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E-Mail

editor.ijmece@gmail.com

editor@ijmece.com

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The Energy Return on Investment for Algal Biocrude: Results for a Research Production Facility

N JASHUVA, K.NAGAMANI

Abstract This study is an experimental determination of the energy return on investment (EROI) for algal biocrude production at a research facility at the University of Texas at Austin (UT). During the period of this assessment, algae were grown at several cultivation scales and processed using centrifugation for harvesting, electromechanical cell lysing, and a microporous hollow fiber membrane contactor for lipid separation. The separated algal lipids represent a biocrude product that could be refined into fuel and the post-extraction biomass could be converted to methane. To determine the EROI, a second-order analysis was conducted, which includes direct and indirect energy flows, but does not include energy expenses associated with capital investments. The EROI for the production process evaluated here was significantly less than 1, however, the majority of the energy consumption resulted from non-optimized growth conditions. While the experimental results do not represent an expected typical case EROI for algal fuels, the approach and end-to-end experimental determination of the different inputs and outputs provides a useful outline of the important parameters to consider in such an analysis. The *Experimental Case* results are the first known experimental energy balance for an integrated algal biocrude production facility, and as such, are expected to be helpful for setting research and development priorities. In addition to the *Experimental Case* (based on direct measurements), three analytical cases were considered in this work: (1) a *Reduced (Inputs) Case*, (2) a *Highly Productive Case*, and (3) a *Literature Model*. The *Reduced (Inputs) Case* and the *Highly Productive Case* speculate the energy use for a similar system in an improved, commercial-scale production setting.

Keywords Algae · Energy return on investment · Energy balance · Net energy ratio · Biofuel · Biodiesel

Introduction

Algae are a potential biofuel feedstock that have received a great deal of research interest. Theoretically, algae are promising as feedstock because they grow rapidly, do not require fresh water or arable land, and, in some cases, can produce large amounts of energy products (e.g., lipids). These potential advantages have been discussed at length elsewhere [1–5]. Practically, however, algal biofuel production has proven to be quite challenging. One way to evaluate the production of algal biofuels is to calculate the energy return on (energy) investment (EROI), which is similar to the net energy ratio (NER), and can be used to assess the feasibility and sustainability of an energy source. In brief, the EROI is the amount of energy

Asst. Professor^{1,2}
Department of Mech

SRINIVASA INSTITUTE OF TECHNOLOGY AND SCIENCE, KADAPA
Chennai- Hyderabad Bypass Road, Ukkayapalli, kadapa -516002

produced divided by the amount of energy required for that production, and it has been used to characterize many resources. For example, the EROI for production of conventional oil and gas, coal, wind energy, and corn cially, the EROI must be competitive with those for current energy sources. Similarly, the financial return on investment (FROI) for algal fuels must be competitive with those for current energy sources. The relationship between the

EROI and FROI is considered in this study, and characterized more thoroughly elsewhere [10, 11].

When calculating the energy balance for algal biofuel, researchers are left with two choices: (1) to calculate energy flows for theoretical systems, which risk incorporating unrealistic assumptions, or (2) to characterize production based on research-scale processes, which are often known a priori to be uneconomical. In this study, both approaches are explored. Several studies have evaluated the energy requirements for growing algae [2, 4, 12–20] and many have also considered the energy required to process algae into a commercial product (i.e., food or fuel) [4, 13, 15–21]. Many of these analyses rely on rough estimates and sometimes omit necessary inputs because there is no commercial algal biofuel industry to serve as a reference. This work describes initial attempts at a clearly defined model for the second-order EROI of algal fuels (which includes direct and indirect energy inputs) and the use of end-to-end experimental data to populate the model.

The scope of this study is limited to evaluating operating energy expenses (including direct and indirect energy flows, but omitting capital energy expenses) according to the EROI framework provided by Mulder and Hagens [22]. A quality-adjusted EROI value is also presented, which considers the impact of using high quality fuels (i.e., high value fuels, mainly electricity) for production of lower quality fuels (i.e., lower value fuels, bio-oil and methane). The experimental results reported in this study are not representative of a commercial-scale algal biocrude facility. Such a facility does not yet exist. Moreover, it is unlikely there will be published information on commercial processes until the industry matures, as this information is mostly proprietary. The value of this study is to utilize a functional research facility to develop the experimental approach for determining the EROI for algal biocrude production. This type of analysis will be important for the algal fuels industry, as it has been for current biofuel industries [8, 23–28]. It is expected that the EROI will be improved for optimized growth conditions, refined processing methods, and with the

application of future technology (and biotechnology) improvements.

The experimental data for producing algal lipids (i.e., biocrude) were acquired during processing of five large-scale batches at the University of Texas (UT; with a total processed volume of roughly 7,600 L), where outdoor algal growth was integrated with several critical processing steps. The research focus is on processing; growth is done to provide material to process. The growth facilities at UT were built to balance capital costs with operational costs for low-volume production on a research budget. Consequently, the growth process included many inefficient techniques (e.g., artificial lighting, oversized pumps, etc.) that were appropriate for a research setting (but not a commercial

operation). The group operated in a batch processing mode, allowing continuous operation of most of the processing steps, albeit for relatively short times. To date, nearly 20

large-scale batches have been completed (with processed volumes of ~900–4,000 L per batch).

The *Reduced (Inputs) Case* presents speculated energy

consumption values for the operation of a similar production pathway at commercial scale, while yielding the same energy outputs as obtained in the experiments. The *Highly Productive Case* uses similar assumptions for the energy inputs as the *Reduced Case* and assumes greater energy output productivity. In addition, the *Literature Model* provides an estimate for the EROI of algal biocrude based on data that has been reported in the literature. In this way, the *Reduced Case* is grounded on one side by the sub-optimal experimental data and on the other side by the *Highly Productive Case* and the *Literature Model*, which are largely comprised of theoretical data.

Methods and Materials

Production Pathway

There are several energy carriers that can be produced from algae, including renewable diesel (such as biodiesel from lipids), ethanol (from carbohydrates), hydrogen produced photobiologically, methane (via anaerobic digestion or gasification), and electricity via direct combustion [17, 29–36]. Biodiesel is the most commonly studied algal biofuel, and can be produced by transesterification of algal lipids [33]. However, additional refining technologies exist that can produce a range of refined fuels from lipids depending

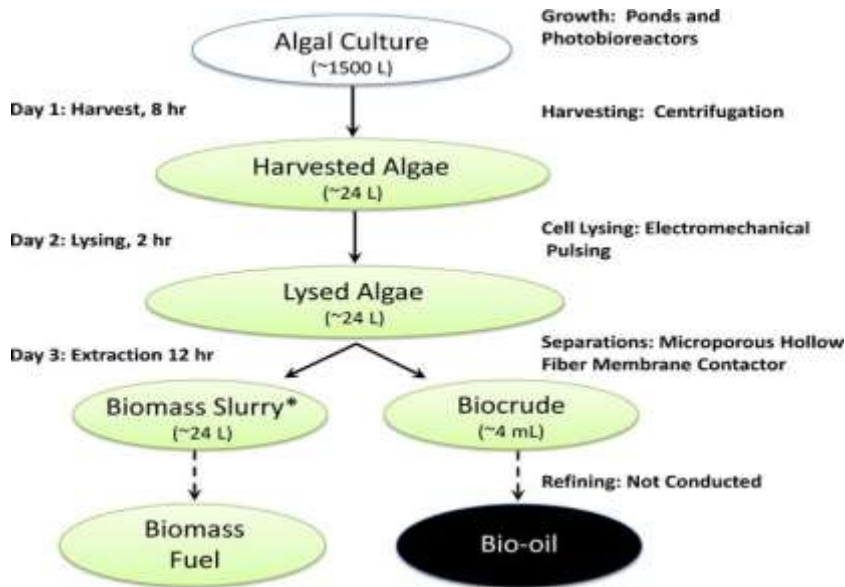
on the lipid composition (e.g., hydrocracking [37] and gasification). Algal lipids include neutral lipids and polar lipids and the proportion of each type is highly variable [1, 2, 38, 39]. As a result, it is not clear what refining processes will be used on an industrial scale. With this in mind, the experiments in this study measured the energy requirements associated with producing biocrude (i.e., algal lipids), but do not include the energy associated with upgrading the biocrude into a refined fuel product. In other words, this is a “strain-to-refinery door” analysis. ponds were inoculated from small-scale bioreactors. The diversity of existing growth approaches and the results of this

However, the energy requirement of refining, noted as E_R , will be included in the analysis in symbolic notation (according to a convention established in a prior publication [33]) and estimated values will be used when necessary.

Figure 1 presents the production pathway used at UT in this investigation. In this approach, algae were grown in outdoor “raceway” ponds (~0.2 m deep), which are similar to those discussed in previous studies [2–4, 40] and the

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Fig. 1 The algal biocrude



The EROI analysis used in this study is based on the framework provided by Mulder and Hagens [22]. Specifically, the second-order EROI model has been adopted (cf. Fig. 2 in [22]), which accounts for direct energy flows as well as indirect energy flows, as shown in Eq. 1. The process specific nomenclature in this study is based on the framework provided by Beal et al. [33]

$$\frac{ED_{out}}{ED_{in}} = \sum_j \frac{P_j}{v_j}$$

crude) and biomass fuel (produced from the biomass slurry). Thus, the direct energy output includes the bio-oil energy, ED_{BO} , and the biomass fuel energy, ED_{BMF} , as,

$$ED_{out} = \frac{1}{4} ED_{BO} + \frac{3}{4} ED_{BMF}$$

Discussion

If the biomass is used to produce non-energy products (e.g., protein, nutritional supplements, or cosmetics), then it could be represented as an indirect energy flow. In Eq. 1, indirect energy flows include material inputs that contain embedded energy (e.g., the embedded energy in nitrogen fertilizer) and material outputs. Specifically, the quantity of the k th non-energy input is I_k and the per-unit energy equivalent value for that input is denoted as v_k . Similarly, the quantity of the j th non-energy output is O_j and the per-unit energy equivalent value for that output is denoted as v_j . However, in this study, there are no indirect energy outputs. A quality-adjusted EROI (analogous to a partial FROI [10, 41]) was also determined for all of the cases except for the *Literature Model* by multiplying each of the input and output flows by a corresponding quality factor. For energy flows, the

quality factors (QF) were calculated according to the energy price (EP), which is the price of each energy source per joule, which correlates the relative value of the energy consumed in the smaller growth volume was allocated between the two growth volumes according to

Where P is the price (in \$/kg), EE is the energy equivalent (with units of MJ/kg), and EP_{coal} is the energy price for coal (\$1.4/GJ). By using quality factors that are based on price, the quality-adjusted EROI analysis is equivalent to the partial FROI analysis that is calculated using the same inputs and outputs (i.e., excluding capital expenses, labor costs, regulatory fees, etc.) [10].

Experimental Analysis

Figure 2 displays the input and output products of algal biocrude production at UT. Detailed descriptions of all data collection and uncertainty analysis can be found in [10] (cf. Chapter 4, Appendix 4A and Appendix 4B of [10]). The alga processed in these batches was a marine species of *Chlorella* (KAS 603, provided by Kuehnle AgroSystems, Inc.) and was grown in four different growth stages: flasks, airlift photobioreactors, greenhouse tanks, and covered raceway ponds (cf. Fig. 3). In general, the larger growth volumes were inoculated from the smaller growth volumes, and all of the algae transfers are illustrated in a flow diagram in [10] (cf. Appendix 4A in [10]). Energy consumption for growth and processing equipment was either measured with energy meters or estimated according to the manufacturer specifications. When algae were transferred from a smaller growth volume to a larger one, batches, hereafter referred to by batch numbers 1–5,

compressed air from a general-use shop compressor. Therefore, the compressor power for the airlift reactors could not be measured, and was estimated from the compressor data obtained for the greenhouse tanks and outdoor pond.

Four greenhouse tanks (G1–G4, about 0.25–0.50 m deep and nominally 946 L each) were periodically inoculated from the airlift bioreactors, and then used to inoculate the ponds (P1 and P2, about 0.2 m deep and nominally 2,400 L each). Inoculations were made at irregular intervals ranging from days to months (cf. Appendix 4A of [10]). A mixture of CO_2 and air was bubbled into the greenhouse tanks and ponds, and was supplied by a compressor and a CO_2 tank (different than those used for the airlift reactors). The total CO_2 flow rate for all of the greenhouse tanks and ponds was measured daily, and allocated by relative volume. Two compressors were used: the energy consumption for the first compressor was measured directly with an energy meter and that for the second compressor (used for only 8% of the cultivation time) was calculated by measuring

each fuel [42]. Setting coal as the standard with a quality factor

the percentage of the smaller volume that was transferred. The

varied between 947 and 1,942 L of growth volume processed and were all processed between May and July, 2010. The average cultivation time (from inoculation in the airlift reactors until harvesting from the ponds) was 123 days, on average.

Growth

In all stages, the growth media were prepared with *Instant Ocean* salts at a salinity of ~ 15 g/L, and the consumption of salts, nutrients, water, and antibiotics was recorded. The first

airlift bioreactor was inoculated from flasks on January 26, 2010 and the energy consumed for the flask growth stage was neglected. Seven indoor, airlift bioreactors (L1–L7) were used to grow the algae and were supplied with artificial lighting (multiple 54 W, Hg bulbs) for 12 h per day. The electricity consumption for lighting was measured with energy meters and secondary room lighting was neglected. The bioreactors were maintained at about 24°C and a CO_2 /air mixture (average of 1.0% CO_2) was bubbled into the bioreactors continuously (the out-gassed CO_2 /air mixture from the top of the reactors was 0.72% CO_2 , on average). The CO_2 /air flow rate and the percentage of CO_2 in the mixture were recorded daily for each reactor. The CO_2 /air mixture was provided by mixing CO_2 from a gas tank with

the current, voltage, and duty cycle. In addition, the greenhouse contains two fans that are activated by a thermostat (set to 32.2°C), and the electricity consumed by these fans, which varied according to the ambient temperature, was also measured. A pump requiring approximately 0.8 kJ/L was used to transfer algae from the tanks to the ponds. The energy required for transfers from the indoor airlift bioreactors to the greenhouse tanks was also estimated to be 0.8 kJ/L. Confer [10] for more details.

The final growth stage was in outdoor, covered, raceway ponds that can hold approximately 2,400 L each. The ponds were covered with a plastic liner to reduce evaporation and contamination, and circulation was accomplished by a pump that was operated 24 h per

day (requiring $\sim 1,130$ W).

Harvesting

The algae were pumped from the ponds into 1,200-L totes and transported to the centrifuge facility by a propane powered vehicle. The pumping energy was measured using an energy meter and the transportation energy

was estimated roughly (0.26 miles roundtrip and 10 miles/gallon of propane). During centrifugation, energy was consumed by an algae feed pump and the centrifuge. One feed pump was used for Batch 1 and another pump was used for Batches 2–5. The first was a hard-wired 220 V pump and the second was a 120 V pump. The energy consumption for the first pump was estimated according to the manufacturer specifications (0.7 A, 215 V, and 0.9 power factor) and the energy consumption for the second pump was measured directly. The centrifuge was operated on a variable frequency drive, which controlled the power consumption (continuous at 2.48 A, 215 V, and 0.9 power factor). On average, centrifugation achieved a 65× concentration of algal dry weight per volume from 0.26 to 16.7 g/L.

Cell Lysing

being conducted, the separation was conducted by cycling the algae and heptane through the MHF contactor for the time equivalent of three passes. Then, the contactor was washed with fresh solvent (heptane), and the wash solvent was added to the initial solvent volume. The algal lipids were recovered via distillation, and most of the heptane was recovered as distillate. On average, 1.6 L of solvent was consumed per batch (equivalent to 0.98 mL of solvent per L of growth volume processed). However, the MHF contactor retains about 1.5 L of solvent, and due to batch processing, this solvent was lost to evaporation. In continuous operation, the solvent consumption would be much lower (cf. *Reduced Case*). The electricity consumed during the separation processes was either measured directly with energy meters or estimated from the equipment manufacturer specifications. The energy-consuming equipment included: (1) an algae feed pump for the contactor, (2) a solvent feed pump for the contactor, (3) a distillation peristaltic solvent/oil feed pump, (4) a distillation vacuum pump, and (5) two electrical heaters for distillation. In addition, the amount of chilled water used to condense the heptane distillate was measured. For Batch 3 only, the post-extraction biomass was re-extracted (half of which was re-lysed), yielding additional oil, and accruing additional energy inputs. Thus, the data reported for the lysing and extraction of Batch 3 include contributions from the re-lysis and re-extraction.

Reduced Case and Highly Productive Case

The purpose of the *Reduced (Inputs) Case* and *Highly Productive Case* is to provide a more realistic model for operating energy expenses that are expected in a

The electromechanical cell lysing process was conducted by applying short pulses of strong electric fields to algae flowing through a 20-mL test-cell that consists of two electrodes. Each electrical pulse was applied by the discharge of several parallel capacitors that are charged on a three-phase, 480 V, AC circuit. The electricity consumed during each pulse was determined to be 480 J, on average (cf. [10]).

Lipid Separation (Extraction)

A microporous hollow fiber membrane contactor (MHF contactor) was used to separate the algal lipids from the other biomass into heptane. Due to the specific research that was

continuous, commercial-scale production facility. The energy outputs for the *Reduced Case* are assumed to be the same as those in the experiments, while the *Highly Productive Case* assumed a

greater biomass productivity (0.08 g/L d, ~16 g/m² d) and a higher neutral lipid fraction (30%), which yields a greater

energy output. The energy associated with capital expenditures required to achieve these cases is not considered and the ability to achieve all of these conditions is speculative. The *Reduced Case* and *Highly Productive Case* models use the same basic production pathway that was used for the experimental results (cf. Fig. 2), but substitute bioreactors for growth and an advanced flocculation technique in place of centrifugation. Several modifications are implemented to improve energy efficiency.

In the *Reduced Case* and *Highly Productive Case*, algal cultivation is envisioned to be accomplished in a closed, outdoor reactor (which does not require volume transfers) that is mixed by rotary stirring (rather than pumping). Harvesting is modeled as an advanced flocculation technique. Energy is consumed by a pump to move the growth volume to the harvesting facility and by flocculants that are

consumed. The energy consumption for lysing is modeled using the same process as the experiments, but with a more efficient power supply and a properly sized pump. As in the experiments, a MHF contactor separation process and subsequent distillation are used for the *Reduced Case* and *Highly Productive Case*. However, by modeling proper equipment size and assuming continuous operation, the energy consumed during separations in these cases is significantly less than that of the experiments. With proper design, a

single pump can be used to move algal concentrate from harvesting, through lysing, and through the lipid separation contactor. Thus, only one additional pump is required for passing solvent through the contactor.

Results

Summary of Batches

Table 1 summarizes processing efficiency data obtained for each of the five batches in this study. To calculate these data, samples were collected during processing of each batch using a methodology that has been described previously [10]. The terminology and nomenclature that is used has been defined previously by Beal et al. [33]. The efficiencies are calculated as the mass ratio of the output of a production step divided by the input for that step (e.g., the separation efficiency is the mass of biocrude divided by the mass of lysed algal biomass. The neutral lipid fraction is embedded in this efficiency). Therefore, these terms do not represent the effectiveness of each step (except for the harvesting efficiency, which also represents the harvesting

across the five batches. In addition, the percentage of the total energy consumption/production, the uncertainty, and the standard deviation are listed.

There are three types of uncertainties associated with using the experimental data presented in this study for evaluating the EROI of algal biofuels in general: measurement error, artifacts associated with sub-optimal research-scale production, and batch-to-batch variations. A detailed error analysis is provided in [10] that addresses measurement error, and the uncertainty results are tabulated for each input and output in Tables 2 and 3. The *Reduced Case* and *Highly Productive Case* are provided below in an attempt to address research-scale artifacts by estimating the EROI for an optimal commercial-scale operation of a similar production pathway. Finally, batch-to-batch variations in the growth and processing methods are characterized by the standard deviation (cf. Table 3). For example, the average (indirect) energy consumption for urea was 11.18 ± 2.55 kJ/L with a standard deviation of 8.9 kJ/L. The uncertainty in this measurement is the average measurement error for the energy consumption by urea of the five batches. The standard deviation is high because different nutrient feeding schedules were implemented throughout the year, resulting in different nutrient consumption for each batch. Similar variability exists for many inputs.

On average, the energy consumed for growth, harvesting, cell lysing, and lipid separations account for 96.23%, 0.89%, 0.15%, and 2.73%, of the total requirement, respectively. The energy requirements are dominated by growth inputs, and of these inputs, mixing, lighting, air compression, and CO₂ consumption

effective- ness). Similarly, the overall processing efficiency is the mass of biocrude divided by the grown mass and incorporates each of the individual processing efficiencies. Neutral lipid recovery is the percentage of neutral lipids detected in the initial biomass (as determined by HPLC analysis (Poenie, personal communication), data not shown) that were recovered as biocrude. There are several variables that influence the neutral lipid recovery, including each processing efficiency and changes in the neutral lipid composition throughout processing [10, 44].

Experimental Energy Flow Results

Table 2 lists the data obtained for the growth and processing of Batches 1–5. All of the indirect energy inputs were converted to energy values using the energy equivalent per unit of each indirect input (e.g., the energy equivalent of urea is 26.30 MJ/kg). Since the volume that was processed for each batch was different, the data are normalized per liter of growth volume processed and reported in units of kJ/L. Table 3 lists the average value for each input and output

represent the parameters with the most significant contributions, as shown in Fig. 4. Mixing in the pond

was accomplished by an oversized pump (~1,130 W, operated 24 h/day and 7 days/week); the use of a paddle-wheel or pump duty cycle would significantly reduce this

consumption. Artificial lighting of the airlift photobioreactors was used to enable stable growth conditions, but could be replaced by the use of sunlight. Air compression requirements and CO₂ consumption could be reduced by employing more efficient CO₂ delivery methods (to improve CO₂ uptake rates, therefore reducing the amount of CO₂/air needed) and using an appropriately sized compressor. The amount of water used for each batch was calculated to be

1.91 L for every liter processed (due to evaporation from the growth volumes). About 98% of the water processed is recovered after harvesting and could be recycled, but would likely require additional treatment. Although no recycling is included in this study, if 100% recycling were accomplished, the water consumption would be reduced to 0.91 L/L (limited to just the evaporation during growth) and the energy required to treat the recycled water would need to be added (cf. [10, 41] for additional water intensity analysis).

On average, the direct energy inputs account for 94.2% of the total energy requirement. The indirect energy inputs, which include water, nutrients, CO₂, etc., account for 5.8% of the total energy consumed. The energy equivalent values of the non-energy inputs represent the total embedded energy for their production, and are therefore much greater than the

chemical energy content of each input. For example, the embedded energy content of CO₂ (g_{CO₂}, which results from collection and compression) is estimated at 7.33 MJ/kg [12, 19]. The most significant non-energy

where M_{BMF} is the mass of biomass fuel produced from an associated amount of algal mass in the post-separations slurry, M_{BS} (cf. Fig. 2). There are several potential methods to convert post-extraction biomass to useful energy, including direct combustion, anaerobic digestion, and catalytic hydrothermal gasification (CHG) [17, 31, 56, 46]. For algal slurries with algal density of ~150 g/L, CHG has been used by Genifuel to produce ~0.25 kg of methane/kg of algal biomass slurry $\delta\phi_{refBMF} \approx 0.25$ [46] and methane contains ~55 MJ/kg ($v_{BMF} = 55$ MJ/kg). Although not considered in this study, CHG also has the potential to enable nutrient recycling

On average, 2.1 mg of biocrude and 165 mg of biomass (in slurry at ~15 g/L) were produced for each liter of growth volume processed. Using Eqs. 12 and 13, the direct energy production is therefore:

where the refining efficiencies and bio-oil energy contents are not known, as refining was not conducted. Combining Eqs. 10, 11, 12, 13, 14, 15, the EROI for algal biofuel production, on average, is,

$$\delta 16b$$

If the biomass slurry is converted to methane (biomass fuel) using the CHG process described above, it is speculated that the refining efficiency $\delta\phi_{refBMF}$ and biomass fuel energy content (v_{BMF}) would be 0.25 and 55 MJ/kg, respectively, yielding $\dot{E}_{D_{BMF}} = 2.31$ kJ/L [46]. The energy required for the CHG process is estimated to be 0.23 kJ/L. Using these speculative estimates, and if the other unknown terms in Eq. 16 are estimated by optimistic values ($\phi_{refBO} \approx 1$, $v_{BO} = 40$ MJ/kg, and $\dot{E}_{R_{BO}}$ (using 2.21 MJ for refining per kg of bio-oil [15] applied to 2.1

inputs are CO₂ and heptane, which accounted for 2.7% and 1.6% of the total energy consumption on average, respectively. Approximately 36 kg of CO₂ were consumed per kg

(including nitrogen, phosphorus, potassium, and carbon dioxide; [46]). Combining these terms (and neglecting the energy required to concentrate the post-extraction biomass from ~15 to ~150 g/L), roughly 13.8 MJ of methane energy could be produced per kg of post-extraction algae. These rough estimates do not consider the effect of extracting lipids from algae prior to conversion or the dependence of conversion performance on algal species. Other studies have suggested that (dry) algal biomass has a heating value between 17.5 and 26 MJ/kg [12, 13, 17, 57]. The energy requirements to operate this process are estimated to be ~10% of the methane energy produced (~1.4 MJ/kg; [46]).

mg of biocrude)), the average EROI for all five batches in this study would be 9.2×10^{-4} to 3.3×10^{-4} .

The quality-adjusted EROI was calculated by applying the quality factors listed in Table 4 to each input and output flow. Adjusting for quality yielded an EROI

of 9.2×10^{-5} . Due to high quality factors for electricity inputs and material inputs, the quality-adjusted total

energy input was 31 times greater than the non-adjusted total. The quality-adjusted total energy output was three times greater than the non-adjusted total energy output, reflecting the bio-oil and biomass fuel (methane) quality factors.

Reduced Case and Highly Productive Case Results

The *Reduced Case* and *Highly Productive Case* model estimates the EROI for a configuration that uses closed bioreactors, chemical flocculation for harvesting, and optimized lysing and separations processes. The energy flow data are presented in Table 4. Using closed growth containers could nearly eliminate evaporation (a result observed for the indoor bioreactors), which would reduce the water consumption to 1 L/L, on average without

recycling, and 0.05 L/L with 95% recycling (equivalent to

0.07 kJ/L processed). The amount of CO₂ required to produce 1 kg of algal biomass has been estimated to be between 1.7 and 2 kg [3, 12, 13, 58], although this value corresponds to the theoretical minimum by assuming 100% uptake and no respiration [10]. The algal concentration for Batches 1–5, on average, was 0.26 g/L. With 100% conversion efficiency, this grown mass would require about 0.52 g/L of CO₂. However, for the indoor bioreactors, the amount of CO₂ supplied was roughly 4× the amount that was absorbed. Applying this rate of absorption to 0.52 g of CO₂ required/L of growth volume processed, the CO₂ consumption for the *Reduced Case* is modeled as being 2.08 g/L (with 7.33 MJ/kg of energy equivalent), which is 22% of the CO₂ consumed per liter for Batches 1–5, on average. The same assumptions are used to calculate the CO₂ required in the *Highly Productive Case*, except for an algal concentration of 1 g/L, resulting in CO₂ consumption of 8 g/L.

Nutrient requirements modeled in the *Reduced Case* are estimated from averaged literature data to be ~70 g of nitrogen/kg of grown mass and ~8 g of phosphorus/kg of grown mass [12, 13, 18, 19]. Although it is acknowledged that these nutrient requirements are near the theoretical minimum [10], specific uptake rates are not considered here. For the *Reduced Case* with an algal concentration of 0.26 g/L, 18 mg/L of nitrogen and 2 mg/L of

where: density (ρ) is 1 kg/L, elevation (Δz) is 3 m, friction factor (f) is 0.03 (for a Reynolds number of $\sim 10^4$), pumping distance (L) is 20 m, pipe diameter (D) is 1.3 cm, flow

velocity (V) is 4.8 m/s, minor loss coefficient (K_L) is 1.5 (assuming a square entry and discharge orifice), and g is the gravity constant (9.8 m/s²). This relationship yields a ΔP of 573 kPa, which corresponds to an energy consumption of

0.96 kJ/L (assuming $\eta=0.6$) for both cases. The embedded energy of flocculants is estimated at 20 MJ/kg and 354 mg of flocculants are assumed to be consumed per g of algae. With algal densities of 0.26 and 1 g/L, the indirect energy consumption of flocculants is 1.82 and 7.08 kJ/L for the *Reduced* and *Highly Productive Cases*, respectively.

For cell lysing, energy efficiency improvements of 17× have been demonstrated with respect to the power supply used during the processing of Batches 1–5 [10]. Thus, the energy consumed by the lysing power supply in the *Reduced Case* and *Highly Productive Case* is 0.21 kJ/L. The energy used to pump algal concentrate from harvesting, through lysing, and through the contactor is modeled using Eq. 17 ($\Delta P=138$ kPa, $\eta=0.6$, and $\frac{1}{2} V_P$ (due to a 65× concentration factor)) to be 3.5 J/L of growth volume processed.

With proper sizing of separations equipment, the volumetric ratio of heptane used (not consumed) to

phosphorus are consumed, with energy equivalent values of 59 MJ/kg [12, 19, 49–51] and 44 MJ/kg [12, 19, 49], respectively. The indirect energy consumption from nitrogen and phosphorus nutrients in the *Reduced Case* is 10% and 44% of the experimental results, respectively. For an algal concentration of 1 g/L in the *Highly Productive Case*, 70 mg/L nitrogen and 8 mg/L of phosphorus are consumed.

For a closed system (without volume transfers) it is

expected that contamination would be less problematic. Therefore, the *Reduced* and *Highly Productive Cases* estimate the antibiotic consumption as 0.28 mg/L and

0.1 mg/L (which is ~15% and 5% of that consumed for Batches 1–5, on average, respectively. cf. Table 2). It is

assumed that artificial lighting and volume transfers would not be needed, and therefore these energy values are reduced to zero. In these cases, an air compressor is not required: pure CO₂ is modeled as being delivered directly from pressurized tanks and mixing is accomplished via rotary stirring. Also, there is no greenhouse modeled (and thus no fans). The mixing energy is estimated at 99 J/(L-d) which is an average of data that have been used in previous studies [4, 12–14, 18, 19]. This value for mixing energy is equivalent to

algal concentrate could be reduced to 1:20. Assuming a concentration of 65×, this corresponds to a heptane-to-growth-volume-processed ratio of 1:1,300. The energy required for passing this heptane through the contactor is

modeled using Eq. 17 and is negligible ($8\frac{1}{4} \times 10^{-1} \times \frac{1}{2} V_P$,

required for the chilled water (9.4°C). Per liter, 39.4 kJ are required for chilling (9.4°C, 4.18 kJ/(kg-K)) and an ideal vapor-compression refrigeration cycle is assumed to remove the heat from the water (coefficient of performance of 3.97), resulting in a compressor energy requirement of 9.9 kJ/L of chilled water. The embedded energy in the chilled water includes the energy to provide the water (1.33 kJ/L [47]) and the energy consumed for chilling (9.9 kJ/L). The total energy embedded in the chilling water is therefore 48.6 J per L of processed volume (the product of 4.3 mL of water consumed and

11.23 kJ/L of embedded energy).

With all of these reductions, the total energy input for the *Reduced Case* is estimated at 31.77 kJ/L, which is two orders of magnitude less than the energy consumption for Batches 1–5. If the same biocrude and biomass production as in the experiments can be achieved (the feasibility of which is not known), the EROI can be represented as,

If the unknown terms in Eq. 20 are estimated with the same values as for Eq. 16 ($\phi_{\text{refBO}} = 1$, $v_{\text{BO}} = 40$ MJ/kg, $\phi_{\text{refBMF}} = 0.25$, $v_{\text{BMF}} = 55$ MJ/kg, $\Delta P = 7$ kPa, and $\eta = 0.6$).

Heptane loss into the algal slurry is estimated at the solubility limit in water (5 ppm) and neglects heptane evaporation into non-condensing gas during distillation. The energy consumption of the solvent/oil feed pump is negligible ($\frac{8}{1.300} V_G$, $\Delta P = 69$ kPa, and $\eta = 0.6$ in Eq. 17). The heat of vaporization required to distill heptane is 318 kJ/kg, which translates to 0.17 kJ/L of growth volume processed (assuming a heptane density of 0.68 kg/L, $\frac{8}{1.300} V_G$, and a heat loss of 10%). Commonly, the energy required to establish a vacuum during distillation is less than 2% of the heat of vaporization, and it is therefore modeled as being 3.3 J/L for the *Reduced Case* and *Highly Productive Case*. Finally, the amount of chilled water needed per liter processed, $\dot{M}_{\text{CW}}$, is estimated to be 4.3 g (4.3 mL) per liter of processed volume according to,

Case), while only consuming 2.7% of the experimental energy consumption. The *Literature Model* estimates CO_2 consumption to be 0.200 g/(L-day), which corresponds to

2.29 kg of CO_2 /kg of algae (compared to 36 kg/kg in the *Experimental Case* and 8 kg/kg in the *Reduced* and

Using the same quality factors as described above for the experimental results, the quality-adjusted EROI for the *Highly Productive Case* was determined to be 0.36. The quality-adjusted EROI is greater than the non-adjusted result because 78% of the energy input is associated with CO_2 , which has a relatively low quality *Reduced Case*, where electricity (with high quality) was the primary energy input.

references for each data point. The majority of literature sources report energy consumption and production data as rates for a continuous system (e.g., MJ/(ha-year)). All of the energy data was converted into units of J/(L-day) and the non-energy input data were similarly converted into units such as mL/(L-day) or mg/(L-day). In these units, L represents liters of growth volume and an inverted apostrophe accent ($\bar{x}$) is used to represent data in units of J/(L-day). In order to compare directly with the experimental results, the analytical

and
= , the EROI for the *Reduced Case*

would be 0.074. This result indicates that the energy productivity needs to be increased by more than an order of magnitude or the energy inputs need to be further reduced by more than an order of magnitude to have net positive energy production from algae with the system modeled in this scenario. Using the same quality factors as described above for the experimental results, the quality-adjusted EROI for the *Reduced Case* was determined to be 0.013.

The growth and processing energy inputs for the *Highly Productive Case* are estimated to be 72.92 kJ/L, which is about twice as much as that for the *Reduced Case*, and primarily due to increased indirect energy consumed by nutrients to produce more algal biomass. Based on the nomenclature defined in [33], the direct energy output for the *Highly Productive Case* is calculated as,

Highly Productive Cases).

Using energy production and consumption rates (in units of J/(L-day)), rather than amounts (in units of J/L), the EROI for the analytical data can be calculated as,

factor of 2.1, while the energy outputs have relatively high quality factors. This result is in contrast with the *Experimental Case* and the where P_{BC} is the biocrude productivity and P_{BS} is the biomass in slurry productivity. The biocrude productivity is calculated according to,

results would need to be converted from units of J/(L-day) to J/L by multiplying by the cultivation duration. However, the multi-scale growth scenario and batch processing methods used at UT make this approach an inconsistent comparison. Furthermore, the UT results include burdens associated with start-up operations required to scale-up algal growth from the flask volume to a pond volume, where each of these terms is listed in Table 3 (and defined in [33], except for ϕ_{sepBS} , which is the algal biomass (in slurry) separations efficiency. This term is defined as the mass of algal biomass in the post-extraction slurry

divided by the lysed mass). The separations efficiency, ϕ_{sep} , contains the LF and the ULF. The refining energy inputs (per liter of growth volume per day) include the bio-oil refining, $\dot{E}_{RBO}$, and biomass fuel refining, $\dot{E}_{RBMF}$, as,

$$\dot{E}_R = (\dot{E}_{D_{in}} + \sum_k \gamma_k \dot{I}_k)_R = \dot{E}_{RBO} + \dot{E}_{RBMF}$$

energy forms of the *Literature Model* inputs are not specified, a quality-adjusted EROI was not calculated.

Discussion

This study presents the first known experimental results with end-to-end measurements for determining the EROI for an integrated algal biocrude facility. Although the EROI was significantly less than 1 for the biocrude production process evaluated here, it is the result for a single, research system that was not designed to optimize EROI. However, the less-than-unity EROI results for the *Reduced Case*, *Highly Productive Case*, and the *Literature Model* also support the need to develop alternative, energy-efficient production methods. As noted, the majority of the energy consumption in all four calculations is from growth.

In addition to reducing many of the high energy inputs, it is reasonable to expect algal productivity and lipid yields to be increased. For Batches 1–5, the grown mass productivity was roughly 0.002 g/(L-day), which is 40 times less than yields that have been demonstrated at similar scales (e.g., 0.08 g/(L-day)) [2]. Similarly, based on chromatography analysis (not shown), the neutral lipid fraction of the algae processed in Batches 1–5 was a mere 0.02 (i.e., 2% of dry cell weight). As shown above, for the *Highly Productive Case* the energy output is 16.6 kJ/L of growth volume. Therefore, for a system operating under these conditions, the total energy input for growth, processing, and refining must be less than 16.6 kJ/L to obtain an EROI that is greater than 1. This result illustrates the challenge for profitable algal biofuel production and the need for ultra-low-energy methods, as even the speculative

Reduced Case energy input was estimated to be 32 kJ/L.

The energy used for processing (harvesting, cell lysing, growth systems. However, the NEC_{GV} is preferred in this study so as not to confuse it with an end-to-end energy ratio for biofuel production (i.e., the EROI). For the EROI to be greater than 1 and assuming an ideal process (all efficiencies in Eq. 22 being equal to 1, $v_L = v_{BO}$, and $v_{BM} = 14$ MJ/kg), Eqs. 16 and 30 can be combined and manipulated to be

Therefore, for energy to be produced from algae, assuming an ideal process (i.e., 100% efficiency throughout), the volumetric net energy content of the growth volume must be greater than the processing and refining energy

$$\left[\frac{J}{L-d} \right]$$

ð28Þ

Inserting the data from Table 5 into Eq. 25 yields an EROI of

$$0.006 \frac{\text{g}}{\text{L}} \cdot v_{BO} \text{ þ } 0.013 \frac{\text{g}}{\text{L}} \cdot v_{BMF}$$

and separations), $\dot{E}_P$, was measured to be 118 kJ/L, on average. This amount is seven times greater than the theoretical value

for the energy production of the growth volume in the *Highly Productive Case* (16.6 kJ/L). The centrifuge itself consumed nearly as much energy per liter of growth volume processed (14.0 kJ/L) as the *Highly Productive Case* output (16.6 kJ/L). Furthermore, the energy required to pump algae roughly 10 m from the pond for harvesting was 1.8 kJ/L, on average, which is nearly 11% of the *Highly Productive Case* energy production of that volume (16.6 kJ/L). Specific analysis of those steps had already led the UT team to develop low-energy alternatives to centrifugation and to focus on the minimization of pumping. In the *Highly Productive Case*, the energy consumption for processing and refining, $\dot{E}_R$, was modeled to be 3.58 kJ/L, which is only 22% of the theoretical energy production (16.6 kJ/L).

Therefore, if growth could be accomplished for less than

13.03 kJ/L of growth volume, the second-order EROI would be greater than 1.

The volumetric net energy content of the growth volume,

NEC_{GV} , is the energy contained in the growth volume per liter, $\dot{E}_G$, minus the energy inputs for growth per liter, $\dot{E}_G$, and can be expressed as,

ð30Þ

where v_L is the energy content of the lipids, v_{BM} is the energy content of the non-lipid biomass, and the other terms are defined above. The NEC_{GV} is a similar metric as the “Net Energy Ratio” defined by Jorquera et al. [14] to evaluate

requirements per liter of growth volume. For energy production in real pathways, the net energy content of the growth volume must be significantly greater than the processing and refining energy requirements to compensate for processing inefficiencies and useful product fractions (cf. Eq. 22). Increasing the biomass productivity, lipid content, and processing efficiencies of Eq. 22 would result in a greater energy output, therefore allowing a greater energy input while achieving an EROI of 1. As a theoretical case, the photosynthetic limit for the

maximum algal biomass productivity, P_{GM} , can be estimated to be ~ 184 g/(m²-day), which is ~ 0.92 g/(L-

day) in a 0.2-m-deep pond (cf. [10, 57]). As optimistic assumptions, the LF

and ULF can be estimated as 0.3 and 1, respectively. Inserting these data into a modified form of Eq. 22 (omitting the cultivation time (t_c), which results in units of J/(L-day)) yields,

$$\frac{E_{Q_{out}}}{E_{Q_{in}}} = 0.92$$

$$E_{Q_{out}} = 15.2 \left[\frac{kJ}{L-d} \right]$$

To achieve this biomass productivity, additional carbon,

nitrogen, and phosphorus would be required. For each kilogram of algae, the minimum possible CO₂, nitrogen, and phosphorus consumption can be approximated as 1.8 kg, 70 g, and 8 g, respectively [3, 12, 13, 18, 19, 58]. Using these data, and the energy equivalent values for each nutrient as listed in Table 2, the energy input for nutrients can be calculated as,

Therefore, the embedded energy expense in CO₂ and nutrients would require more energy than the total energy produced (Eq. 33). This result can be calculated as the ratio of Eqs. 32 and 34, and is therefore independent of the biomass productivity, but is dependent on production efficiencies (including the lipid fractions). This result demonstrates the need to acquire usable waste forms of carbon, nitrogen, and phosphorus, which have energy equivalent values near zero (because little or no energy is required to obtain the nutrients). The actual energy embedded in CO₂ and nutrients of any real algal production system will depend on the specific methods used to produce and acquire those materials. Using atmospheric carbon dioxide could also reduce the indirect energy input, but would likely reduce the biomass productivity.

These results highlight the reason why the nascent industry is focusing on the development of low-energy input, high-energy output algal growth and processing

typical of even the full UT process, as some of the UT processes are licensed to a company and could not be disclosed in this investigation.

Also, these results are limited to the operating energy balance, and do not include capital energy expenses. Clearly, direct capital energy expenses (earthworks, water supply, etc.) and materials (pond liners, processing equipment, etc.) will significantly impact the overall life-cycle assessment and “cradle-to-grave” energy balance for algal biofuel production. Lundquist et al. provide a thorough analysis of capital costs for a similar

methods. While the discussion in this section considers a break-even scenario in which the EROI is equal to 1 (cf. Eq. 31), for algal fuels to be economically competitive, the EROI must be comparable to that of current energy sources (i.e., fossil fuels, nuclear, wind, and solar). Ways to improve the EROI (beyond the *Reduced Case* and *Highly Productive Case* scenarios) include: (1) using waste forms of nitrogen and phosphorus (e.g., wastewater and animal waste) [12, 15, 40], (2) using waste heat and flu-gas CO₂ from industrial plants [17], (3) minimizing pumping [65], (4) employing less energy-intensive harvesting methods [21, 66, 67], and (5) avoiding separation methods that require distillation. However, Lundquist et al. determined that relying on cheap waste materials as feedstocks relegates algal biofuel production to relatively low levels of production (a few percent of US demand) [40].

Limitations

It is important to re-state the limitations of this study. First of all, this work focused on developing and assessing a process to determine the EROI for algal biofuels. There was not a system available for study that provided a representative surrogate for future commercial processes. So, this study characterized the EROI for a functional research process. It is expected that technology improvements, biology improvements, and industrial synergies (e.g., the use of wastewater nutrients or CO₂ from power plants) will enable algal biofuel production with a more favorable EROI.

In addition, for a variety of reasons related to the research goals of the project, UT did not incorporate its most efficient processes into this investigation. Consequently, the experimental data are a reflection of energy consumption during these specific tests. They are not

algal biofuel production system, which are roughly 50% of the total cost for the biofuel production cases presented in that study (cf. Case 5) [40]. Finally, the growth scenario evaluated here includes scale-up burdens associated with cultivating algae from small-scale (flasks) to large-scale (2,500-L pond), and commercial production is envisioned as a continuous, large-scale process.

The value of this study, in our opinion, is to provide an initial result for the operating EROI associated with algal biofuel production and to outline many of the important parameters that need to be included in such

an analysis. As production is scaled-up, algal biofuels have the potential to experience exponential improvements in energy efficiency, analogous to the advances made in solar and wind technology over the last several decades.

Conclusion

With significant rigor and effort it is possible to experimentally assess the energy return on energy investment for algal biofuel production. Such assessments on operating facilities will likely remain proprietary for an extended time, because making them public requires revealing significant information about what are generally perceived as proprietary processes. Such assessments are critical, however, to help identify and

eliminate process inefficiencies. This assessment of a research facility shows an approach and the information required.

The results of the four cases presented in this study are summarized in Table 6. As shown, the EROI for all four cases was determined to be less than unity. Furthermore, the quality-adjusted EROI, which parallels a partial FROI analysis, was also less than unity for all cases. Several other studies have presented hypothetical energy analyses of algal biofuel production, and although the scope and systems

evaluated vary, each of these studies have also demonstrated that without discounted inputs (e.g., nutrients and water from waste water, excess heat from a power plant, CO₂ from flue gas), the energy return on investment is not competitive with conventional fuels [12, 13, 15, 20, 40]. However, it is most important that the cumulative EROI for an entire energy profile is greater than unity, including the contributions from all energy sources (e.g., fossil fuels, solar energy, wind energy, biofuels, etc.), while providing the necessary fuels for essential services (i.e., transportation, industry, defense, etc.). Therefore, although the EROI for algal fuels might remain less than one in the foreseeable future, algae represent one of the most promising petroleum fuel substitutes, particularly for high-energy density fuels, such as aviation fuel. Therefore, although large-scale algal biofuel production remains quite challenging, algal fuels have the potential to satisfy some of these niche markets.

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