Calculated
Water Supply Energy	20.0	kWh/ha-d	Calculated
C:N:P	106:16:1	-	[37, 38]
Productivity	20.0	g AFDW/m ² -d	[8, 14, 36, 38]
Lipid Fraction	0.25	kg lipid/kg AFDW	[8, 14, 36, 38]
Protein Fraction	0.40	kg protein/kg AFDW	[8, 14, 36, 38]
<u>Algae Harvesting</u>			
Overall Harvesting Efficiency	0.77	-	[9, 10, 14, 15, 36]
Pumping Electricity	0.22	kJ/kg algae	Calculated
DAF Electricity	431	kJ/kg algae	[10, 15]
Centrifuge Electricity	107	kJ/kg algae	[10, 15]
Water Recycling	27.4	kJ/kg algae	Calculated
Water Discharge	84.5	kJ/kg algae	Calculated
<u>Bioproduct Separations</u>			
Drying Heat	7.20	MJ/kg algae	Calculated
Electricity Consumption	79.9	kJ/kg algae	Calculated
Extraction Heat Consumption	864	kJ/kg algae	Calculated
Solvent Consumption	1.22	g/kg algae	[15]
Biocrude Recovery	0.23	kg biocrude/kg algae	[14]
Lipid-extracted Biomass Recovery	0.77	kg LEA/kg algae	[14]

Figure 1. Baseline process flow diagram for utilizing flare gas to produce protein from algae

2.1 Flare Gas Recovery

For the proposed system, repurposed flare gas could be sourced for a single processing facility from multiple nearby wells to ensure a steady supply considering that the flow rates of individual wells vary. The flare gas could also be sourced from a single large facility such as a refinery or an offshore rig. The CHP plant is co-located with the oil-and-gas operations and we assume the flare gas (with chemical properties of methane) is compressed isentropically for transport to the CHP plant, requiring approximately 95 kJ/kg of gas [30]. The specific pipeline system required for an algae production facility depends on the nearby sources of flare gas and therefore varies for each site. The high density of dependable flare sites in countries such as Nigeria presents an opportunity to minimize pipelines for gas gathering. There are hundreds of potential flare gas sources in the United States, Nigeria, Venezuela, the Middle East, and elsewhere that could be

integrated with algae production by meeting the volumetric flow rate needs described in this study [16, 21].

2.2 Combined Heat and Power (Cogeneration)

The CHP plant has a reciprocating engine and the waste heat is captured with a two-phase water heat exchanger, allowing for 87% conversion to electricity and heat (i.e., 44% useable electrical energy and 43% useable thermal energy) [31, 32]. Thermal energy is transported through steam pipelines and the process water is recycled. The steam pipeline has an isothermal energy loss of 10%, which, when combined with imperfect heat exchange yields an overall heat recovery of 38%. Energy required for circulating water for heat transfer is minor (415 kPa pressure drop, 1.5 safety factor, and a pump efficiency of 60%). Accounting for the water circulation energy and the thermal losses, the overall system efficiency is 82% (44% of outgoing energy is electrical and 38% is thermal, with the balance as waste heat). The CHP plant has an electrical and thermal output capacity of 0.40 MW and 0.39 MW, respectively. The flue gas produced from CHP is collected and transported to the algae ponds assuming isentropic compression requiring 68 kJ/kg-gas [30].

2.3 Ammonia Production

Ammonia production is based on the catalytic reaction of hydrogen and nitrogen (commonly referred to as the Haber-Bosch process and used worldwide) as described by Jiménez-González et al. [35], which compares closely with the process described by

Lawrence Berkeley National Laboratory [34]. Inputs required for ammonia production include air, methane (in this case, flare gas), water, electricity, and heat. In addition to ammonia, the process generates high purity carbon dioxide. The ammonia plant was sized to provide sufficient nitrogen fertilizer for algae cultivation. The carbon dioxide generated during ammonia production is captured and used for cultivation requiring 89 kJ/kg gas [30]. The energy requirements for the ammonia production facility were accounted for in the sizing of the CHP facility.

2.4 Algae Cultivation

For this proof-of-principle study, an algae production model was developed relying on the authors' prior experience with algae cultivation [38-42], leveraging prior models that contain much greater complexity [9, 10, 15, 43, 44] and other highly-cited models in the literature [12-14, 45]. Appendix A presents a detailed mass balance of elements (carbon, nitrogen, and phosphorus) and biomass components (lipid, protein, carbohydrates, chlorophyll, and ash) from cultivation through harvesting and lipid extraction.

Algae are produced in open raceway ponds and the modeled facility is 10 hectares with a 0.8 packing factor to account for infrastructure. The culture is modeled as a monoculture of *Desmodesmus sp.* There are eight 1-ha ponds based on the design by Beal et al. [9] operated at a depth of 0.2 m with a bulk velocity of 0.35 m/s delivered through a circulation device with 25% efficiency. Assuming a manning coefficient of 0.01 yields 0.16 m head loss (ΔP) for circulation according to the following equation provided by Lundquist et al. [14],

$$\Delta P = \Delta P_c + \Delta P_b + \Delta P_s$$

to include head loss in the channels (c), bends (b), and sump (s). The channel head loss, ΔP_c , is calculated as the product of channel length (L) and the head loss per unit length (S),

$$\Delta P_c = L \cdot S = L \cdot \frac{(n^2 \cdot V^2)}{R_h^{\frac{4}{3}}} \quad [m]$$

where n is the Manning coefficient, V is the bulk flow velocity, and R_h is the hydraulic radius [46]. Head loss in the bends (ΔP_b) and in the sump (ΔP_s) are estimated using the following equation,

$$\Delta P = \frac{C \cdot V^2}{2 \cdot g} \quad [m]$$

where C is the loss coefficient for the bends (4) or the sump (4). Under these conditions, required mixing power is 109 kWh/ha-d.

The annual average productivity of the system (20 g/m²-d) is based on locating the facility in southwest Texas [12, 47, 48] and more conservative than the results published in recent experimental and modeling studies [10, 36, 38]. One fifth of the volume is harvested daily at an algal concentration of 0.5 g/L corresponding to a nitrogen depletion growth period. Nutrient inputs are based on the Redfield ratio (C:N:P = 106:16:1) and carbon is delivered through a sump system with an assumed CO₂ uptake efficiency of 75%, which is on the conservative side of values in the literature (85% Quinn et al. [15], 79% Beal et al. [9], 75% Lundquist et al. [14], 95% Davis et al. [45]). Nitrogen and phosphorus are assumed to be utilized by the algae with a 90% efficiency (based on values in the literature of 95% Quinn et al. [15], 100% Beal et al. [9], 95% Lundquist et al. [14], 80% Davis et al. [45]); the 10% loss is attributed to non-algal organisms such as

bacteria and minor outgassing. Nitrogen is supplied from the co-located ammonium plant and phosphorous is purchased as diammonium phosphate (DAP) [9, 45]. Culture water is supplied from a saline well and recycled five times (after being recovered as supernatant during harvesting, described below) and eventually returned to the reservoir. Evaporation is modeled at 2.8% of the culture volume per day based on Beal et al. [9] (compared to literature sources of 0.9% [15], 1.8% Lundquist et al. [14], 0.4% Davis et al. [45]). Thus, roughly 1.2 million liters of new culture water are required each day for makeup. Water supply energy is modeled as pumping with 283 kPa of head and 60% pump efficiency based on the water acquisition system design in Beal et al. [9].

2.5 Harvesting

The dewatering processes is based on a three-stage system described by Bennion et al. [10] and Quinn et al. [15]. Alternative harvesting methods exist, but have not been validated as thoroughly. For instance, several studies model the use of a filter press for dewatering [9], but it is unclear how effective a filter press will be with microalgae. Other new technologies include membrane separation [45], but experimental data has yet to be provided publicly. Pumping to and through the harvesting process is approximated with a combined head loss of 14.9 kPa and 60% pump efficiency (authors' estimates), consuming 25 J per L processed. The primary harvesting stage is a passive bioflocculation settling step assumed to generate a maximum density of 10 g/L. Bioflocculation has been demonstrated at scale for *Desmodesmus sp.* [38]. The second stage is dissolved air flotation (DAF) that further dewateres the microalgae to 100 g/L, while consuming 0.48 MJ per kg of algae processed [10, 15]. The final dewatering stage

is a continuous clarifier (centrifuge) to remove the free water taking the system to 200 g/L, or 20% solids based on the use of an Alfa Laval machine [10, 15]. The centrifuge requires 11.8 kJ per L processed. The harvest efficiencies of the settling, DAF, and centrifuge are assumed to be 90%, 90%, and 95%, respectively. Water recycling (~2.4 million L per day) and water discharge (~0.8 million L per day) are modeled as pumping through 10 kPa and 100 kPa of head loss, respectively, with 60% pump efficiency (authors' estimates) – thereby requiring 17 J/L and 167 J/L, respectively.

2.6 Lipid Recovery and Conversion

A variety of technologies exist for the recovery and conversion of lipids or the production of biocrude and upgrading to a fuel product [8, 11, 49]. This work assumes the lipids are separated using a solvent extraction process that is analogous to soy oil extraction that yields a protein-rich algae meal co-product, similar to soy meal [14, 38, 50]. Under normal conditions, biomass drying incurs massive energetic penalties and, as a result, the field of algal biofuels has almost entirely focused on wet extraction processes. However, due to the unique synergistic configuration proposed in this study, a surplus of heat generated by CHP can be used to dry the biomass at no energetic cost. Thus, we model drying the biomass from 20% solids to 80% solids using waste heat from CHP followed by hexane oil extraction based on the Crown IronWorks Company process described by Lundquist et al. [14]. Solvent consumption was estimated from Quinn et al. [15] for a similar process. The extraction process consumes 80 kJ of electricity, 860 kJ of heat, and 1.2 g of solvent per kg of algae processed and recovers 95% of the lipid contained in the biomass, which represents a biocrude product. The marginal remainder of the lipid is

retained in the biomass and we assume all of the biomass is recovered as a lipid-extracted algae (LEA) product with 52% protein content (AFDW) suitable for inclusion in animal feed products. The high protein content makes the LEA product an appealing substitute for soymeal and fishmeal in livestock feed and aquafeeds.

2.7 Energy Return on Investment

Energy analysis is based on the EROI, defined as the total energy output divided by the total energy input [22]. An EROI greater than 1 is desirable. The energy impacts of material and energy flows include embodied (upstream) energy associated with production and the chemical energy contained in that product. Inventory data (listed in Table 2) were collected from GREET [51] and supplemented with values from literature as needed. Co-products were assigned displacement credits according to the avoidance of conventional biocrude, animal feed, and electricity production. Estimates from Beal et al. [9] were used for the algae meal displacement credit: 3.6 MJ of non-renewable energy per kg of algae meal and 25.1 MJ of total energy per kg of algae meal. These estimates are based on the replacement by algae meal of a composite animal feed consisting of 75% soy meal and 25% corn meal [9].

2.8 Energy Impact of Protein Meal

The energy impact of animal feed ingredients quantifies the amount of energy required to produce feed components, such as corn, soy meal, fishmeal, or algae meal. Analogous to the energy impact of a fuel, this metric contains two components: embedded energy

(which includes the energy resources consumed to produce the feed product) and chemical energy content (which is the higher heating value or caloric value of the feed itself). For the EROI analysis described above, the energy impact of algae meal was assigned based on the assumed displacement of corn and soy meal. In contrast, here, we calculate the energy impact of producing algae meal by allocating the net energy input to the integrated system among all three co-products (biocrude, algae meal, and electricity when applicable) on an energy-weighted basis. For allocation, the chemical energy content of the output products are assumed to be: 42 MJ/kg for biocrude, 21.5 MJ/kg for algae meal [9, 44, 52] and 1 MJ/MJ for electricity.

2.9 System Boundary and Accounting Scenarios

The system boundary is shown in Figure 1 and includes all of the sub-processing systems outlined. The baseline analysis treats the flare gas as a waste stream with no energy value. The baseline model also assumes excess electricity can be delivered as a co-product to the market, but assigns no value for excess heat generated. Sensitivity to these assumptions are assessed by calculating the energy and environmental impacts for three alternative scenarios: Case II) excluding the energy value of excess electricity as a co-product, Case III) assigning the HHV of methane as the energy impact of flare gas (rather than assuming it to be 0), and Case IV) excluding the electricity co-product *and* assigning the HHV of methane to be the flare gas energy impact.

2.10 Life Cycle Assessment

The environmental impact of the process was assessed through a life cycle assessment of greenhouse gas emissions. The engineering system model was used as the foundation for the analysis. Energy and mass results were coupled with life cycle inventory data to evaluate the environmental impact of the scenarios outlined above. The environmental impact of the system was evaluated based on a total global warming potential. The IPCC 100 year global warming equivalency factors for carbon dioxide, methane and di-nitrogen oxide, 1, 25, and 298, respectively, were used to determine the total equivalent carbon dioxide emission for each of the scenarios outlined. Compounds contributing minor emissions from CHP (e.g., ammonia, formaldehyde, etc.) were neglected [32]. The functional unit of this study was defined as 1 MJ of fuel for comparative purposes to other studies. Life cycle inventory data for energy and the various materials consumed in the process were sourced from GREET, NREL LCI database [51, 53], and literature. Specifically, these impacts are: 0 gCO_{2-eq} kg⁻¹ for water, 2,681 gCO_{2-eq} kg⁻¹ for ammonia, 40 gCO_{2-eq} kg⁻¹ for DAP, 942 gCO_{2-eq} kg⁻¹ for hexane, and 47 gCO_{2-eq} MJ⁻¹ for heat. The system modeled has multiple products (fuel, electricity, protein, and heat) requiring an allocation of the total emissions. The excess heat produced in the system is not included as a product for life cycle accounting as it cannot realistically be exported. For the remaining products – fuel, electricity, and protein – a displacement allocation method is used. The excess electricity is assumed to displace grid electricity with an environmental impact of 700 gCO_{2-eq} kWh⁻¹. The protein feed is assumed to displace animal feed ingredients with an environmental impact of 2,000 gCO_{2-eq} kg⁻¹ [54]. Using algal biomass as a feed ingredient is an area of recent interest and widespread research [9, 55-58]. Currently it is unclear which animal feed ingredients can be replaced by algal

biomass. Further research is needed in this field to determine more specific values for the displacement credit for algal biomass as a substitute for cornmeal, soymeal, fishmeal, and possibly human food. Due to this ambiguity, the animal feed displacement credit was selected as a generic credit for substitution as an animal feed ingredient based on data by González et al. [54] and evaluated with sensitivity analysis. A biogenic carbon credit associated with the utilization of atmospheric carbon dioxide for algal growth is included. The system boundary for the process, as defined above, represents a well to product system boundary and does not include the transportation and distribution of the fuel or the emissions associated with the use (e.g., combustion) of the output products.

The environmental impact of four scenarios are evaluated based on the scenarios defined for the EROI analysis. Case I allocated the emissions of the flare gas combustion to the oil and gas industry and exports the excess electricity. Case II assumes the excess electricity cannot be exported. Case III assumes flare gas is being procured for the system and includes emissions for the carbon contained in the natural gas to satisfy the needs of the CHP plant. This scenario includes the exporting of the excess electricity. Case IV includes the purchasing of flare gas and assumes the excess electricity cannot be exported. All scenarios produce excess heat that is assumed to be rejected.

3. RESULTS

The input and output flows for the integrated model along with the associated energy impacts for those flows based on the system boundary shown in Figure 1 are presented in Table 2. A summary of the EROI and life cycle emission results for the four cases considered in this study is presented in Table 3.

Table 2. Input (red) and output (black) flows for the unit operations shown in Figure 1. Individual Flow Impacts are associated with each material or energy flow, but the overall system is characterized according to “System Boundary Impacts,” which only include flows that cross the system boundary (Figure 1). ¹ Case II and Case IV assume no electricity is produced as a co-product. ² Case III and Case IV assign 55 MJ/kg as the energy impact for flare gas, resulting in 115,500 MJ/d of additional energy input. ³ All energy impacts were obtained from Argonne National Laboratory GREET model [51] except for the algae meal, which is from Beal et al. [9].

	<u>Amount</u> (X)	<u>Units</u> (X/d)	<u>Energy</u> <u>Impact</u> ³ (MJ/X)	<u>Individual</u> <u>Flow</u> <u>Impacts</u> (MJ/d)	<u>System</u> <u>Boundary</u> <u>Impacts</u> (MJ/d)
<u>Combined Heat and Power</u>					
(Flare Gas)	1,435	kg/d	0.00	0	0 ²
(Flare Gas Transport to CHP)	136	MJ/d	2.34	318	-
(Heat Exchanger Pumping)	82	MJ/d	2.34	191	-
Electricity Generation	34,727	MJ/d	2.34	81,296	-
Heat Generation	29,986	MJ/d	1.18	35,263	-
Carbon Dioxide Produced	3,749	kg/d	0.00	0	-
<u>Ammonia Production</u>					
(Flare Gas)	69	kg/d	0.00	0	0
(Air)	276	kg/d	0.00	0	0
(Water)	184	kg/d	0.01	2	2
(Electricity)	108	MJ/d	2.34	252	-
(Heat)	1,930	MJ/d	1.18	2,270	-
Ammonia Produced	154	kg/d	38.72	5,951	-
Carbon Dioxide Produced	181	kg/d	0.00	0	-
<u>Cultivation</u>					
(Carbon Transport)	5,127	MJ/d	2.34	12,002	-
(Saline Water Supply)	569	MJ/d	2.34	1,332	-
(Circulation)	3,139	MJ/d	2.34	7,349	-
(Carbon Dioxide)	3,911	kg/d	0.00	0	-
(Ammonia)	154	kg/d	38.72	5,951	-
(DAP)	36	kg/d	16.38	587	587
<u>Harvesting</u>					
(Harvesting Processes)	798	MJ/d	2.34	1,867	-
(Water Recycling)	41	MJ/d	2.34	95	-
(Discharge Water Pumping)	125	MJ/d	2.34	294	-
<u>Separations</u>					
(Drying Heat)	9,126	MJ/d	1.18	10,732	-
(Electricity)	101	MJ/d	2.34	237	-

(Process Heat)	1,095	MJ/d	1.18	1,288	-
(Hexane)	2	kg/d	16.38	25	25
Biocrude	292	kg/d	54.49	15,919	15,919
Algae Meal	976	kg/d	25.08	24,478	24,478
<u>Net System Excesses</u>					
Carbon Dioxide	19	kg/d	0.00	0	0
Ammonia	0	kg/d	38.72	0	0
Net Electricity Yield	24,501	MJ/d	2.34	57,358	57,358 ¹
Net Heat Yield	17,834	MJ/d	0.00	0	0

Table 3. Results for Cases I-IV. ¹The algae meal is 52% protein.

	Case I	Case II	Case III	Case IV
Biocrude Yield (kg/d)	292	292	292	292
Algae Meal Yield (kg/d)	976	976	976	976
Electricity Yield (MJ/d)	24,501	24,501	24,501	24,501
Excess Electricity Use	Grid	None	Grid	None
Flare Gas Energy Penalty (MJ/kg)	0	0	55	55
Flare Gas Emissions (kgCO _{2-eq} /kg)	0	0	2.7	2.7
Energy Input (MJ/d)	614	614	83,309	83,309
Energy Output (MJ/d)	97,755	40,397	97,755	40,397
Emissions (kgCO _{2-eq} /d)	3	3	4,138	4,138
Displacement Credits (kgCO _{2-eq} /d)	-6,720	-1,952	-6,720	-1,952
Biogenic Credits (kgCO _{2-eq} /d)	-2,933	-2,933	-2,933	-2,933
EROI	159.2	65.8	1.2	0.5
Energy Impact Algae Meal (MJ/kg)	0.23	0.40	31.0	53.9
Energy Impact Protein ¹ (MJ/kg protein)	0.44	0.76	59.1	102.7
Greenhouse Gas Emissions (gCO _{2-eq} /MJ)	-786	-398	-450	-61

3.1 Energy Return on Investment

The EROI for Case I is the highest EROI ever reported for an algal energy production system [8, 59] due to the convenient use of flare gas to power the system and the discounted value of the gas because of its status as a waste stream. The large return on investment highlights the potential benefit to society that this system could provide. For

instance, as shown in Figure 2, the EROI for Case I exceeds that for all fossil fuels *and* all conventional crop production systems.

Energy Return on Investment

Figure 2. EROI for various fuels and crops including results from this study. Data are from: Beal et al. [9], Quinn et al. [15], De Vries and De Boer [23], Beal et al. [26], Batan et al. [43], Argonne National Laboratory [51], Carlsson-Kanyama et al. [60], Pelletier [61], United States Department of Agriculture [62], Shapouri et al. [63], Field and Taylor [64], Gupta and Hall [65], Kubiszewski et al. [66], Cleveland [67], Kubiszewski et al. [68], King [69], Cleveland [70]

The large return on investment of Case I is afforded due to the investment that was undertaken during oil-and-gas production that generated the flare gas; namely, the investments of energy and capital count as inputs to the oil-and-gas system rather than the algal production system. Widespread deployment of the proposed algae systems would likely require reconsidering the system boundaries to include the entire oil-and-gas operation in addition to the algae production system, thereby generating an overall EROI for the integrated oil-and-gas-and-algae facility. For instance, the energy and emissions

associated with establishing the oil-and-gas facilities would then be allocated among all process outputs, including algae. Such an integrated EROI is expected to be lower, though still relatively high.

Removing the electricity co-product from the system (Case II), which might apply if the algae facility could not be connected to the grid, reduces the EROI significantly.

However, the EROI for Case II is still higher than any other algae production models [8, 59]. When the energy impact of flare gas is implemented (Case III) the EROI is reduced considerably near unity. Lastly, if the electricity co-product is removed and the energy value of the flare gas is included, representing the most conservative evaluation, (Case IV) the EROI further is decreased below unity. These latter scenarios are comparable to typical algal biofuel analyses that incur negative impacts associated with market electricity and heat consumption. As expected, the large heat requirements for drying the algal biomass are detrimental to the EROI. For Case IV, where the chemical energy in flare gas is counted *and* electricity is excluded as a co-product, the EROI drops below unity, indicating that more energy is consumed by the system than produced. The accounting of flare gas for these systems is challenging, as the current mode of operation is flaring the gas, rendering the gas as a zero-value waste product. The sensitivity of model results through the various scenarios illustrates the importance of understanding the inputs and products for the system.

3.2 Energy Impact of Protein-Rich Animal Feed

The energy required to produce a variety of food products has been reported by numerous researchers and the results for Case I and Case II from this study are among the lowest

energy inputs of any products reported, including fruits, vegetables, cereals, meat, and dairy products, some of which are compared in Figure 3 [23, 60, 61, 71-73]. As for the promising EROI results for these cases, the low energy impact results can be attributed to omitting the energy content of flare gas from the system accounting for these cases. This accounting standard is consistent for how waste streams are treated in lifecycle analysis. Still, these results demonstrate that the proposed system in this study could produce food products in an energetically favorable way utilizing a waste stream, low quality land, and saline water.

Figure 3. Energy impact of various food products per kg and per kg of protein. (Impact per kg protein not shown for products with very low protein content.) Data is sourced from: Beal et al. [9], De Vries and De Boer [23], Carlsson-Kanyama et al. [60], Pelletier [61], Field and Taylor [64], Frorip et al. [72], Williams et al. [73]

The results of this study are favorable when compared to previous studies. Using data from the recent study by Beal et al. [9], the energy impact of algae meal produced in that system can be estimated to be 26 MJ/kg (Case 8T), which is roughly 10 times that of corn, 7 times that of soy, and 3 times that of fishmeal [61]. The energy inputs in the system described by Beal et al. [9] are mostly associated with water supply and circulation energy (the carbon source for that study was 94% pure and nearby, thus reducing carbon-related inputs). Meanwhile, utilizing waste flare gas enables algae meal production for Case I (0.2 MJ/kg) and Case II (0.4 MJ/kg) at fractions of the energy required for corn, soy, and fishmeal, which are directly comparable animal feed ingredients [55, 56, 58, 74]. The protein quality of algae meal is comparable to soy meal, with potential advantages associated with desirable omega-3 fatty acids. Furthermore, the algae meal produced in Case I (0.4 MJ/kg protein) and Case II (0.8 MJ/kg protein) greatly outperforms other protein sources such as soy meal (8 MJ/kg protein), milk (91 MJ/kg protein), eggs (97 MJ/kg protein), and meats, including beef (225 MJ/kg protein) [23, 72].

However, when the energy content of the flare gas used to power the system is included, the energy impact of algae meal increases for Cases III and IV to 31 and 54, respectively, and no longer is competitive with corn, soy, and fishmeal. As expected, the results are also worse than the algae meal reported by Beal et al. [9] (Case 8T) that did not require complete algae drying. Cases III and IV compare more closely with the energy impact of meat production (pork, chicken, and beef) than that of crops.

Protein has the potential to be a limited resource due to global population increase and the finite agricultural land available for traditional protein production. The proposed

process represents an alternative production pathway that does not directly compete for valuable agricultural land or fresh water. The promising EROI for protein production is achieved through the direct integration with an energy dense waste stream from the oil and gas industry. The proposed process has the potential to be an alternative production pathway for protein with economic assessment required to critically assess the commercial viability.

3.3 Environmental Impact

The environmental impact of the system was evaluated for the various cases with results presented in Table 3 and Figure 4. In all of the scenarios, the environmental impact of the system benefits from microalgae utilizing waste carbon dioxide. Case I represents the most environmentally favorable scenario as expected. The results from this scenario are an order of magnitude more beneficial than the most beneficial value reported in literature for algal biofuel production [8]. The favorable results are due to receiving flare gas as a waste product and allocating the associated emissions to the oil and gas industry. The flare gas, if not utilized by the proposed system, is burned and released to the atmosphere. The system utilizes the flare gas to generate valuable products that are not only used in the microalgae biorefinery but exported as co-products. Specifically electricity and protein rich animal feed represent environmentally impactful co-products. The excess electricity that was produced without carbon emissions in Case I displaces grid electricity resulting in a significant environmental credit. Results for Case II illustrate the impact of eliminating the excess electricity as a co-product. However, the environmental impact is still a factor of four better than any other study. Case III

assumes the methane fuel is not a waste product (and is therefore treated as procured natural gas rather than flare gas) and emissions associated with carbon contained in the natural gas are integrated in the analysis. The promising environmental impact for Case III is dominated by the co-product credit associated with excess electricity production. Results from Case IV represent purchasing methane for the system (rather than assuming a waste product in flare gas) and exclude the excess electrical energy exports. The vast differences in results for Cases I-IV indicate the sensitivity of life-cycle assessments to the associated accounting methods for repurposing a waste stream.

Co-product displacement emissions dramatically impact the results from this study. The displacement method represents the standard allocation method for biofuel systems [24]. Alternatively, an energy allocation method was also evaluated for all cases resulting in the following net CO₂eq emissions for Cases I-IV, respectively: -51, -88, 21, and 36 g CO₂eq/MJ. For this accounting method, the net emissions from the facility (total emissions less net biogenic carbon uptake into the biomass) are allocated based on the energy content of the products included in each case: biocrude, animal feed, and when applicable, electricity. The different accounting methods generated notably different results, once again indicating the importance of accounting assumptions in life-cycle assessment. Environmental impact results, independent of allocation method, for the integration of flare gas with algae cultivation illustrate a synergistic relationship.

GHG Emissions (g CO₂eq/MJ)

Figure 4. GHG impact of various fuels per MJ of energy output based on the displacement accounting method [51].

3.5 Sensitivity Analysis

Sensitivity analysis was used to understand model inputs that dramatically impact results. Figure 5 presents the sensitivity analyses for the EROI, energy impact of algae meal, and greenhouse gas emissions for Cases I and III. All parameters evaluated with sensitivity and shown in Figure 5 were varied by +/- 20% with respect to the baseline values listed in Table 1 unless otherwise noted. The largest impact to the EROI is associated with variations in the assumed HHV for flare gas (Case III only), followed by assigning a non-renewable energy impact to the algae meal displacement credit (3.5 MJ/kg, rather than

the total energy impact of 25 MJ/kg [9]), which reduced the EROI for Cases I and III by over 20% each. As expected, both cases are strongly dependent on the HHV of flare gas and the electricity generation efficiency, indicating the importance of selling excess electricity in these cases (see Cases II and IV for comparison with results without credit for excess electricity). Surprisingly, an increase in the biomass productivity negatively impacts results for Case I due to increased DAP consumption (which is 95% of the energy input at the system boundary). Conversely, a 20% increase in productivity triggers over 5% improvement of the EROI for Case III because the energy inputs are dominated by the flare gas energy content and increased yield increases meal and biocrude production, which directly impact the functional units of the system. Due to the dependence of Case I on DAP consumption, the nutrient uptake efficiency also has a large impact, where reducing the phosphorus uptake efficiency to 75% results in over 15% reduction of EROI and a nearly 20% adverse impact in the algae meal energy impact. Sensitivity results for the GHG emissions are highly dependent on the oil yield (i.e., the denominator of $\text{g CO}_2\text{eq/MJ}$) and the allocation of emissions to end products, as large displacements for LEA and electricity skew results in a non-intuitive direction. The model shows relatively little sensitivity to the other algae production parameters and zero sensitivity to 20% variations in heat recovery efficiency due to the large excess in heat produced by CHP.

Figure 5. Sensitivity analysis results for the EROI, algae meal energy impact, and greenhouse gas emissions. Results are shown as percent change. All parameters were varied by +/- 20% except where noted. ¹ Favorable C:N:P uptake rates are 0.9:0.95:0.95, while unfavorable rates are 0.5:0.75:0.75. ² Favorable biocrude recovery is 100%; unfavorable is 75%. ³ Baseline LEA biomass recovery efficiency is 100% so there is no favorable value; unfavorable value is 80%. ⁴ Total (25.08 MJ/kg) and non-renewable (3.5 MJ/kg) energy impacts.

4. DISCUSSION AND CONCLUSION

4.1 Production Potential

The scalability of the proposed systems is directly coupled to flare gas production. The proposed system produces roughly 300 kg/d of biocrude and 1,000 kg/d of algae meal when integrated with a flare gas recovery system yielding roughly 2,000 m³/day of natural gas equivalent fuel. If all of the flare gas in the United States were used in the proposed system, 8.8 million bbl of biocrude and 3.6 million metric tonnes of dry protein-rich meal could be produced annually, equating to 29% of domestic biodiesel production and 14% of the U.S. soybean meal market [75, 76]. For a global perspective,

if all of the flare gas in the world were used in the proposed system, 126 million bbl of biocrude and 57 million metric tonnes of algal protein meal could be produced annually. At the same time, this approach would dramatically reduce flaring. Geographic siting represents a critical component to the feasibility of the proposed process. As of 2014, a large fraction (about 45%) of the flared and vented gas in the US was in North Dakota [17] where the climate would decrease the productivity of the system, even needing to be shut down during winter months. Approximately 34% of all flare gas is in Texas and the gulf coast region, which represents a more optimal location for algal growth. As previously discussed, the site could also be located abroad where flaring is much more prevalent. Countries such as Nigeria and Venezuela have favorable climates for growing algae and large quantities of unused flare gas.

4.2 Additional Benefits of Algae Meal Production

In addition to the promising energetics associated with using flare gas to produce algae, algae meal production provides several resource benefits including low land-intensity, limited fresh water impacts, improved nutrient use as compared to terrestrial crops, and value-added protein meal containing omega-3 fatty acids. The land intensity of the algae meal in this model is 0.3 m² per year per kg of meal produced, which is order(s) of magnitude less than milk (1.5 m²/kg-yr), eggs (5.5 m²/kg-yr), pork (~10 m²/kg-yr), chicken (~9 m²/kg-yr), and beef (~38 m²/kg-yr) [23]. By using saline water to grow the algae, the only direct consumption of fresh water in the proposed system is for ammonia production (0.19 L/kg algae meal); the freshwater consumption represents massive fresh water reductions compared to corn (246 L/kg) and soy (42 L/kg) production [9].

Upstream and embedded water impacts (which were not calculated explicitly) are minimized by onsite CHP with recycled cooling water for heat recovery. Water impacts could be minimized further by treating and recycling produced water from oil and gas operations that could then be used in algae ponds. Nutrient use was modeled at 90% for this study although elemental balances near 100% have been measured at pilot scale [77]. Uptake rates of 90-100% are significant improvements compared to terrestrial crops [78, 79] and could contribute to reduced eutrophication. Finally, the added benefits of algae meal composition include high protein content (~50%) and inclusion of valuable omega-3 fatty acids that could improve livestock health and be passed through to human consumers.

4.3 Alternative Scenarios

Alternative scenarios for flare gas utilization were considered. For instance, rather than using the flare gas to power an integrated algae facility, the energy-dense fuel could be used to produce electricity delivered to regional grids. The EROI for the CHP facility modeled in this study would be 232 omitting the energy content of flare gas (thereby outperforming Case I) or 1.03 when including flare gas energy (underperforming Case III due to the large animal feed displacement credit). Constructing natural gas pipelines to connect reserves with population centers has been proposed [80], although the overall energy impact of adapting this policy to flare gas (thus requiring energy to construct pipelines and transport the gas) is not explicitly known. Alternatively, the excess gas could be used to power energy-intensive processes such as aluminum production [81], desalination plants [82], internet data centers [83], or ammonia fertilizer production

independent of an algal cultivation system [84, 85]. Biological fermentation processes also exist for converting gaseous streams such as flare gas into lipids useful for fuel production [86]. The scenario could be modified to focus on biofuel production from algae with the integration of a thermochemical conversion route that can recycle nutrients (~50-90% recycling), although this approach would destroy the valuable protein fraction [49]. Each of these scenarios has challenges associated with raw material and end product transportation. Further, the discussed processes do not provide products that are expected to be in limited supply such as protein, and thus the integration of algal production with flare gas represents a unique synergistic activity.

The proposed concept of using flare gas to power an algal production facility could be extended to include other sources of waste energy. For instance, until recent improvements in transmission capacity, significant amounts of electricity from wind turbines in west Texas had to be curtailed. Similar underutilized energy resources could be repurposed to power facilities that grow algae for protein and bio-fuels. Repurposing the underutilized energy resources for productive means can thus be used as a proxy for large-scale energy storage.

4.4 Logistics

The flow rate and composition of flare gas at oil and gas well sites can vary significantly over time. The composition of the flare gas often varies from well-to-well and also over the course of a well's lifetime. As oil-and-gas production rates drop off over the lifetime of the well it can be expected that the flow rate of flare gas will also decline. During the first few days of operation a hydraulically fractured oil well might produce associated gas

volumes of over 28,000 m³/day (1,000,000 mmscfd), all of which is flared. The flow rate of flare gas might decrease to less than 280 m³/day (10,000 scfd) by the end of the first year. A conventional oil well might operate productively for 10 years or more, but unconventional shale oil wells might only last 3-5 years [87]. The declining production rates and subsequent decrease in flow rates of flare gas present a challenge for the proposed algal production facility if it sources flare gas from unconventional wells. To achieve economic viability a location needs ample supply of excess flare gas for the foreseeable future (20-30 year facility lifetime [8, 9]). Such assurance might be accomplished by aggregating the supply of flare gas from multiple adjacent production sites or to store excess flare gas for use during a flare gas shortage. Flare sources within a reasonable distance from the existing algae production facility could be transported to the facility by pipeline. Or, the algae facility could be located near a more dependable supply of flare gas, such as large refineries and production sites abroad that consistently flare significant quantities of natural gas [16].

Alternatively, the algae production facility could be designed to enable relocation after a flare source is exhausted prematurely. The oil-and-gas industry re-locates equipment routinely, including massive onshore and offshore drilling rigs that are much more complex than the system proposed here. If a source of flare gas is terminated, the algae production and processing facilities could be re-located and re-used. If re-location is anticipated, the pond liners could be installed in pieces, above ground piping could be used, and portable buildings could be installed. Other mechanical equipment (paddlewheels, CHP, processing equipment, etc.) could also be re-located. Transporting

gas from a remote flare gas source or relocating the facility would incur a large additional cost that needs further consideration during a complete techno-economic analysis.

4.5 Future Work

Future work will consider the economic constraints for constructing and operating the proposed algae growth facility. The modeled system includes the production of a valuable co-product, protein feed, as it is expected that this co-product is required to improve the economic viability of an algae-based biofuel facility. A more detailed consideration of the logistical challenges associated with producing a steady source of biomass from a variable source of flare gas will also be considered, including the impact of utilizing natural gas storage. In order to accomplish this, further analysis will be completed to identify promising domestic and international sites for the proposed concept. Lastly, the potential economic cost associated with re-locating the algae production facility if a flare gas source is closed will be determined.

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Appendix A: Mass, element, and biomass component balances. (AFDW – Ash Free Dry Weight, DW – Dry Weight)

AFDW Concentration at Harvest (g/L)	0.500
Ash Content at Harvest (g/L)	0.015
DW Concentration at Harvest (g/L)	0.515
AFDW Biomass Composition	
Lipid Content (g/g AFDW)	0.250
Protein & NA Content (g/g AFDW)	0.400
Carbohydrate Content (g/g AFDW)	0.340
Chlorophyll Content (g/g AFDW)	0.010
Ash Content (g/g AFDW)	0.000
Carbon Content (g/g AFDW)	0.500
Nitrogen Content (g/g AFDW)	0.075
Phosphorus Content (g/g AFDW)	0.005
DW/AFDW Ratio (-)	1.031
Carbon Content (g/g DW)	0.485
Nitrogen Content (g/g DW)	0.073
Phosphorus Content (g/g DW)	0.005
Lipid Content (g/g DW)	0.243
Carbon Content in Lipid (g/g lipid)	0.700
Nitrogen Content in Lipid (g/g lipid)	0.000
Phosphorus Content in Lipid (g/g lipid)	0.000
Protein (& NA) Content (g/g DW)	0.388
Carbon Content in Protein (g/g protein)	0.452
Nitrogen Content in Protein (g/g protein)	0.180
Phosphorus Content in Protein (g/g protein)	0.012
Carbohydrate Content (g/g DW)	0.330
Carbon Content in Carb (g/g carb)	0.341
Nitrogen Content in Carb (g/g carb)	0.000
Phosphorus Content in Carb (g/g carb)	0.000
Chlorophyll Content (g/g DW)	0.010
Carbon Content in Chl (g/g Chl)	0.620
Nitrogen Content in Chl (g/g Chl)	0.060
Phosphorus Content in Chl (g/g Chl)	0.000
Cultivation	
Carbon Added (kg/day)	1,066.67
Nitrogen Added (kg/day)	134.17
Phosphorus Added (kg/day)	8.39
Carbon Loss from PBRs & Ponds (kg/day)	266.67
Nitrogen Loss (kg/day)	13.42
Phosphorus Loss (kg/day)	0.84

DW Biomass Produced (kg/day)	1,649.48
AFDW Biomass Produced (kg/day)	1,600.00
Lipid Produced (kg/day)	400.00
Protein & NA Produced (kg/day)	640.00
Carbohydrate Produced (kg/day)	544.00
Chlorophyll Produced (kg/day)	16.00
Ash Produced (kg/day)	49.48
Carbon in Biomass Yield (kg/day)	764.70
Nitrogen in Biomass Yield (kg/day)	116.16
Phosphorus in Biomass Yield (kg/day)	7.68
Harvesting	
Primary Harvesting Efficiency	0.90
Biomass Lost in Primary Supernatant (kg/day)	164.95
Secondary Harvesting Efficiency	0.90
Biomass Lost in Secondary Supernatant (kg/day)	148.45
Tertiary Harvesting Efficiency	0.95
Biomass Lost in Tertiary Supernatant (kg/day)	66.80
Biomass Yield after Harvesting (kg DW/day)	1,268.14
Biomass Yield after Harvesting (kg AFDW/day)	1,230.09
Overall harvesting Efficiency (kg/day)	0.77
Lipid Produced (kg/day)	307.80
Protein& NA Produced (kg/day)	492.48
Carbohydrate Produced (kg/day)	418.61
Nucleic Acid Produced (kg/day)	12.31
Ash Produced	38.08
Carbon in Biomass Yield (kg/day)	588.44
Nitrogen in Biomass Yield (kg/day)	89.39
Phosphorus in Biomass Yield (kg/day)	5.91
Separations	
Lipid Recovery Efficiency	0.95
Biocrude Yield (kg/day)	292.15
Lipid in Biocrude (kg/day)	292.15
Protein & NA in Biocrude (kg/day)	0.00
Carbohydrate in Biocrude (kg/day)	0.00
Nucleic Acid in Biocrude (kg/day)	0.00
Ash in Biocude (kg/day)	0.00
Biomass in Biocrude (kg/day)	292.15
Carbon in Biocrude (kg/day)	204.50
Nitrogen in Biocrude (kg/day)	0.00
Phosphorus in Biocrude (kg/day)	0.00
Biomass Yield (kg DW/day)	977.13

Biomass Yield (kg AFDW/day)	939.05
Lipid in Biomass Yield (kg/day)	15.65
Protein & NA in Biomass Yield (kg/day)	492.48
Carbohydrate in Biomass Yield (kg/day)	418.61
Nucleic Acids in Biomass Yield (kg/day)	12.31
Ash in Biomass Yield (kg/day)	38.08
Carbon in Biomass Yield (kg/day)	383.94
Nitrogen in Biomass Yield (kg/day)	89.39
Phosphorus in Biomass Yield (kg/day)	5.91