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

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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. The *Literature Model* is populated with relevant data that have previously been reported in the literature. For the *Experimental Case*, *Reduced Case*, *Highly Productive Case*, and *Literature Model*, the estimated second-order EROI was 9.2×10^{-4}, 0.074, 0.22, and 0.35, respectively. These results were dominated by growth inputs (96%, 89%, 87%, and 61% of the total energy requirement, respectively). Furthermore, the EROI was adjusted using quality factors that were calculated according to the price of each input, yielding a quality-adjusted EROI that parallels a partial financial return on investment analysis. For the *Experimental Case*, the *Reduced Case*, and the *Highly Productive Case*, the quality-adjusted EROI was 9.2×10^{-5}, 0.013, and 0.36, respectively.

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

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Abbreviations

Products

BO Bio-oil
BMF Biomass fuel
BF Biofuel
BS Biomass in slurry
BC Biocrude
GM Grown mass
HM Harvested mass
LM Lysed mass

Processes

G Growth
P Processing
R Refining
H Harvesting
CL Cell lysing
S Separations

Efficiency

proc Processing
ref Refining
harv Harvesting
cellys Cell lysing
sep Separations

Composition

LF Lipid fraction
ULF Useful lipid fraction
NLF Neutral lipid fraction

Nomenclature

EROI Energy return on investment
FROI Financial return on investment
P Productivity (in units of grams per liter per day)
M Mass (in units of grams)
V Velocity (in units of meters per second)
t_c Cultivation time (in units of days)
φ Efficiency
E Energy (in units of joules)
ED Direct energy flows (in units of joules)
EI Indirect energy flows (in units of joules)
O Indirect energy (i.e. material) output (in units of kilograms)
υ Energy equivalent of indirect energy outputs (in joules per kilogram)
I Indirect energy (i.e., material) input (in units of kilograms)
γ Energy equivalent of indirect energy inputs (in units of joules per kilogram)
MP Material price (in units of dollars per kilogram)
EP Energy price (in units of dollars per joule)
QF Quality factor
v Energy content (in units of joules per kilogram)
$\forall$ Volume pumped (in units of liters)
ΔP Pressure drop (in units of pascals)
η Pump efficiency
ρ Density (in units of grams per liter)
Δz Change in elevation (in units of meters)
f Friction factor
K_L Loss coefficient
U Flow velocity (in units of meters per second)
Q Heat (in units of joules)
c_p Specific heat capacity (in units of joules per kilogram kelvin)
ΔT Temperature difference (in units of kelvin or degrees Celsius)
g Gravity constant (9.81 m/s^2)
L Pipe length (in units of meters)
D Pipe diameter (in units of meters)
NEC Net energy content (in units of joules per liter or joules per liter per day)

Accents

$\tilde{X}$ Tilde denotes an input for a processing step
$\acute{X}$ Apostrophe indicates units of joules per liter of processed volume
$\grave{X}$ Inverted apostrophe indicates units of joules per liter of processed volume per day of cultivation

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 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 ethanol has been estimated to be ~15, ~80, ~19, and ~1, respectively [6–9]. For algal fuels to be produced commercially, 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. However, the energy requirement of refining, noted as $\widetilde{E}_{\mathrm{R}}$, 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 ponds were inoculated from small-scale bioreactors. The diversity of existing growth approaches and the results of this

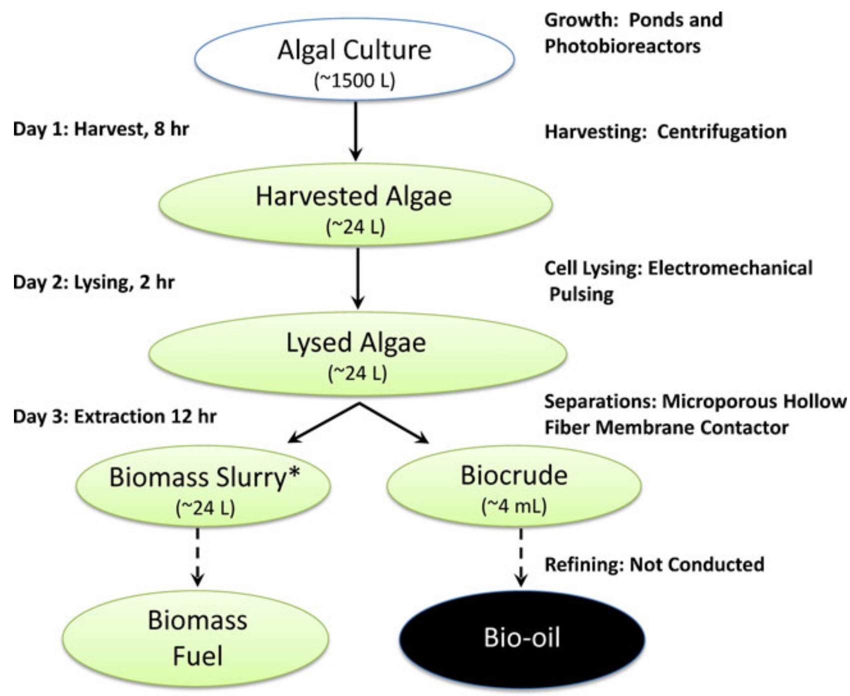

Fig. 1 The algal biocrude production pathway used in this investigation. Due to relatively small volumes, these processing steps are conducted in batch mode, and the steps between growth and refining last about 3 days. *Wet biomass will require additional processing/refining

work underscore the fact that this approach, while quite useful for research, will likely be modified for commercial application. The algae were concentrated by a factor of ~65 into a slurry (i.e., harvesting) using centrifugation and then electromechanically lysed by exposure to electrical pulses. After the cells were lysed, a microporous hollow fiber membrane contactor (MHF contactor) was used to separate the lipids from the biomass. The lipids constitute a biocrude product that can be upgraded to a refined fuel. The biomass also has the potential to be used to produce fuels or chemicals, and for this study, a thermochemical conversion process is modeled that produces methane from the post-extraction biomass. Energy required to distribute the refined fuel(s) is not included.

Energy Return on Investment Framework

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]

$$\mathrm{EROI} = \frac{\mathrm{ED_{out}} + \sum_j v_j o_j}{\mathrm{ED_{in}} + \sum_k \gamma_k I_k} \qquad (1)$$

Direct energy flows include electricity and fuel consumed during production ($\mathrm{ED_{in}}$) and the biofuel produced ($\mathrm{ED_{out}}$). In this study, the biofuel products (which are not actually produced) include bio-oil (produced from biocrude) and biomass fuel (produced from the biomass slurry). Thus, the direct energy output includes the bio-oil energy, $\mathrm{ED_{BO}}$, and the biomass fuel energy, $\mathrm{ED_{BMF}}$, as,

$$\mathrm{ED_{out}} = \mathrm{ED_{BO}} + \mathrm{ED_{BMF}} \qquad (2)$$

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 kth non-energy input is I_k and the per-unit energy equivalent value for that input is denoted as γ_k. Similarly, the quantity of the jth 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 each fuel [42]. Setting coal as the standard with a quality factor of 1 ($1.4/GJ, $1.5/MMBtu), the quality factors used in this study were: electricity 19.5 ($27.8/GJ, ¢10/kWh), petroleum 14.5 ($20.6/GJ, $2.50/gal), and natural gas 2.7 ($3.8/GJ, $4/MMBtu) [43]. Methane was assigned the quality factor of natural gas and the bio-oil was assigned the quality factor of petroleum. For material inputs, the quality factor was determined according to Eq. 3,

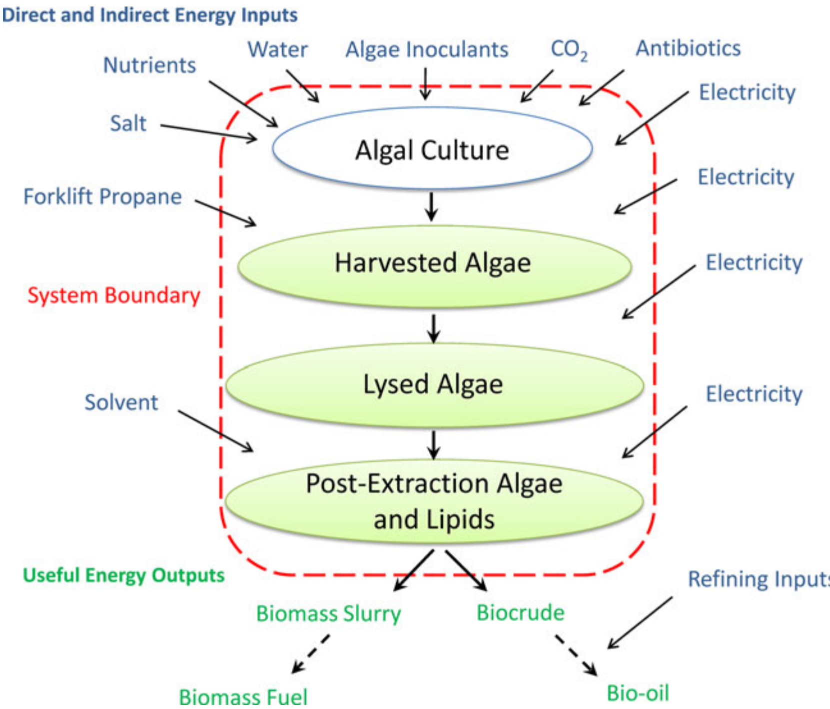

Fig. 2 Material and energy flows for biocrude production at UT are marked as arrows crossing the system boundary

$$\mathrm{QF} = \frac{P}{\mathrm{EE} \cdot \mathrm{EP}_{\mathrm{coal}}} \equiv \frac{[\$/\mathrm{kg}]}{[\mathrm{MJ/kg}] \cdot [\$/\mathrm{MJ}]_{\mathrm{coal}}} \quad (3)$$

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, the energy consumed in the smaller growth volume was allocated between the two growth volumes according to the percentage of the smaller volume that was transferred. The batches, hereafter referred to by batch numbers 1–5, 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

Fig. 3 Algae were grown in four growth stages: 1) flasks 2) seven indoor photobioreactors (L1 – L4 shown, ~100 L each) 3) four greenhouse tanks (G1 and G2 shown, ~1000 L each) and 4) two covered outdoor ponds (shown without the cover, ~2400 L each)

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 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 ~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

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 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-lysing 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 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/m^2 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 separations 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 effectiveness). 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

Table 1 Processing summary for the five batches in this study

Batch	Proc. vol. V_P (L)	Algal conc. μ (g/L)	Grown mass M_{GM} (g)	Grown mass prod.[a] P_{GM} (mg/L-d)	Neutral lipid fraction[b] *NLF* (%DCW)	Harv. effic. φ_{harv} (−)	Lysing effic. φ_{cellys} (−)	Sep effic. φ_{sep} (−)	BC mass M_{BC} (g)	Biomass M_{BS} (g)	Proc. effic. φ_{proc} (−)	BC prod.[a] P_{BC} (mg/L-d)	Neut. lipid recovery[b] (%)
1	947	0.27	260	2.76	0.015	*1.19*[c]	*0.65*[c]	0.007	1.44	154	0.006	0.015	37%
2	974	0.25	244	2.55	0.019	0.90	0.92	0.014	2.88	138	0.012	0.030	62%
3	1891	0.25	470	2.12	0.011	0.97	0.94	0.012	4.96	301	0.011	0.022	96%
4	1893	0.22	*425*[d]	3.05	0.026	-[d]	0.95	0.011	4.44	310	0.010	0.018	40%
5	1942	0.29	570	1.70	NA	0.88	0.88	0.005	2.15	378	0.004	0.006	NA
Ave	1529	0.26	394	2.17	0.018	0.92[c]	0.92[c]	0.010	3.17	256	0.008	0.02	59%
Stdev	520	0.02	140	0.47	0.006	0.05	0.03	0.004	1.49	105	0.004	0.01	27%

[a] The cultivation time and growth volume used for the grown mass productivity and biocrude productivity calculations are rough estimates

[b] The initial neutral lipid fraction was estimated by HPLC analysis and includes lipid species with polarity less than or equal to MAG (e.g., LCH, TAG, and DAG) [45]. HPLC data is not reported

[c] The post-harvesting algal concentration measured for Batch 1 is high, resulting in a harvesting efficiency greater than 1 and a low lysing efficiency. These effects are offset in the processing efficiency calculation for Batch 1 and these data were omitted from the average

[d] The data reported was measured after harvesting, and therefore the harvesting efficiency cannot be determined

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 CO_2 consumption 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 CO_2 consumption could be reduced by employing more efficient CO_2 delivery methods (to improve CO_2 uptake rates, therefore reducing the amount of CO_2/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, CO_2, 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 CO_2 (γ_{CO_2}, which results from collection and compression) is estimated at 7.33 MJ/kg [12, 19]. The most significant non-energy inputs are CO_2 and heptane, which accounted for 2.7% and 1.6% of the total energy consumption on average, respectively. Approximately 36 kg of CO_2 were consumed per kg

Table 2 Direct and indirect energy flows (inputs and outputs) and associated uncertainty ("Unc")

Inputs and outputs	Energy equivalent	#1 (kJ/L)	#1 Unc (kJ/L)	#2 (kJ/L)	#2 Unc (kJ/L)	#3 (kJ/L)	#3 Unc (kJ/L)	#4 (kJ/L)	#4 Unc (kJ/L)	#5 (kJ/L)	#5 Unc (kJ/L)
Volume processed (L), V_P		947 L		974 L		1889 L		1893 L		1941 L	
Growth total, $\tilde{\hat{E}}_G$		**2400**	**158**	**2520**	**175**	**2040**	**162**	**4650**	**274**	**762**	**69.8**
Water supply (kJ/L)[a]	–	–		–		–		–		–	
Direct water (kJ/L)[b]	1.33 kJ/L[k]	2.79	0.89	2.82	0.89	2.24	1.07	3.22	1.00	1.63	0.57
Indirect water (kJ/L)[c]	–	–		–		–		–		–	
CO_2 supply (kJ/L)[d]	–	–		–		–		–		–	
CO_2 (kJ/L)	7.33 MJ/kg[l]	75.5	15.3	77.6	15.8	52.1	11.0	107	21.5	30.5	6.59
Nutrient supply (kJ/L)[e]	–	–		–		–		–		–	
Urea (kJ/L)	26.3 MJ/kg[m]	6.14	1.40	6.20	1.42	13.5	3.09	25.9	5.91	4.13[r]	0.94
F/2 media (kJ/L)[f]											
Sodium phosphate monobasic dehydrate	8.6 MJ/kg[n]	0.06	0.03	0.06	0.03	0.13	0.07	0.30	0.16	0.10	0.05
Ferric chloride hexahydrate	20 MJ/kg[j]	0.08	0.02	0.09	0.02	0.20	0.05	0.44	0.11	0.15	0.04
EDTA dihydrate	20 MJ/kg[j]	0.12	0.03	0.12	0.03	0.27	0.07	0.60	0.15	0.20	0.05
Copper sulfate pentahydrate	20 MJ/kg[j]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manganese(II) chloride tetrahydrate	20 MJ/kg[j]	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.01	0.01	0.00
B3N media (kJ/L)[g]											
Sodium nitrate	9.38 MJ/kg[m]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.96[r]	0.20
Instant ocean salts (kJ/L)	1.15 MJ/kg[o]	18.6	13.9	18.8	14.1	25.6	19.3	33.5	25.2	15.4	11.6
Antibiotics (kJ/L)	50 MJ/kg[j]	0.10	0.03	0.10	0.03	0.04	0.01	0.23	0.07	0.00	0.00
Lighting (kJ/L)		987	24.0	998	24.2	591	16.9	1590	47.9	134	4.24
Compressor (kJ/L)		412	52.1	424	53.3	321	42.8	658	117	149	20.3
Transfers (kJ/L)		0.74	0.74	0.75	0.75	0.77	0.77	1.76	1.76	0.05	0.05
Mixing (kJ/L)		841	37.5	929	52.1	993	57.5	2150	37.0	360	15.5
Greenhouse fans (kJ/L)		60.8	11.8	61.4	11.9	44.1	9.67	70.6	16.7	65.1	9.68
Harvesting total, $\tilde{\hat{E}}_H$		**19.4**	**1.17**	**18.7**	**1.13**	**28.0**	**1.04**	**25.1**	**0.91**	**23.0**	**0.83**
Pump from pond (kJ/L)		1.25	0.04	1.29	0.04	1.75	0.02	2.59	0.02	2.11	0.02
Propane (kJ/L)	27 MJ/L[j]	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Centrifuge (kJ/L)		14.1	0.80	13.5	0.77	16.1	0.91	13.7	0.77	12.3	0.70
Centrifuge pump (kJ/L)		3.97	0.23	3.76	0.23	10.02	0.02	8.65	0.02	8.42	0.02
Cell lysing total, $\tilde{\hat{E}}_{CL}$		**3.08**	**0.46**	**3.65**	**0.54**	**5.26**	**0.50**	**3.56**	**0.50**	**3.44**	**0.48**
Pump (kJ/L)		0.02	0.00	0.02	0.00	0.03	0.02	0.04	0.02	0.02	0.02
Power supply (kJ/L)		3.05	0.46	3.63	0.54	4.66	0.46	3.14	0.46	3.05	0.45
Fans (kJ/L)		0.00	0.00	0.00	0.00	0.57	0.02	0.38	0.02	0.37	0.02
Separations total, $\tilde{\hat{E}}_S$		**130**	**25.0**	**-10.1**[s]	**12.0**	**137**	**14.3**	**67.0**	**12.9**	**27.2**	**3.51**
MHF contactor											
2 pumps (kJ/L)		0.26	0.03	1.26	0.09	1.54	0.05	0.50	0.03	2.55	0.14
Distillation											
Feed pump (kJ/L)		1.33	0.04	1.89	0.04	2.90	0.04	0.91	0.03	0.65	0.02
Vacuum pump (kJ/L)		21.9	0.04	17.5	0.04	23.1	0.04	10.4	0.03	8.01	0.02
Stage 1 heater (kJ/L)		5.44	0.04	6.28	0.04	9.99	0.04	4.03	0.03	2.52	0.02
Stage 2 heater (kJ/L)		1.82	0.04	0.44	0.04	1.28	0.04	0.49	0.03	0.39	0.02
Chill water (kJ/L)	11.23 kJ/L[p]	4.34	1.15	4.51	1.23	3.47	0.58	5.51	1.40	1.84	0.49
Heptane loss (kJ/L)	41.75 MJ/L[q]	94.5	23.6	-42.0[s]	10.5	95.2	13.6	45.2	11.3	11.2	2.80
Refining total[h], $\tilde{\hat{E}}_R$		**0.23**	**0.23**	**0.20**	**0.20**	**0.23**	**0.23**	**0.23**	**0.23**	**0.27**	**0.27**
Bio-oil refining (kJ/L)		0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
Refining materials[i] (kJ/L)	40.70 MJ/kg[q]	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01
Biomass fuel refining (kJ/L)		0.22	0.22	0.19	0.19	0.22	0.22	0.23	0.23	0.27	0.27

Table 2 (continued)

Inputs and outputs	Energy equivalent	#1 (kJ/L)	#1 Unc (kJ/L)	#2 (kJ/L)	#2 Unc (kJ/L)	#3 (kJ/L)	#3 Unc (kJ/L)	#4 (kJ/L)	#4 Unc (kJ/L)	#5 (kJ/L)	#5 Unc (kJ/L)
Total input (kJ/L), $\acute{E}_{in}$		**2560**	**185**	**2530**	**188**	**2210**	**178**	**4740**	**288**	**816**	**74.9**
Biocrude (g), M_{BC}		1.5 g	0.2 g	2.9 g	0.5 g	4.9 g	0.8 g	4.4 g	0 g	2.1 g	0 g
Biomass in slurry (g), M_{BS}		154 g	7.7 g	238 g	6.9 g	301 g	15.1 g	310 g	15.5 g	383 g	18.9 g
Bio-oil (kJ/L)	40 MJ/kg[j]	0.06	0.03	0.12	0.05	0.10	0.04	0.09	0.03	0.04	0.01
Methane (kJ/L)	55 MJ/kg	2.25	0.79	1.96	0.69	2.21	0.77	2.27	0.79	2.74	0.95
Total output (kJ/L), $\acute{E}_{out}$		**2.32**	**0.81**	**2.08**	**0.73**	**2.31**	**0.81**	**2.36**	**0.82**	**2.78**	**0.97**
EROI (x10^3)		**0.91**	**0.32**	**0.82**	**0.29**	**1.04**	**0.37**	**0.50**	**0.18**	**3.41**	**1.29**

Unless specifically included, all data is reported in kJ per liter of processed volume. Direct energy inputs have energy equivalents of 1 MJ/MJ

[a] Water was supplied from a public utility, and therefore the water supply power is not known. However, embedded energy in water is included in the water energy equivalent

[b] Recycling is not included in these data

[c] Indirect water consumption is not included in this analysis

[d] CO_2 was delivered from pressurized tanks. The energy for delivery is included in the embedded energy of CO_2 and the compressor used to provide the CO_2/air mixture

[e] Nutrients were added by hand

[f] Other minor ingredients include: copper sulfate pentahydrate, zinc sulfate heptahydrate, cobalt(II) chloride hexahydrate, vitamin B12, vitamin H, and vitamin B1. (cf. utex.org)

[g] Other minor ingredients include: calcium chloride dihydrate, magnesium sulfate heptahydrate, potassium hydrogen phosphate, sodium chloride, metal solution, soilwater, and vitamin B12. (cf. utex.org)

[h] Refining was not conducted. These data were taken from the literature [13, 15, 46] as estimates for refining energy requirements

[i] Refining materials depend on specific refining process. Data listed here is based on estimated methanol consumption [13, 15]

[j] Rough estimate

[k] [47, 48]

[l] [12, 19]

[m] [12, 19, 49–53]

[n] [12, 19, 49]

[o] [52, 54]

[p] Energy for chilled water is estimated as the sum of the embedded energy in public water supply (1.33 kJ/L) [47, 48] and the energy required to chilled water 9.4°C using an ideal refrigeration system with a COP of 3.97 (9.90 kJ/L)

[q] [55]

[r] Urea was replaced by sodium nitrate between harvesting of Batches 4 and 5

[s] Solvent from the contactor wash process of Batch 1 was recovered during Batch 2, resulting in a heptane gain

of algae produced (which is about 18 times greater than the estimated theoretical minimum CO_2 requirement) were consumed, and the impact of indirect energy associated with CO_2 is described in the "Discussion" section, below.

Using the notation specified in [33], the total energy input for algal biofuel production (per liter of growth volume processed), $\acute{E}_{BF}$, can be expressed as,

$$\acute{E}_{in} = \acute{E}_{BF} = \acute{\tilde{E}}_G + \acute{\tilde{E}}_P + \acute{\tilde{E}}_R \quad [J/L] \tag{4}$$

where $\acute{\tilde{E}}_G$, $\acute{\tilde{E}}_P$, and $\acute{\tilde{E}}_R$, are the energy requirements for growth, processing (which includes harvesting, cell lysing, and lipid separation), and refining, respectively. The tilde specifically indicates energy associated with a production step and an apostrophe accent denotes data with respect to the growth volume processed [33]. These units can be related to energy inputs per gallon of bio-oil by multiplying by the ratio of processed volume-to-bio-oil volume. The total energy input (consisting of l direct inputs and k indirect inputs), as described by Mulder and Hagens, can also be represented as

$$\acute{E}_{in} = \acute{ED}_{in} + \acute{EI}_{in} = \sum_l \acute{ED}_l + \sum_k \gamma_k \acute{I}_k \quad [J/L] \tag{5}$$

Each component of Eq. 4 can be expressed as the direct and indirect parts of Eq. 5, such as,

$$\acute{\tilde{E}}_G = (\acute{ED}_{in} + \sum_k \gamma_k \acute{I}_k)_G \quad [J/L] \tag{6}$$

Table 3 Average results of most impacting inputs for Batches 1 – 5. Data are reported in units of kJ per L of processed volume

Inputs and outputs	Ave total energy (kJ/L)	Percent of total (%)	Ave tot energy unc. (kJ/L)	Standard deviation
Growth total (kJ/L), $\acute{\tilde{E}}_G$	**2480**	**96.23**	**168**	**1400**
CO_2 (kJ/L)	68.6	2.67	14.0	28.9
Urea (kJ/L)	11.2	0.43	2.55	9.0
Instant ocean salt (kJ/L)	22.4	0.87	16.8	7.3
Lighting (kJ/L)	860	33.45	23.4	541
Compressor (kJ/L)	393	15.27	57.0	185
Mixing (kJ/L)	1055	41.00	39.9	662
Greenhouse fans (kJ/L)	60.4	2.35	12.0	9.9
Harvesting total, $\acute{\tilde{E}}_H$	**22.8**	**0.89**	**1.02**	**3.9**
Centrifuge (kJ/L)	14.0	0.54	0.79	1.37
Centrifuge pump (kJ/L)	6.96	0.27	0.10	2.9
Cell lysing total, $\acute{\tilde{E}}_{CL}$	**3.80**	**0.15**	**0.50**	**0.8**
Power supply (kJ/L)	3.51	0.14	0.47	0.7
Separations total, $\acute{\tilde{E}}_S$	**70.2**	**2.73**	**13.5**	**63.9**
Vacuum pump (kJ/L)	16.2	0.63	0.03	6.7
Stage 1 heater (kJ/L)	5.65	0.22	0.03	2.8
Chill water (kJ/L)	3.94	0.15	0.97	1.4
Heptane loss (kJ/L)	40.8	1.59	12.4	58.3
Refining total[a]**,** $\acute{\tilde{E}}_R$	**0.24**	**0.01**	**0.23**	**0.03**
Total input (kJ/L), $\acute{E}_{in}$	**2570**	**100.00**	**183**	**1410**
Biocrude (g), M_{BC}	2.1 g		0.31 g	1.5 g
Biomass in slurry (g), M_{BS}	165 g		12.8 g	107 g
Bio-oil (kJ/L)[b]	0.08	3.56	0.03	0.03
Methane (kJ/L)[b]	2.29	96.44	0.80	0.28
Total output (kJ/L), $\acute{E}_{out}$	**2.37**	**100.00**	**0.83**	**0.25**
EROI	**9.2×10^{-4}**	**-**	**3.3×10^{-4}**	

[a] Refining was not conducted. These data were taken from the literature [13, 15, 46] as estimates for refining energy requirements.

[b] Bio-oil and biomass fuel (methane) were not actually produced in the experiments.

$$\acute{\tilde{E}}_P = (\acute{ED}_{in} + \textstyle\sum_k \gamma_k \acute{I}_k)_P \quad [J/L] \tag{7}$$

$$\acute{\tilde{E}}_R = \acute{\tilde{E}}_{R_{BO}} + \acute{\tilde{E}}_{R_{BMF}} = (\acute{ED}_{in} + \textstyle\sum_k \gamma_k \acute{I}_k)_R \quad [J/L] \tag{8}$$

In Eq. 8, the refining energy requirement includes the bio-oil refining energy, $\acute{\tilde{E}}_{R_{BO}}$, and the biomass fuel refining energy, $\acute{\tilde{E}}_{R_{BMF}}$ (cf. Fig. 2). Therefore, the total energy input can be written as,

$$\acute{E}_{in} = (\acute{ED}_{in} + \textstyle\sum_k \gamma_k \acute{I}_k)_G + (\acute{ED}_{in} + \textstyle\sum_k \gamma_k \acute{I}_k)_P + (\acute{ED}_{in} + \textstyle\sum_k \gamma_k \acute{I}_k)_R \quad [J/L] \tag{9}$$

In this study, only the energy consumption for growth and processing were measured. Using the experimental data in Tables 2 and 3, the average energy consumed in each batch is (keeping refining inputs in symbolic form because they were not measured experimentally),

$$\acute{E}_{in} = 2572 + \acute{\tilde{E}}_R \quad [kJ/L] \tag{10}$$

The direct energy outputs are the biocrude (2.1 mg per liter of growth volume processed) and the biomass slurry (containing 165 mg per liter of growth volume processed, on average). The bio-oil energy content can be calculated as the mass of biocrude produced, M_{BC}, multiplied by the refining efficiency, $\varphi_{ref_{BO}}$, and the energy content of the bio-oil, v_{BO}. The bio-oil refining efficiency is defined as,

$$\varphi_{ref_{BO}} = \frac{M_{BO}}{M_{BC}} \; [-] \tag{11}$$

where M_{BO} is the mass of bio-oil produced from an associated amount of biocrude, M_{BC}. Therefore, the bio-oil energy is calculated as,

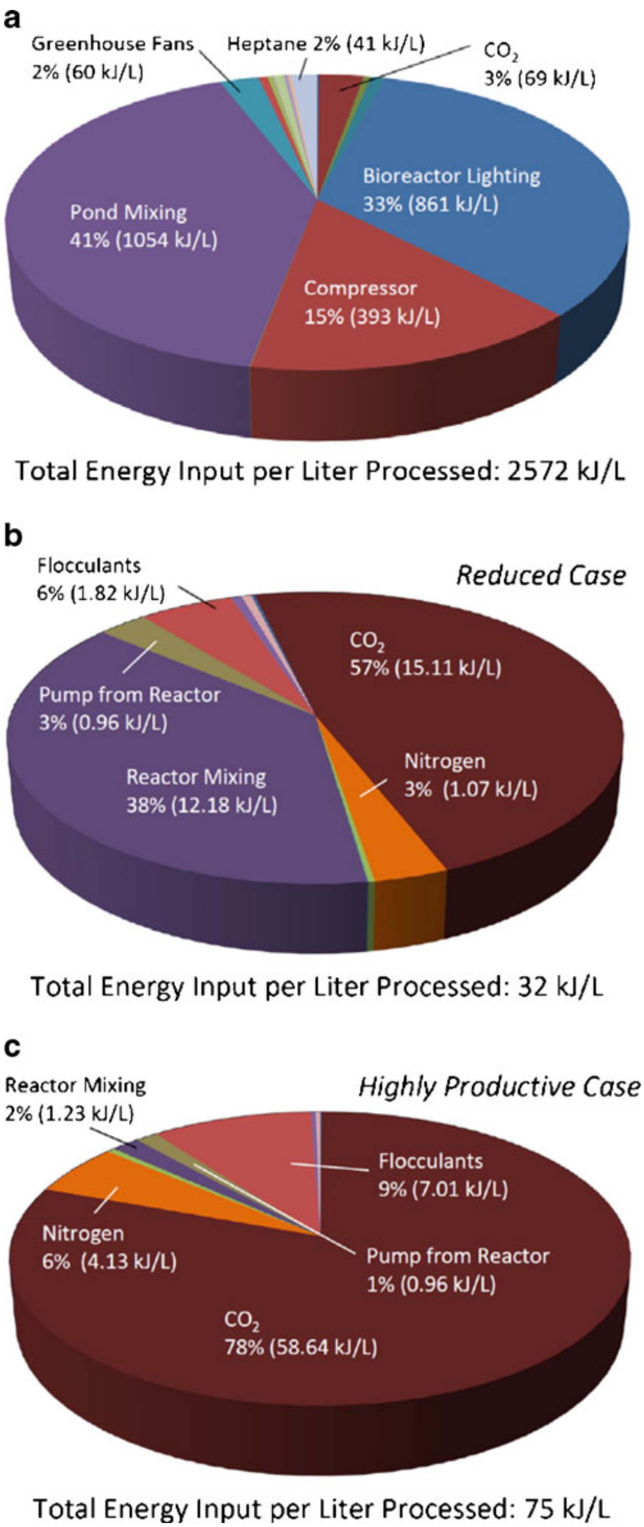

Fig. 4 **a** Most impacting energy inputs for the *Experimental Case* (EROI = 9.2×10^{-4}). **b** Most impacting *Reduced Case* energy inputs (EROI=0.079) **c** Most impacting *Highly Productive Case* inputs (EROI=0.22). Data reported in kJ per L of processed volume

$$\acute{ED}_{BO} = \acute{M}_{BC} \cdot \varphi_{ref_{BO}} \cdot \nu_{BO} \quad [J/L] \tag{12}$$

In this study, the biomass co-product is also modeled as a direct energy output with the expectation that it will be used as an energy source (to produce methane, as described below). This direct energy flow can be reported as,

$$\acute{ED}_{BMF} = \acute{M}_{BS} \cdot \varphi_{ref_{BMF}} \cdot \nu_{BMF} \quad [J/L] \tag{13}$$

where $\acute{M}_{BS}$ is the algal mass in the biomass slurry per liter of processed volume, $\varphi_{\mathrm{ref_{BMF}}}$ is the refining efficiency of the biomass into fuel, and ν_{BMF} is the biomass fuel energy content. The biomass fuel refining efficiency is defined as,

$$\varphi_{\mathrm{ref_{BMF}}} = \frac{M_{\mathrm{BMF}}}{M_{\mathrm{BS}}}[-] \tag{14}$$

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 ($\varphi_{\mathrm{ref_{BMF}}} = 0.25$) [46] and methane contains ~55 MJ/kg (ν_{BMF}=55 MJ/kg). Although not considered in this study, CHG also has the potential to enable nutrient recycling (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]).

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:

$$\acute{E}D_{out} = \acute{E}D_{BO} + \acute{E}D_{BMF} = 0.0021 \cdot \varphi_{ref_{BO}} \cdot \nu_{BO} + 0.165 \cdot \varphi_{ref_{BMF}} \cdot \nu_{BMF} \quad \left[\frac{J}{L}\right] \tag{15}$$

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,

$$EROI = \frac{\acute{E}D_{out}}{\acute{\tilde{E}}_G + \acute{\tilde{E}}_P + \acute{\tilde{E}}_R} = \frac{0.0021 \cdot \varphi_{ref_{BO}} \cdot \nu_{BO} + 0.165 \cdot \varphi_{ref_{BMF}} \cdot \nu_{BMF}}{2572 + \acute{\tilde{E}}_{R_{BO}} + \acute{\tilde{E}}_{R_{BMF}}} \tag{16}$$

If the biomass slurry is converted to methane (biomass fuel) using the CHG process described above, it is speculated that the refining efficiency ($\varphi_{ref_{BMF}}$) and biomass fuel energy content (ν_{BMF}) would be 0.25 and 55MJ/kg, respectively, yielding $\acute{E}D_{BMF}$=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 ($\varphi_{ref_{BO}} = 1$, ν_{BO}=40 MJ/kg, and $\acute{\tilde{E}}_{R_{BO}} = 4.6\, J/L$ (using 2.21 MJ for refining per kg of bio-oil [15] applied to 2.1 mg of biocrude)), the average EROI for all five batches in this study would be $9.2 \times 10^{-4} \pm 3.3 \times 10^{-4}$.

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 CO_2 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 CO_2. However, for the indoor bioreactors, the amount of CO_2 supplied was roughly 4× the amount that was absorbed. Applying this rate of absorption to 0.52 g of CO_2 required/L of growth volume processed, the CO_2 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 CO_2 consumed per liter for Batches 1–5, on average. The same assumptions are used to calculate the CO_2 required in the *Highly Productive Case*, except for an algal concentration of 1 g/L, resulting in CO_2 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 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 CO_2 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

Table 4 Quality-adjusted experimental results, Reduced Case and Highly Productive Case results, and the quality-adjusted Reduced Case and Highly Productive Case results

	Quality factors	Quality-adjusted experiments energy (kJ/L)	Reduced case energy (kJ/L)	Quality-adjusted reduced case (kJ/L)	Highly productive case energy (kJ/L)	Quality-adjusted highly productive case (kJ/L)
Growth Total, $\tilde{\acute{E}}_G$		**74,000**	**28.5**	**522**	**64.4**	**302**
Water	568	1440	0.07	37.7	0.07	37.7
CO_2	2.14	147	15.1	32.4	58.6	126
Urea	8.96	100	1.07	9.62	4.13	37.0
Phosphorus	27.4	5.69	0.09	2.51	0.35	9.65
Instant Ocean Salts	11,100	24700	0.00	0.00	0.00	0.00
Antibiotics	14,300	1350	0.01	202	0.00	67.4
Lighting	19.5	16800	0.00	0.00	0.00	0.00
Compressor	19.5	7660	0.00	0.00	0.00	0.00
Transfers	19.5	15.9	0.00	0.00	0.00	0.00
Mixing	19.5	20600	12.2	237	1.24	24.1
Greenhouse Fans	19.5	1180	0.00	0.00	0.00	0.00
Harvesting Total, $\tilde{\acute{E}}_H$		**445**	**2.78**	**25.8**	**8.04**	**46.4**
Pump from Pond	19.5	35.1	0.96	18.6	0.96	18.6
Centrifuge	19.5	272	0.00	0.00	0.00	0.00
Centrifuge Pump	19.5	136	0.00	0.00	0.00	0.00
Flocculants	3.93	0.00	1.82	7.17	7.08	27.8
Cell Lysing Total, $\tilde{\acute{E}}_{CL}$		**74.1**	**0.21**	**4.09**	**0.21**	**4.09**
Power Supply	19.5	68.4	0.21	4.02	0.21	4.02
Separations Total, $\tilde{\acute{E}}_S$		**4820**	**0.24**	**31.5**	**0.24**	**30.9**
Vacuum Pump	19.5	315	0.00	0.06	0.00	0.06
Stage 1 Heater	19.5	110	0.18	3.60	0.18	3.60
Chilled Water	568	2230	0.05	27.6	0.05	27.0
Heptane Loss	51.3	2090	0.00	0.25	0.00	0.25
Refining Total, $\tilde{\acute{E}}_R$		**0.67**	**0.24**	**0.67**	**2.13**	**8.84**
Bio-oil Refining	2.66	0.01	0.00	0.01	0.46	1.22
Refining Materials	6.40	0.06	0.01	0.06	0.85	5.41
Biomass Fuel Refining	2.66	0.60	0.23	0.60	0.83	2.21
Total Input, $\acute{E}_{in}$		**79300**	**32.0**	**584**	**75.1**	**392**
Bio-oil	14.5	1.22	0.08	1.22	8.31	120
Methane	2.66	6.08	2.29	6.08	8.30	22.1
Total Output (kJ/L), $\acute{E}_{out}$		**7.31**	**2.37**	**7.31**	**16.6**	**142**
EROI		**9.2×10^{-5}**	**0.074**	**0.013**	**0.22**	**0.36**

1.2 W/m^3, which is very optimistic as compared to data reported by Jorquera et al. [14]. With 123 days of cultivation (the average for Batches 1–5), the mixing energy in the *Reduce Case* is 12.18 kJ/L (<2% of the experimental mixing energy). The algal productivity assumed in the *Highly Productive Case* is 0.08 g/L-d, which is equivalent to 16 g/m^2-d in a 20-cm deep pond. Thus, 12.5 days are required to yield an algal concentration for harvest of 1 g/L, resulting in 1.24 kJ/L of mixing energy for the *Highly Productive Case*. The ability to achieve these mixing scenarios and yield the assumed biomass and lipid productivities is not known.

Harvesting energy includes a pump and the embedded energy of flocculants. The energy for pumping is modeled as,

$$E_{\text{pump}} = \frac{\forall \cdot \Delta P}{\eta} \tag{17}$$

where $\forall$ is the volume that is transported, ΔP is the pressure drop, and η is the pump efficiency. The pressure drop associated with pumping the growth volume for harvesting is modeled as,

$$\Delta P = \rho g \left(\Delta z + f \frac{L}{D} \frac{V^2}{2g} + K_L \frac{V^2}{2g} \right) \tag{18}$$

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/s^2). This relationship yields a ΔP of 573 kPa, which corresponds to an energy consumption of 0.96 kJ/L (assuming η=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 (ΔP= 138 kPa, η=0.6, and $\forall = \frac{1}{65} \overline{V}_P$ (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 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 ($\forall = \frac{1}{1{,}300} \cdot \overline{V}_P$, ΔP=7 kPa, and η=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 ($\forall = \frac{1}{1{,}300} \cdot \overline{V}_G$, ΔP=69 kPa, and η=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, $\forall = \frac{1}{1{,}300} \cdot \overline{V}_G$, 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, $\acute{M}_{CW}$, is estimated to be 4.3 g (4.3 mL) per liter of processed volume according to,

$$\acute{M}_{CW} = \frac{Q}{c_p \cdot \Delta T} \tag{19}$$

where Q is the amount of heat required to chill the water (which is equal to the amount of heat required to vaporize the heptane, 0.17 kJ per liter of growth volume processed), c_p is the specific heat capacity of water (4.18 kJ/(kg-K)), and ΔT is the temperature difference 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,

$$EROI_{RC} = \frac{0.0021 \cdot \varphi_{ref_{BO}} \cdot \nu_{BO} + 0.65 \cdot \varphi_{ref_{BMF}} \cdot \nu_{BMF}}{31.77 + \tilde{\acute{E}}_R} \tag{20}$$

If the unknown terms in Eq. 20 are estimated with the same values as for Eq. 16 ($\varphi_{\mathrm{ref_{BO}}} = 1$, ν_{BO}=40 MJ/kg, $\tilde{\acute{E}}_{R_{BO}}$=4.6 J/L, $\varphi_{\mathrm{ref_{BMF}}} = 0.25$, ν_{BMF}=55 MJ/kg, and $\tilde{E}_{R_{BMF}} = 0.23\ kJ/L$), 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,

$$\acute{ED}_{out} = \acute{ED}_{BO} + \acute{ED}_{BMF} \quad [J/L] \tag{21}$$

$$\acute{ED}_{out} = P_{GM} \cdot t_c \cdot \varphi_{harv} \cdot \varphi_{cellys} \cdot (\varphi_{sep} \cdot \varphi_{ref_{BO}} \cdot v_{BO} + (1-LF) \cdot \varphi_{sep_{BS}} \cdot \varphi_{ref_{BMF}} \cdot v_{BMF}) \quad \left[\frac{J}{L}\right] \tag{22}$$

with lipid fraction (LF)=0.3, useful lipid fraction (ULF)=1, φ_{harv}=0.9, φ_{cellys}=0.95, $\varphi_{\text{sep}_\text{L}} \times \varphi_{\text{sep}_\text{UL}} = 0.9$, v_{BO}=40 MJ/kg, $\varphi_{\text{ref}_\text{BO}} = 0.9$, $\varphi_{\text{sep}_\text{BS}} = 1$, $\varphi_{\text{ref}_\text{BMF}} = 0.25$, and v_{BMF}= 55 MJ/kg. This yields

$$\acute{ED}_{out} = 8.31 + 8.30 \left[\frac{kJ}{L}\right] = 16.61\ kJ/L \tag{23}$$

Therefore, using an $\widetilde{E}_\text{R} = 2.13$ kJ/L, the EROI can be represented as,

$$EROI_{HPC} = \frac{16.61}{72.92+2.13} = 0.22 \tag{24}$$

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 factor of 2.1, while the energy outputs have relatively high quality factors. This result is in contrast with the *Experimental Case* and the *Reduced Case*, where electricity (with high quality) was the primary energy input.

Literature Model Results

The *Literature Model* is a spreadsheet model that combines data from studies in the literature that are relevant to this study. Table 5 lists the data used and the associated 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 ($\grave{\chi}$) is used to represent data in units of J/(L-day). In order to compare directly with the experimental results, the analytical 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, which are not included in the analysis used for the analytical model data. For these reasons, the analytical data were left in the rate form of J/(L-day).

The energy consumed in the *Literature Model* for growth, harvesting, cell lysing, lipid separations, and refining account for 65%, 5%, 4%, 15%, and 11%. As for the experimental results, growth is the most energy-intensive portion of the production pathway, followed by lipid separation.

CO_2 consumption is responsible for 54% of the total energy input in the *Literature Model* (as compared to 47% and 78% in the *Reduced Case* and *Highly Productive 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 *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,

$$EROI = \frac{P_{BC} \cdot \varphi_{ref_{BO}} \cdot v_{BO} + P_{BS} \cdot \varphi_{ref_{BMF}} \cdot v_{BMF}}{(\grave{ED}_{in} + \sum_k \gamma_k \grave{I}_k)_G + (\grave{ED}_{in} + \sum_k \gamma_k \grave{I}_k)_P + (\grave{ED}_{in} + \sum_k \gamma_k \grave{I}_k)_R} \tag{25}$$

where P_BC is the biocrude productivity and P_BS is the biomass in slurry productivity. The biocrude productivity is calculated according to,

$$P_\text{BC} = P_\text{GM} \cdot \varphi_\text{harv} \cdot \varphi_\text{cellys} \cdot \varphi_\text{sep} \left[\frac{\text{g}}{\text{L-d}}\right] \tag{26}$$

and the biomass in slurry productivity (in g of algal mass per L per day) is,

$$P_\text{BS} = P_\text{GM} \times (1 - \text{LF}) \cdot \varphi_\text{harv} \cdot \varphi_\text{cellys} \cdot \varphi_{\text{sep}_\text{BS}} \left[\frac{\text{g}}{\text{L-d}}\right] \tag{27}$$

where each of these terms is listed in Table 3 (and defined in [33], except for $\varphi_{\text{sep}_\text{BS}}$, 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, $\grave{\tilde{E}}_{R_{BO}}$, and biomass fuel refining, $\grave{\tilde{E}}_{R_{BMF}}$, as,

$$\grave{\tilde{E}}_R = (\grave{ED}_{in} + \textstyle\sum_k \gamma_k \grave{I}_k)_R = \grave{\tilde{E}}_{R_{BO}} + \grave{\tilde{E}}_{R_{BMF}} \quad \left[\frac{J}{L-d}\right] \tag{28}$$

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

$$\text{EROI} = \frac{0.006\left[\frac{\text{g}}{\text{L-d}}\right] \cdot v_\text{BO} + 0.013\left[\frac{\text{g}}{\text{L-d}}\right] \cdot v_\text{BMF}}{2657[\text{J}/(\text{L-d})]} \tag{29}$$

If the unknown terms in Eq. 29 are estimated by optimistic values (v_BO=40 MJ/kg and v_BMF=55 MJ/kg) the EROI for the *Literature Model* would be 0.35. Since the

Table 5 Literature model EROI data

Inputs and outputs	Model value	Energy equiv.[a]	Total energy (J/(L-d))	% of total	Data, [source]
Growth energy, $\tilde{\tilde{E}}_G$			**1800**	**65**	
Mixing (J/(L-d))	100	1 MJ/MJ	100	4	22 [4], 50 [60], 31–53 [59], 6.4 [12], 100 [13], 28–240 [19], 346 (4,800–220,000 bioreactors) [14], 674 [15], 72 [18], 60 [16], 130 [17], 58 [40]
Water supply (surface to pond)[b] (J/(L-d))	20	1 MJ/MJ	20	1	1.1 [59], 43 [60], 7.7 [12], 12 [19]
Nutrient supply (J/(L-d))	2	1 MJ/MJ	2	0	2.0 [59], 2.6 [60], In Mixing [15]
Carbon supply (J/(L-d))	40	1 MJ/MJ	40	1	120 [59], 11 (In Mixing) [13], 6.6 [16], 35 [17], 0 [12], In Mixing [15]
Direct water use[c] (mL H_20 consumed/L/d)	0.2	1.33 kJ/L	0.3	0	0.16–0.23[h] [12], 0.33 [13]
Nutrients			–		
Nitrogen (mg/(L-d))	3	59 MJ/kg	130	5	1.6–2.2 [12], 0.7–3.9 [13], 10 [19], 60 [15], 0.56 [18], 5 [16], 0.01 [17]
Phosphorus (mg/(L-d))	0.5	44 MJ/kg	22	1	0.2–0.3 [12], 0.2–0.6 [13], 0.6 [19], 8.2 [15], 0.06 [18], 0.7 [16], 0.0008 [17]
CO_2 (mg/(L-d))	200	7.33 MJ/kg	1500	54	255–510 [4], 34–47 [12], 130–150 [13], 240 [19], 170 [18], 113 [16], 0.0004 [17]
Biomass productivity[d] (mg/(L-d)), P_{GM}	80	–	–		50–170 [3], 95–300 [4], 19–26 [12], 64–83 [13], 80 [19], 35 [14], 410 [15], 100 [18], 83 [16], 200 [17], 70 [40], 550 [61]
Lipid fraction (−), ***LF***	0.23	–	–		0.25 [1], 0.22 [2], 0.3 [14], 0.5 [15], 0.5 [17], 0.25 [40], 0.23 [61], 0.15 [62], 0.21–0.25 [60], 0.16–0.75 [63], 0.18–0.39 [13], 0.2–0.35 [19]
Useful lipid fraction (−), ***ULF***	0.50	–	–		0.4 [19], up to 0.8 [1], 1 (In LF) [40], 0.2–0.4 [19]
Harvesting energy, $\tilde{\tilde{E}}_H$			**140**	**5**	
Pumping energy (J/(L-d))	40	1 MJ/MJ	40	1	46 [16], 37 [19]
Concentration energy[e] (J/(L-d))	100	1 MJ/MJ	100	4	11 [12], 92 [13], 237 [19], 500 [15], 13 [16], 0 [17], 63 [60], 37 [59]
Drying energy (J/(L-d))	0[e]	1 MJ/MJ	0.00	0.00	1,135 [13], 4,200 [19], 0 [17]
Flocculants (mg/(L-d))	0[e]	NA	0.00	0.00	38–50 [13], 0.24 [18], 0.16 [19]
Harvesting efficiency (−)	0.90	–	–		0.9 [13], 0.85 [19], 0.95 [17], 0.95 [64]
Cell lysing energy, $\tilde{\tilde{E}}_{CL}$			**100**	**4**	
Lysing electricity[f]	100	1 MJ/MJ	100	4	90 [10]
Lysing efficiency	0.92	–	–		0.92 cf. Tables 1–4
Separation energy, $\tilde{\tilde{E}}_S$			**415**	**15**	
Electricity (J/(L-d))	100	1 MJ/MJ	100	4	17–83 [13], 206 [15], 5.3 [40]
Heat (J/(L-d))	300	1 MJ/MJ	300	11	76–221 [13], 641 [15], 210 [40]
Solvent (mg/(L-d))	0.35	41.75 MJ/L	15	1	0.16–0.54 [13]
Fraction of lipids recov.	0.90		–		0.7 [13], 0.9 [19], 0.9 [15]
Bio-oil refining energy, $\tilde{\tilde{E}}_{R_{BO}}$			**230**	**8**	
Refining energy (J/(L-d))	150	1 MJ/MJ	150	5	8.8–21 [13], 428 [15]
Methanol (mg/(L-d))	2	40.7 MJ/kg[g]	80	3	1.1–2.7 [13], 0.02 [15]
Refining efficiency	0.90	–	–		NA
Biomass fuel refining energy, $\tilde{\tilde{E}}_{R_{BMF}}$			**70**	**3**	
Biomass refining energy (J/(L-d))	70	1 MJ/MJ	70	3	70 [46]
Biomass refining efficiency	0.25	–	–	–	0.25 [46]
Energy input (J/(L-d)), $\tilde{\tilde{E}}_{in}$			**2700**	**100**	
Output					
Bio-oil (g/(L-d)),	0.006	40 MJ/kg	250		0.006 [19], 0.16 [15], 660 J/(L-d) [40][j]
Methane (g/(L-d))	0.013	55 MJ/kg	700		350 J/(L-d)[i] [18], 630 J/(L-d) [40][j]

Table 5 (continued)

Inputs and outputs	Model value	Energy equiv.[a]	Total energy (J/(L-d))	% of total	Data, [source]
Energy output (J/(L-d)), $\grave{E}_{out}$			**950**		
EROI			**0.35**		cf. [12, 13, 15, 16, 17, 18, 19]

[a] References listed in Tables 2–4.

[b] It is assumed that water is available at the ground surface (*e.g.*, seawater). Energy for recycling water is neglected (which could potentially be accomplished by gravity).

[c] Indirect water use is omitted from this study, although it is a large contribution in other studies (*e.g.*, Clarens et al. [12]).

[d] This volumetric productivity (0.08 g/(L-d)) corresponds to an areal productivity of 16 g/m^2/d, which has been demonstrated at scale. (Sheehan J. et al. [2])

[e] Harvesting is modeled as centrifugation without flocculation or additional drying.

[f] Lysing energy is estimated from personal experience, assuming 200 J/pulse and a grown mass productivity of 0.08 g/(L-d).

[g] [55]

[h] Only includes carry-out water

[i] Electricity produced from methane

[j] Case 5 is used for Lundquist et al.

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, and separations), $\acute{\hat{E}}_P$, 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, $\acute{\hat{E}}_P + \acute{\hat{E}}_R$, 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, $NE\acute{C}_{GV}$, is the energy contained in the growth volume per liter, $E\acute{C}_{GV}$, minus the energy inputs for growth per liter, $\acute{\hat{E}}_G$, and can be expressed as,

$$NE\acute{C}_{GV} = E\acute{C}_{GV} - \acute{\hat{E}}_G = P_{GM} \cdot t_c \cdot (LF \cdot \nu_L + (1 - LF) \cdot \nu_{BM}) - \acute{\hat{E}}_G \quad [\tfrac{J}{L}] \tag{30}$$

where ν_L is the energy content of the lipids, ν_{BM} is the energy content of the non-lipid biomass, and the other terms are defined above. The $NE\acute{C}_{GV}$ is a similar metric as the “Net Energy Ratio” defined by Jorquera et al. [14] to evaluate growth systems. However, the $N\acute{E}C_{GV}$ 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, $\nu_L = \nu_{BO}$, and $\nu_{BM} = 14$ MJ/kg), Eqs. 16 and 30 can be combined and manipulated to be

$$\acute{\tilde{E}}_P + \acute{\tilde{E}}_R \leq N\acute{E}C_{GV} \quad (for\ EROI \geq 1\ and\ assuming\ ideal\ processing) \tag{31}$$

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 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/(m^2-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,

$$\grave{ED}_{out} = 0.92\left[\frac{g}{L-d}\right]\cdot 0.9\cdot 0.95\cdot(0.3\cdot 1\cdot 0.9\cdot 0.9\cdot 40[kJ/g] + (1-0.3)\cdot 1\cdot 0.25\cdot 55[kJ/g]) \tag{32}$$

$$\grave{ED}_{out} = 15.2\left[\frac{kJ}{L-d}\right] \tag{33}$$

To achieve this biomass productivity, additional carbon, nitrogen, and phosphorus would be required. For each kilogram of algae, the minimum possible CO_2, 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,

$$\grave{ED}_{in_{nutrients}} = 0.92\left[\frac{g_{GM}}{L-d}\right]\cdot\left(1.8\left[\frac{g_{CO2}}{g_{GM}}\right]\cdot 7.33\left[\frac{kJ}{g_{CO2}}\right] + 0.07\left[\frac{g_N}{g_{GM}}\right]\cdot 59\left[\frac{kJ}{g_N}\right] + 0.008\left[\frac{g_P}{g_{GM}}\right]\cdot 44\left[\frac{kJ}{g_P}\right]\right) \tag{34}$$

$$\grave{ED}_{in_{nutrients}} = 16.3\left[\frac{kJ}{L-d}\right] \tag{35}$$

Therefore, the embedded energy expense in CO_2 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 CO_2 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 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 CO_2 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 CO_2 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 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 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, CO_2 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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Table 6 Summary of results

Case	Description	Growth system	Growth inputs, $\widetilde{E}_G$	Processing inputs, $\widetilde{E}_P$	Refining inputs, $\widetilde{E}_R$	Energy output, ED_{out}	EROI	Quality-adjusted EROI
Experimental	Inputs and outputs measured	Bioreactors, tanks, and ponds	2500 kJ/L	97 kJ/L	0.24 kJ/L	2.37 kJ/L (0.26 g/L, ~1.8% LF)	9.2×10^{-4}	9.2×10^{-5}
Reduced Inputs	Inputs estimated, experimental outputs	Bioreactors	29 kJ/L	3.2 kJ/L	0.24 kJ/L	2.37 kJ/L (0.26 g/L, ~1.8% LF)	0.079	0.013
Highly Productive	Inputs estimated, optimistic production outputs	Bioreactors	64 kJ/L	8.5 kJ/L	2.1 kJ/L	16.61 kJ/L (1 g/L, 30% LF)	0.22	0.36
Literature Model	Data based on values reported in the literature	NA	1.8 kJ/L-d	0.7 kJ/L-d	0.3 kJ/L-d	0.96 kJ/L-d (0.08 g/L-d, 23% LF, 50% ULF)	0.35	NA

References

1. Hu Q, Sommerfeld M, Jarvis E, Ghirardi M, Posewitz M, Seibert M et al (2008) Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. Plant J 54 (4):621–639
2. Sheehan J, Dunahay T, Benemann J, Roessler P (1998) A Look Back at the U.S. Department of Energy's Aquatic Species Program, Biodiesel from Algae. NREL and U.S. Department of Energy's Office of Fuels Development (NREL/TP-580-24190)
3. Schenk P, Thomas-Hall S, Stephens E, Marx U, Mussgnug J, Posten C et al (2008) Second generation biofuels: high-efficiency microalgae for biodiesel production. BioEnergy Res 1(1):20–43
4. Benemann J, Oswald W (1996) Systems and economic analysis of microalgae ponds for conversion of CO2 to biomass. In: Department of Energy
5. Wijffels RH, Barbosa MJ An outlook on microalgal biofuels. Science 329:796–799
6. Cleveland CJ (2005) Net energy from the extraction of oil and gas in the United States. Energy 30:769–782
7. Kubiszewski I, Cleveland CJ, Endres PK (2010) Meta-analysis of net energy return for wind power systems. Renewable Energy 35:218–225
8. Farrell AE, Plevin RJ, Turner BT, Jones AD, O'Hare M, Kammen DM (2006) Ethanol can contribute to energy and environmental goals. Science 311:506–508
9. Shapouri H, Duffield J, Wang M (2002) The energy balance of corn ethanol: an update. In: USDA Agricultural Economic Report No. 814
10. Beal CM (2011) Constraints on algal biofuel production. In: Mechanical Engineering. Doctoral Dissertation, University of Texas at Austin, Austin TX
11. King CW, Zarnikau J, Henshaw P (2010) Defining a Standard Measure for Whole System EROI Combining Economic "Top-Down" and LCA "Bottom-up" Accounting. In: ASME ES2010. Phoenix, AZ
12. Clarens AF, Resurreccion EP, White MA, Colosi LM (2010) Environmental life cycle comparison of algae to other bioenergy feedstocks. Environ Sci Technol 44(5):1813–1819
13. Lardon L, Helias A, Sialve B, Steyer J, Bernard O (2009) Life-cycle assessment of biodiesel production from microalgae. Environ Sci Technol 43(17):6475–6481
14. Jorquera O, Kiperstok A, Sales EA, Embiruçu M, Ghirardi ML (2010) Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. Bioresour Technol 101(4):1406–1413
15. Batan L, Quinn J, Willson B, Bradley T (2010) Net energy and greenhouse gas emission evaluation of biodiesel derived from microalgae. Environ Sci Technol 44(20):7975–7980
16. Collet P, Helias A, Lardon L, Ras M, Goy R, Steyer J (2011) Life-cycle assessment of microalgae culture coupled to biogas production. Bioresour Technol 102:207–214
17. Kadam KL (2002) Environmental implications of power generation via coal-microalgae cofiring. Energy 27(10):905–922
18. Campbell PK, Beer T, Batten D (2010) Life cycle assessment of biodiesel production from microalgae in ponds. Bioresour Technol 102(1):50–56
19. Murphy C (2010) Analysis of innovative feedstock sources and production technologies for renewable fuels: chapter 6. Algal Oil Biodiesel, EPA: XA-83379501-0. In: Allen D, Hebner R (eds) University of Texas at Austin
20. Xu L, Brilman DWF, Withag JAM, Brem G, Kersten S (2011) Assessment of a dry and a wet route for the production of biofuels from microalgae: energy balance analysis. Bioresour Technol 102:5113–5122
21. Molina Grima E, Belarbi EH, Acién Fernández FG, Robles Medina A, Chisti Y (2003) Recovery of microalgal biomass and metabolites: process options and economics. Biotechnol Adv 20:491–515
22. Mulder K, Hagens NJ (2009) Energy return on investment: toward a consistent framework. AMBIO: J Hum Environ 37:74–79
23. Kim S, Dale BE (2005) Life cycle assessment of various cropping systems utilized for producing biofuels: bioethanol and biodiesel. Biomass Bioenergy 29:426–439
24. Patzek T (2006) A First-law thermodynamic analysis of the corn–ethanol cycle. Nat Resour Res 15:255–270
25. Pimentel D, Patzek TW (2005) Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. Nat Resour Res 14:65–76
26. Poldy F (2008) Net energy and strategic decision-making. Biofuels, Bioprod Biorefin 2:389–392
27. Ponton JW (2009) Biofuels: thermodynamic sense and nonsense. J Cleaner Prod 17:896–899
28. Schmer MR, Vogel KP, Mitchell RB, Perrin RK (2008) Net energy of cellulosic ethanol from switchgrass. Proc Natl Acad Sci 105:464–469
29. Berberoglu H, Barra N, Pilon L, Jay J (2008) Growth, CO_2 consumption and H_2 production of *Anabaena variabilis* ATCC 29413-U under different irradiances and CO_2 concentrations. J Appl Microbiol 104:105–121
30. Tsukahara K, Sawayama S (2005) Liquid fuel production using microalgae. J Jpn Pet Inst 48:251
31. Sialve B, Bernet N, Bernard O (2009) Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable. Biotechnol Adv 27:409–416
32. Posten C, Schaub G (2009) Microalgae and terrestrial biomass as source for fuels—a process view. J Biotechnol 142:64–69
33. Beal C, Smith C, Webber M, Ruoff R, Hebner R (2011) A framework to report the production of renewable diesel from algae. BioEnergy Res 4:36–60
34. Melis A, Melnicki MR (2006) Integrated biological hydrogen production. Int J Hydrogen Energy 31:1563–1573
35. Amin S (2009) Review on biofuel oil and gas production processes from microalgae. Energ Convers and Manag 50:1834–1840
36. Demirbas A (2010) Use of algae as biofuel sources. Energ Convers and Manag 51:2738–2749
37. Hillen LW, Pollard G, Wake LV, White N (1982) Hydrocracking of the oils of *Botryococcus braunii* to transport fuels. Biotechnol Bioeng 24:193–205
38. Guschina IA, Harwood JL (2006) Lipids and lipid metabolism in eukaryotic algae. Prog Lipid Res 45:160–186
39. Tornabene TG, Holzer G, Lien S, Burris N (1983) Lipid composition of the nitrogen starved green alga Neochloris oleoabundans. Enzyme Microb Technol 5:435–440
40. Lundquist TJ, Woertz IC, Quinn NWT, Benemann JR (2010) A Realistic technology and engineering assessment of algae biofuel production
41. Beal CM, Hebner RE, Webber ME, Ruoff RS, Seibert AF, King CW (In Review) Constraints on algal biofuel production. Environmental Science & Technology
42. Cleveland CJ, Kaufmann RK, Stern DI (2000) Aggregation and the role of energy in the economy. Ecol Econ 32:301–317
43. (2010) Annual Energy Outlook 2010. In: Energy Information Agency
44. Beal CM, Hebner RE, Romanovicz D, Mayer CC, Connelly R (In Review) Progression of lipid profile and cell structure in a research production pathway for algal biocrude. Renewable Energy
45. Poenie M (2009) Personal Communication, Beal C.M., HPLC Analysis
46. Oyler J (2010) Personal Communication, Beal C.M., Genifuel: Catalytic Hydrothermal Gasification
47. King CW, Holman AS, Webber ME (2008) Thirst for energy. Nat Geosci 1(5):283–286

48. Goldstein R, Smith W (2002) Water & Sustainability (Vol. 4): U.S. Electricity Consumption for Water Supply & Treatment. Palo Alto, CA: EPRI #1006787
49. Ramírez CA, Worrell E (2006) Feeding fossil fuels to the soil: An analysis of energy embedded and technological learning in the fertilizer industry. Resour Conserv Recycl 46(1):75–93
50. Sheehan J, Camobreco V, Duffield J, Shapouri H, Graboski M, Tyson KS (2000) An overview of biodiesel and petroleum diesel life cycles. In: NREL/TP-580-24772
51. Wu H, Fu Q, Giles R, Bartle J (2007) Production of mallee biomass in western Australia. Energy Balance Anal Energy Fuels 22(1):190–198
52. (2008) U.S. Life-Cycle Inventory Database. August 16, 2008 ed: NREL
53. Worrell E, Phylipsen D, Einstein D, Martin N (2000) Energy use and energy intensity of the U.S. chemical industry. Report nr LBNL–44314. 40 p.
54. Feldman SR (2005) Sodium Chloride. Kirk-Othmer Encyclopedia of Chemical Technology: John Wiley & Sons, Inc.
55. Capello C, Fischer U, Hungerbuhler K (2007) What is a green solvent? A comprehensive framework for the environmental assessment of solvents. Green Chem 9(9):927–934
56. Yen HW, Brune DE (2007) Anaerobic co-digestion of algal sludge and waste paper to produce methane. Bioresour Technol 98:130–134
57. Weyer K, Bush D, Darzins A, Willson B Theoretical maximum algal oil production. BioEnergy Research 3:204–213
58. Chisti Y (2007) Biodiesel from microalgae. Biotechnol Adv 25:294–306
59. Benemann J, Oswald W (1996a) Systems and economic analysis of microalgae ponds for conversion of CO2 to biomass. Department of Energy, Citing 1987 Study
60. Benemann J, Oswald W (1996b) Systems and economic analysis of microalgae ponds for conversion of CO2 to biomass. Department of Energy, Citing Study by Weissman and Goeble, 1982
61. Pruvost J, Van Vooren G, Cogne G, Legrand J (2009) Investigation of biomass and lipids production with *Neochloris oleoabundans* in photobioreactor. Bioresour Technol 100(23):5988–5995
62. Miao X., Wu Q (2006) Biodiesel production from heterotrophic microalgal oil. Bioresour Technol 97(6):841–846
63. Meng X, Yang J, Xu X, Zhang L, Nie Q, Xian M (2009) Biodiesel production from oleaginous microorganisms. Renewable Energy 34(1):1–5
64. Yang J, Xu M, Zhang X, Hu Q, Sommerfeld M, Chen Y (2010) Life-cycle analysis on biodiesel production from microalgae: water footprint and nutrients balance. Bioresour Technol 102 (1):159–165
65. Bolhouse A, Ozkan A, Berberoglu H (2010) Rheological study of algae slurries for minimizing pumping power. In: ASME-IMECE 2010. Vancouver, BC Canada
66. Henderson R, Parsons S, Jefferson B (2008) The impact of algal properties and pre-oxidation on solid–liquid separation of algae. Water Res 42:1827–1845
67. Poelman E, De Pauw N, Jeurissen B (1997) Potential of electrolytic flocculation for recovery of micro-algae. Resour Conserv Recycl 19:1–10