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# The Energy Return on Investment for Algal Bio crude: 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 Texasat Austin (UT). During the period of this assessment, algaewere grown at several cultivation scales and processed using centrifugation for harvesting, electromechanical cellly sing, and a microporoushollow fiber membrane contactor for lipid separation. The separated algal lipids represent abiocrude product that could be refined into fuel and the post-extraction biomass could be converted to methane. To determine the EROI, as econd-order analysis was con-

 $\label{eq:constraint} ducted, which includes direct and indirect energy flows, but does not include energy expenses associated with capital investments. The EROI for the production process evaluated here was significantly less than 1, however, the majority of the energy consumption resulted from non-$ 

optimizedgrowthconditions. While the experimental results do not represent an expected typical case EROI for algalfuels, the approach and end-to-end experimental determination of the different inputs and outputs provides a useful outline of the important parameters to consider insuch an analysis. The *Experimental Case* results are the first known experimental energy balance for an

 $KeywordsAlgae \cdot {\tt Energy return on investment} \cdot {\tt Energy balance} \cdot {\tt Netenergy ratio} \cdot {\tt Biofuel} \cdot {\tt Biodiesel}$ 

#### Introduction

Algae are a potential biofuel feedstock that have received

agreatdealofresearchinterest. Theoretically, algaearepromi sing as feedstock because they grow rapidly, do notrequire fresh water or arable land, and, in some cases, canproduce large amounts of energy products (e.g., lipids). These potential advantages have been discussed at lengthelsewhere [1–

5].Practically,however,algalbiofuelpro- duction has proven to be quite challenging. One way toevaluate the production of algal biofuels is to calculate theenergyreturnon(energy)investment(EROI),whichissim ilar to the net energy ratio (NER), and can be used toassess the feasibility and sustainability of an energy source.Inbrief,theEROIistheamountofenergyproduceddiv idedbytheamountofenergyrequiredforthatproduction,andi thasbeenusedtocharacterizemanyresources.Forexample,t heEROIforproductionofconventionaloilandgas,coal,wind energy,andcorn

ethanol has been estimated to be  $\sim$  -

cially, the EROI must be competitive with those for currentenergy sources. Similarly, the financial return on invest-ment (FROI) for algal fuels must be competitive with thoseforcurrentenergysources.Therelationshipbetweent he

EROI and FROI is considered in this study, and character-izedmorethoroughlyelsewhere[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

Department of Mech venugopal@gmail.com,srikanth.nrpt@gmail.com, zill22@yahoo.com <u>ISL Engineering College.</u> International Airport Road, Bandlaguda, Chandrayangutta Hyderabad - 500005 Telangana, India. scaleprocesses, which are often known apriori to be une conomical. 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 nocommercial 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-toend experimental data to populate the model.

Thescopeofthisstudyislimitedtoevaluatingoperatingen ergyexpenses(includingdirectandindirectenergyflows,

but omitting capital energy expenses) according tothe 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.,

highvaluefuels, mainly electricity) for production of lowerq uality fuels (i.e., lower value fuels, bio-oil and methane). The experimental results reported in this study are not representative of a commercial-

scalealgalbiocrudefacility.Such a facility does not yet exist. Moreover, it is unlikelythere will be published information on commercial pro-cessesuntil theindustrymatures, as this information ismostly proprietary. The value of this study is to utilize afunctional research facility to develop the experimental app roach for determining the EROI for algal biocrude productio n. This type of analysis will be important for the algal fuels industry, as it has been for current bio fuel indust

ries[8,23–28].ItisexpectedthattheEROIwillbe

improved for optimized growth conditions, refined processing methods, and with the application of future Methods and Materials

ProductionPathway

There are several energy carriers that can be produced fromalgae, including renewable diesel (such as biodiesel fromlipids), ethanol (from carbohydrates), hydrogen

producedphotobiologically,methane(viaanaerobicdiges tionorgasification),andelectricityviadirectcombustion[17,29–36].Biodieselisthemostcommonlystudiedalgal

biofuel, and can be produced by transesterification of algallipids [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 highlyvariable [1, 2, 38, 39]. As a result, it is not clear

technology(andbiotechnology)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 totalprocessed volume of roughly 7,600 L), where outdoor

algalgrowthwasintegratedwithseveralcriticalprocessings teps. The research focus is on processing; growth is done toprovide material to process. The growth facilities at UTwerebuilttobalancecapitalcostswithoperationalcostsf orlow-volume production on a research budget. Consequent-

ly,thegrowthprocessincludedmanyinefficienttechniques( e.g., artificial lighting, oversized pumps, etc.) that wereappropriateforaresearchsetting(butnotacommercial

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, ne arly 20

large-scale batches have been completed (with processedvolumesof~900–4,000Lperbatch).

The*Reduced*(*Inputs*)*Case*presentsspeculatedenergy consumption values for the operation of a similar produc-tion pathway at commercial scale, while yielding the same energy outputs as obtained in the experiments. The HighlyProductive Case uses similar assumptions for the energy inputs as the Reduced Case and assumes greater energyoutputproductivity.Inaddition,theLiteratureMod elprovides an estimate for the EROI of algal biocrude basedon 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 the ore tical data.

whatrefining processes will be used on an industrial scale. Withthis in mind, the experiments in this study measured theenergy 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. Inotherwords,thisisa"strain-to-

refinerydoor"analysis.However, the energy requirement of refining, noted as  $E_{\rm R}$ ,willbeincludedintheanalysisinsymbolicnotation(acc ordingtoaconventionestablishedinapriorpublication[33]) andestimatedvalueswillbeusedwhennecessary.

Figure 1 presents the production pathway used at UT inthis investigation. In this approach, algae were grown inoutdoor "raceway" ponds ( $\sim 0.2$  m deep),

which are similartothosediscussedinpreviousstudies[2-

Growth: Ponds and ponds were in sandtheresultsofthis Algal Culture Photobioreactors Fig. 1The algal t (~1500 L) Day 1: Harvest, 8 hr Harvesting: Centrifugation Harvested Algae (~24 L) **Cell Lysing: Electromechanical** Day 2: Lysing, 2 hr Pulsing Lysed Algae (~24 L) Separations: Microporous Hollow Day 3: Extraction 12 hr Fiber Membrane Contactor Biocrude **Biomass Slurry** (~24 L) (~4 mL) **Refining: Not Conducted** Biomass **Bio-oil** Fuel

4,40]andthe

The ERO I analysis used in this study is based on the framework provided by Mulder and Hagens [22]. Specifically, the second-

orderEROImodelhasbeenadopted(cf.Fig.2in[22]),which accountsfordirectenergy flows as well as indirect energy flows, as shown inEq. 1. The process specific nomenclature in this study isbasedontheframeworkprovidedbyBealetal.[33]

$$ED_{out} \mathbf{p}^{\mathsf{F}}_{j} v_{j} o_{j}$$

crude)andbiomassfuel(producedfromthebiomassslurry) . Thus, the direct energy output includes the biooilenergy, $ED_{BO}$ ,andthebiomassfuelenergy, $ED_{BMF}$ ,as,

 $ED_{out}$   $4ED_{BO}$   $bED_{BMF}$ 

# ð2Þ

If the biomass is used to produce non-

energyproducts(e.g.,protein,nutritionalsupplements,orc osmetics),thenitcouldberepresentedasanindirectenergyf

the energy consumed in the smaller growth volume wasallocated between the two growth volumes according to

Where *P* is the price (in k/kg), EE is the energy equivalent(withunitsofMJ/kg),andEP<sub>coal</sub>istheenergyprice forcoal(1.4/GJ). By using quality factors that are based on price,thequalityadjustedEROIanalysisisequivalenttothepartialFROIanal ysisthatiscalculatedusingthesameinputs and outputs (i.e., excluding capital expenses, low.InEq.1, indirect energy flows include material inputs that contain embedded energy (e.g., the embedded energy innit trogen fertilizer) and material outputs. Specifically, the quantity of the *k*th non-energy input is  $I_k$  and the perunit energy equivalent value for that input is denoted as  $\gamma_k$ . Similarly, the quantity of the *j*th non-

energyoutputisOjandtheper-

unitenergyequivalentvalueforthatoutput

isdenoted as  $v_j$ . However, in this study, there are no indirecte nergy outputs. Aquality-adjusted EROI (analogous to apartial FROI [10,41]) was also determined for all of the cases except

forthe*LiteratureModel*bymultiplyingeachoftheinputand outputflowsbyacorrespondingqualityfactor.Forenergyfl ows,thequalityfactors(QF) werecalculated accordingtotheenergyprice(EP),whichisthepriceofeache nergysource per joule, which correlates the relative value of

eachfuel[42].Settingcoalasthestandardwithaqualityfacto r

the percentage of the smaller volume that was transferred. The

laborcosts, regulatory fees, etc.) [10].

ExperimentalAnalysis

Figure 2 displays the input and output products of algalbiocrudeproductionatUT.Detaileddescriptionsofall datacollection and uncertainty analysis can be found in

[10] (cf.Chapter 4, Appendix 4A and Appendix 4B of [10]). Thealga processed in these batches was a marine provided of*Chlorella* (KAS 603. species bv KuehnleAgroSystems,Inc.) and was grown in four different growth stages: flasks,airliftphotobioreactors,greenhousetanks,andcover edraceway ponds (cf. Fig. 3). In general, the larger growthvolumes were inoculated from the smaller growth

volumes, and all of the algae transfers are illustrated in a flowd iagramin[10](cf.Appendix4Ain[10]).Energyconsumptio nforgrowthandprocessingequipmentwaseither measured with energy meters or estimated accordingtothemanufacturerspecifications. When algaew eretransferred from a smaller growth volume to a larger one, batches, hereafter referred to by batch numbers 1-5, varied between 947 and 1,942 L of growth volume processed andwere all processed between May and July, 2010. Theaverage cultivation time (from inoculation in the airliftreactors until harvesting from the ponds) was 123 days, onaverage.

#### Growth

compressedairfromageneral-useshopcompressor.Therefore, the compressor power for the airlift reactors could notbe measured, and was estimated from the compressor

data obtained for the greenhouse tanks and outdoor pond.

Fourgreenhousetanks(G1-G4,about0.25-0.50m deepandnominally946Leach)wereperiodicallyinoculated from the airlift bioreactors, and then used toinoculate the ponds (P1 and P2, about 0.2 m deep and nominally 2,400 Leach). Inoculations were made a tirreg ularintervalsrangingfromdaystomonths(cf.Appendix4Ao f[10]).AmixtureofCO<sub>2</sub>andairwasbubbledintothegreenho usetanksandponds, and wassupplied by a compressor and a CO<sub>2</sub> tank (different thanthose used for the airlift reactors). The total CO<sub>2</sub> flow ratefor all of the greenhouse tanks and ponds was measureddaily, and allocated by relative volume. Two compressorswere used: the energy consumption for the first compressorwasmeasureddirectlywithanenergymeterandt hatforthesecond compressor (used for only 8% of the cultivationtime) was calculated by measuring the current, voltage, andduty cycle. In addition, the greenhouse contains two fansthat are activated by a thermostat (set to 32.2°C), and theelectricity consumed by these fans, which varied accordingto the ambient temperature, was also measured. A pumprequiring approximately 0.8 kJ/L was used to transfer algae from the tanks to the ponds. The energy required for tran sfers from the indoor airlift bioreactors to the greenIn all stages, the growth media were prepared with InstantOceans alts a tas a linity of  $\sim 15 \text{g/L}$ , and the consumpt ion 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 stagewasneglected.Sevenindoor,airliftbioreactors(L1–L7)

wereusedtogrowthealgaeandweresuppliedwithartificiall ighting (multiple 54 W, Hg bulbs) for 12 h per day. Theelectricityconsumptionforlightingwasmeasuredwith 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 thebioreactors continuously (the outgassed  $CO_2$ /air mixture from the top of the reactors was 0.72% CO<sub>2</sub>, on average). The CO<sub>2</sub>/air flow rate and the percentage of CO<sub>2</sub> in themixture were recorded daily for each reactor. The CO<sub>2</sub>/airmixturewasprovidedbymixingCO<sub>2</sub> from agastan kwith

house tanks was also estimated to be 0.8 kJ/L. Confer [10]formoredetails.

Thefinalgrowthstagewasinoutdoor, covered, racewayp ondsthatcanholdapproximately2,400Leach. Thepondswe recovered with a plastic liner to reduce evaporation and conta mination, and circulation was accomplished by apumpthat was operated 24 hper

day(requiring~1,130W). Harvesting

The algae were pumped from the ponds into 1,200-L totes andtransported to the centrifuge facility by a propane poweredvehicle. Thepumpingenergywasmeasuredusing anenergymeter and the transportation energy was estimated roughly(0.26 miles roundtrip and 10 miles/gallon of propane). Duringcentrifugation, energywasconsumedby analgae fee dpumpand the centrifuge. One feed pumpwasused for Batc h1 and another pumpwasused for Batches 2–

5.Thefirstwasahard- wired 220 V pump and the second was a 120 V pump. Theenergyconsumptionforthefirstpumpwasestimatedacc ord-

ingtothemanufacturerspecifications(0.7A,215V,and0.9 power factor) and the energy consumption for the secondpumpwasmeasureddirectly. The centrifuge was opera tedonavariable frequency drive, which controlled the power con-sumption (continuous at 2.48 A, 215 V, and 0.9 power factor). On average, centrifugation achieved a  $65 \times$  concentration

ofalgaldryweightpervolumefrom0.26to16.7g/L.

Theelectromechanicalcelllysingprocesswasconductedb yapplying short pulses of strong electric fields to algae flowingthrough a 20-mL test-cell that consists of two electrodes. Eachelectrical pulse was applied by the discharge of

several parallel capacitors that are charged on a three-

being conducted, the separation was conducted by cycling thealgae and heptane through the MHF contactor for the timeequivalent of three passes. Then, the contactor was washedwithfreshsolvent(heptane),andthewashsolventwas addedtotheinitialsolventvolume.Thealgallipidswerereco veredvia distillation, and most of the heptane was recovered asdistillate. On average, 1.6 L of solvent was consumed perbatch (equivalent to 0.98 mL of solvent per L of growthvolume processed). However, the MHF contactor retainsabout 1.5 L of solvent, and due to batch processing,

thissolventwaslosttoevaporation.Incontinuousoperation, thesolvent consumption would be much lower (cf. *ReducedCase*).Theelectricityconsumedduringtheseparati onprocesses was either measured directly with energy metersor estimated from the equipment manufacturer specifications.The energy-consuming equipment included: (1) an algaefeedpumpforthecontactor,(2)asolventfeedpumpfort hecontactor,(3)adistillationperistalticsolvent/oilfeedpum p,

(4)adistillationvacuumpump,and(5)twoelectricalheatersf ordistillation.Inaddition,theamountofchilledwaterusedto condensetheheptanedistillatewasmeasured.ForBatch3onl y, the post-extraction biomass was re-extracted (half ofwhich was re-lysed), yielding additional oil, and accruingadditional energy inputs. Thus, the data reported for thelysing and extraction of Batch 3 include contributions fromthere-lysingandre-extraction.

Reduced Case and Highly Productive Case

Thepurposeofthe*Reduced(Inputs)Case* and *HighlyProduc tive Case* is to provide a more realistic model foroperatingenergy expenses that are expected in a continuo us, commercial-

scaleproduction facility. The energy outputs for the *Reduced Case* are assumed to be the same as those in the experiments, while the *HighlyProductiveCase* assumed a

greaterbiomassproductivity  $(0.08g/Ld, \sim 16g/m^2d)$  and a higher neutral lipid fraction (30%), which yields a greater

energy output. The energy associated with capital expendi-tures required to achieve these cases is not considered andthe ability to achieve all of these conditions is speculative. The *Reduced Case* and *Highly* 

#### *LipidSeparation*(*Extraction*)

Amicroporoushollow fiber membrane contactor(MHFcontactor)wasusedtoseparatethealgallipi dsfromtheotherbiomassintoheptane.Duetothespecificres earchthatwas

*Productive Case* models usethe 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*, algalcultivation is envisioned to be accomplished in a closed,outdoor reactor (which does not require volume transfers)thatismixedbyrotarystirring(ratherthanpumpin g).Harvesting is modeled as an advanced flocculation tech-nique. Energy is consumed by a pump to move the growthvolume totheharvestingfacility andbyflocculantsthat are

consumed. The energy consumption for lysing is modeledusing the same process as the experiments, but with a

moreefficientpowersupplyandaproperlysizedpump.Asi ntheexperiments,aMHFcontactorseparationprocessands ubsequent distillation are used for the *Reduced Case* and*HighlyProductiveCase*.However,bymodelingproper equipmentsizeandassumingcontinuousoperation,theene rgyconsumedduringseparationsinthesecasesissignifican tly less than that of the experiments. With properdesign,asinglepumpcanbeusedtomovealgalconce ntratefromharvesting,throughlysing,andthroughthelipid separation contactor. Thus, only one additional pump isrequiredforpassingsolventthroughthecontactor.

#### Results

#### SummaryofBatches

Table 1 summarizes processing efficiency data obtained

foreachofthefivebatchesinthisstudy.Tocalculatethesedat a,samples were collected during processing of each batchusing a methodology that has been described previously[10]. The terminology and nomenclature that is used hasbeendefinedpreviouslybyBealetal.[33].Theefficienc iesarecalculatedasthemassratiooftheoutputofaproductio nstep divided by the input for that step (e.g., the separationsefficiency is the mass of biocrude divided by the mass oflysed algal biomass. The neutral lipid fraction

embeddedinthisefficiency).Therefore,thesetermsdonotre presenttheeffectivenessofeachstep(exceptfortheharvesti ngefficiency, which also represents the harvesting effective-

ness).Similarly,theoverallprocessingefficiencyisthemas sof biocrude divided by the grown mass and incorporateseach of the individual processing efficiencies. Neutral lipidrecovery is the percentage of neutral lipids detected in theinitial biomass (as determined HPLC by analysis (Poenie, personal communication), datanot shown) that we rerecoveredasbiocrude. There are several variables that infl uencetheneutrallipidrecovery, including each process-ing efficiency and changes in the neutral lipid

across the five batches. In addition, the percentage of thetotal energy consumption/production, the uncertainty, and thestandarddeviationarelisted.

There are three types of uncertainties associated withusing the experimental data presented in this study for ev aluating the EROI of algal biofuelsing eneral: measurement error, artifacts associated with sub-optimal research-scale production, and batch-to-

batchvariations. Adetailederroranalysisisprovidedin[10]t hataddressesmeasurementerror, and the uncertainty results are tabulated for each input and output in Tables 2 and 3. The *ReducedCase* and *HighlyProductiveCase* are provide dbelowinanattempt to address research-scale artifacts by estimating the EROI for an optimal commercial-scale operation of a similar production pathway. Finally, batc h-to-

batchvariationsinthegrowthandprocessingmethodsarech aracterizedbythestandarddeviation (cf. Table 3). For example, the average (indirect)energyconsumptionforureawas11.18±2.55kJ/Lwi thastandarddeviationof8.9kJ/L.Theuncertaintyinthismea surementistheaveragemeasurementerrorfortheenergycon sumptionby urea of the five batches. The standard deviation i shighbecausedifferentnutrientfeeding schedules were implemented throughout the year, resulting in different nutrient consumption for each batch.Similarvariabilityexistsformanyinputs.

Onaverage, the energy consumed for growth, harvesting, cellly sing, and lipids eparations account for 96.23%, 0.89%, 0.15%, and 2.73%, of the total requirement, respectively. The energy requirements are dominated by growthin puts, and of the se inputs, mixing, lighting, air compression, and  $CO_2$  consumption represent the parameters with the most signif-

icantcontributions, as shown in Fig. 4. Mixing in the pond

compositionthroughoutprocessing[10,44].

ExperimentalEnergyFlowResults

Table 2 lists the data obtained for the growth and processingofBatches1-

5.Alloftheindirectenergyinputswere converted to energy values using the energy equivalent perunitofeachindirectinput(e.g.,theenergyequivalentofur eais 26.30 MJ//kg). Since the volume that was processed

foreachbatchwasdifferent,thedataarenormalizedperliter ofgrowth volume processed and reported in units of kJ/L.Table3liststheaveragevalueforeachinputandoutp ut

wasaccomplished by an oversized  $pump(\sim 1,130W, operat)$ ed 24 h/day and 7 days/week); the use of a paddlewheelorpumpdutycyclewouldsignificantlyreducethis consumption. Artificial lighting of the airlift photobioreactorswas used to enable stable growth conditions, but could bereplaced by the use of sunlight. Air compression requirementsandCO<sub>2</sub>consumptioncouldbereducedbyemployin gmoreefficientCO<sub>2</sub>deliverymethods(toimproveCO<sub>2</sub>upta kerates, therefore reducing the amount of CO<sub>2</sub>/airneeded) and using an appropriately sized compressor. The amount of water used for each batch was calculated to be1.91Lforeveryliterprocessed(duetoevaporationfromthe growth volumes). About 98% of the water processed isrecoveredafterharvestingandcouldberecycled, butwoul dlikelyrequireadditionaltreatment.Althoughnorecycling isincludedinthisstudy, if 100% recyclingwereaccomplishe d,thewaterconsumptionwouldbereducedto0.91L/L(limi tedtojusttheevaporationduringgrowth)andtheenergyreq uiredtotreattherecycledwaterwouldneedtobeadded(cf.[1 0,41]foradditionalwaterintensityanalysis).

On average, the direct energy inputs account for 94.2% of the total energy requirement. The indirect energy inputs, which include water, nutrients, CO<sub>2</sub>, etc., account for 5.8% of the total energy consumed. The equivalent valuesofthenonenergy energyinputsrepresentthetotalembeddedenergy for their production, therefore much and are greaterthanthechemicalenergycontentofeachinput.For example, the embedded energy content of  $CO_2(g_{CO_2})$ ,whichresultsfromcollectionandcompression)isestimate dat7.33MJ/kg[12,19].Themostsignificantnon-energy inputs are  $CO_2$  and heptane, which accounted for 2.7% and 1.6% of the total energy consumption on average, respec-

tively.Approximately36kgofCO<sub>2</sub>wereconsumedperkg ociatedamountofalgalmassinthepost-separa-tions slurry,  $M_{\rm BS}$  (cf. Fig. 2). There are several

potentialmethodstoconvertpost-

extractionbiomasstousefulenergy, including direct combustion, anaerobic digestion,andcatalytichydrothermalgasification(CHG)[ 17,31,

56,46].Foralgalslurrieswithalgaldensityof~150g/L, CHG has been used by Genifuelto produce ~0.25 kg of methane/kg of algal biomass slurry

 $\sim 0.25$  kg of methane/kg of algar biomass sturry  $\delta \phi_{\text{ref_{BMF}}} / 4$   $0:25 \triangleright$ 

[46] and methane contains  $\sim$  55 MJ/kg( $v_{BMF}$ =55 MJ/kg). Although not considered in this study,

CHG also has the potential to enable nutrient recycling(includingnitrogen,phosphorus,potassium,and

On average, 2.1 mg of biocrude and 165 mg of biomass(inslurryat  $\sim$  15g/L)wereproducedforeachliterof growthvolumeprocessed.UsingEqs.12and13,thedirect energyproductionistherefore:

where the refining efficiencies and bio-oil energy contentsare not known, as refining was not conducted. CombiningEqs. 10, 11, 12, 13, 14, 15, the EROI for algal biofuelproduction, on average, is,

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If the biomass slurry is converted to methane (biomassfuel)usingtheCHGprocessdescribedabove,itissp eculated that the refining efficiency  $\delta \phi_{ref_{BMF}}$  b and biomassfuelenergycontent( $v_{BMF}$ )wouldbe0.25and55MJ/k g,

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 un-

known terms in Eq. 16 are estimated by optimistic values( $\varphi_{ref_{BO}}$  ¼1, $v_{BO}$ =40MJ/kg,and  $\hat{E}_{RBO}$ (using 6 //L

2.21MJforrefiningperkgofbio-oil[15]appliedto2.1mgof biocrude)), the average EROI for all five batches in thisstudywouldbe9:24 $0^{-4}$ 3:31 $0^{-4}$ ×

 $\label{eq:constraint} The quality-adjusted EROI was calculated by applying the quality factors listed in Table 4 to each input and output flow. Adjusting for quality yielded an EROI of 9.2 <math display="inline">\times$ 

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

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

ReducedCaseandHighlyProductiveCaseResults

carbondioxide;[46]).Combiningtheseterms(and neglecting the

energyrequiredtoconcentratethepost-extractionbiomassfrom~15to~150g/L),roughly13.8MJofmethaneen ergycouldbeproducedperkgofpostextractionalgae. These roughest imates do not consider thee ffectofextractinglipidsfromalgaepriortoconversion or the dependence of conversion performanceon algal Other studies have species. suggested that (dry)algalbiomasshasaheatingvaluebetween17.5and26 MJ/kg[12,13,17,57]. The energy requirements to operate this process are estimated to be ~ 10% of the methan

eenergyproduced( $\sim 1.4$ MJ/kg;[46]).

The*ReducedCase* and *HighlyProductiveCase* modelestim ates the EROI for a configuration that uses closedbioreactors, chemicalflocculation for harvesting, an doptimizedly sing and separations processes. The energy flow data are presented in Table 4. Using closed growth containers could nearly eliminate evaporation (are su ltobserved for the indoor bioreactors), which would reduce the water consumption to 1L/L, on average without

recycling,and0.05L/Lwith95%recycling(equivalentto 0.07kJ/Lprocessed).TheamountofCO<sub>2</sub>requiredtoproduc

e 1 kg of algal biomass has been estimated to bebetween 1.7 and 2 kg [3, 12, 13, 58], although this valuecorresponds to the theoretical minimum by assuming 100% uptake and no respiration [10]. The algal concentration forBatches1— 5,onaverage,was0.26g/L.With100%

conversion efficiency, this grownmasswould require about 0.52 g/L of CO<sub>2</sub>. However, for the indoor biore actors, the amount of CO<sub>2</sub> supplied was roughly  $4\times$  the amount that was absorbed. Applying this rate of absorption to 0.52 g

 $of CO_2$  required/Lofgrowthvolume processed, the  $CO_2$  con sumption for the *Reduced Case* is modeled as being

2.08 g/L (with 7.33 MJ/kg of energy equivalent), which is22%oftheCO<sub>2</sub>consumedperliterforBatches1– 5,onaverage. The same assumptions are used to calculate theCO<sub>2</sub> required in the *Highly Productive Case*, except for analgal concentration of 1 g/L, resulting in CO<sub>2</sub> consumptionof8g/L.

Nutrientrequirementsmodeledinthe *Reduced Case* are estimated from averaged literature data to be  $\sim$ 70 g ofnitrogen/kg of grown mass and  $\sim$ 8 g of phosphorus/kg

ofgrownmass[12,13,18,19]. Althoughitisacknowledged thatthese nutrientrequirements arenear the theoreticalminimum[10], specific uptake ratesare notconsideredhere. For the *Reduced Case* with an algal concentration of

0.26 g/L, 18 mg/L of nitrogen and 2 mg/L of phosphorusare consumed, with energy equivalent values of 59 MJ/kg[12,19,49–

51]and44MJ/kg[12,19,49],respectively.

The indirect energy consumption from nitrogen and phosph or us nutrients in the *Reduced Case* is 10% and 44% of the experimental results, respectively. For an algal concentration of 1g/Linthe *Highly Productive Case*, 70 mg/Lnitrogen and 8 mg/L of phosphorus are consumed.

Foraclosed system (without volume transfers) it is expected that contamination would be less problematic. The erefore, the *Reduced* and *HighlyProductiveCases* estimate the antibiotic consumption as 0.28 mg/L and

0.1 mg/L (which is  $\sim$ 15% and 5% of that consumed forBatches1–5,onaverage,respectively.cf.Table2).Itis

where: density ( $\rho$ ) is 1 kg/L, elevation ( $\Delta z$ ) is 3 m, frictionfactor(*f*)is0.03(foraReynoldsnumberof~10<sup>4</sup>),pu mpingdistance(*L*)is20m,pipediameter(*D*)is1.3cm,flow velocity (*V*) is 4.8 m/s, minor loss coefficient (*K*<sub>L</sub>) is 1.5(assumingasquareentryanddischargeorifice),and gisth egravity constant (9.8 m/s<sup>2</sup>). This relationship yields a  $\Delta P$ 

of 573kPa, which corresponds to an energy consumption of 0.96 kJ/L (assuming  $\eta$ =0.6) for both cases. The embedded energy offloc culants is estimated at 20MJ/kg and 3 54 mg offloc culants are assumed to be consumed pergofalgae . With algaldensities of 0.26 and 1g/L, the indirect energy con sumption of floc culants is 1.82 and 7.08 kJ/L for the *Reduced* and *HighlyProductiveCases*, respectively.

For cell lysing, energy efficiency improvements of 17×have been demonstrated with respect to the power supply usedduringtheprocessingofBatches1-5[10]. Thus, the energy consumed by the lysing power supply in the Reduced CaseandHighlyProductiveCaseis0.21kJ/L.Theenergyus edtopumpalgalconcentratefromharvesting, throughly sing , and through the contact or is modeled using Eq. 17 ( $\Delta P = 13$ η=0.6, and  $\frac{1}{V_P}$  (due 8 kPa. to a  $65 \times$ concentrationfactor))tobe3.5J/Lofgrowthvolumeproc essed.

Withpropersizing of separations equipment, the volumet ric ratio of heptane used (not consumed) to algalconcentrate could be reduced to 1:20. Assuming a conce  $\Delta P = 7 k Pa, and \eta = 0.6$ ).

Heptane loss into the algal slurry is estimated at thesolubilitylimitinwater(5ppm)andneglectsheptaneevap orationintonon-condensinggasduringdistillation. The energy consumption of the solvent/oil feed pump isnegligible( $8 \frac{1}{4} \frac{1}{1} \frac{V_{GO}}{3006}, \Delta P = 69$ kPa, and  $\eta = 0.6$  in Eq. 17). The heat of vaporization required to distill heptaneis318kJ/kg, which translates to 0.17kJ/Lofgrow thv olume processed (assuming a heptane density of 0.68 kg/ $\frac{1}{8} \frac{1}{4} \frac{1}{4} \frac{V_{GO}}{300}$ . Commonly, the

energyrequiredtoestablishavacuumduringdistillationis less than 2% of the heat of vaporization, and it is thereforemodeled as being 3.3 J/L for the *Reduced Case*  assumed that artificial lighting and volume transfers wouldnotbeneeded,andthereforetheseenergyvaluesarere ducedto zero. In these cases, an air compressor is not required:pureCO<sub>2</sub>ismodeledasbeingdelivereddirectlyfr ompressurized tanks and mixing is accomplished via rotarystirring. Also, there is no greenhouse modeled (and thus

nofans). The mixing energy is estimated at 99J/(L-

d)whichisanaverageofdatathathavebeenusedinpreviouss tudies[4,12–

14,18,19]. This value for mixing energy is equivalent to

ntrationof65×,thiscorrespondstoaheptane-to-growth-volume-

processedratioof1:1,300.Theenergyrequiredforpassingth isheptanethroughthecontactoris

modeledusingEq.17andisnegligible( $8\frac{1}{4}\frac{1}{4}V_{P}$ , required for the chilled water (9.4°C).Perliter, 39.4kJare required for chilling (9.4°C, 4.18 kJ/(kg-K)) and anideal vapor-compression refrigeration cycle is assumed toremovetheheat from the water (coefficient of perfor-

manceof3.97),resultinginacompressorenergyrequirement of 9.9 kJ/L of chilled water. The embeddedenergy in the chilled water includes the energy to provide the water (1.33 kJ/L [47]) and the energy consumed forchilling(9.9kJ/L).Thetotalenergyembeddedinthechillin gwateristherefore48.6JperLofprocessedvolume(theprodu ctof4.3mLofwaterconsumedand

11.23kJ/Lofembeddedenergy).

With all of these reductions, the total energy inputfor the *Reduced Case* is estimated at 31.77 kJ/L, which istwo orders of magnitudeless thantheenergyconsump-tionforBatches1–

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,

 $\label{eq:linear} If the unknown terms in Eq. 20 \qquad are \qquad estimated \\ with the same values as for Eq. 16 ( \phi_{ref_{BO}} \ \ 1/41, \nu_{BO} = 40 MJ/kg, \\$ 

=4.6 J/L,  $\varphi_{ref_{BMF}}$  1/40:25,  $v_{BMF}$ =55 MJ/kg, and ,theEROIforthe*ReducedCase* 

would be 0.074. This result indicates that the energy and

*HighlyProductiveCase*.Finally,theamountofchilledwater needed per liter processed,  $\dot{M}_{CW}$ , is estimated to be 4.3 g(4.3mL)perliterofprocessedvolumeaccordingto, productivityneedstobeincreasedbymorethananorder ofmagnitudeortheenergyinputsneedtobefurtherreduced by more than an order of magnitude to have netpositiveenergyproductionfromalgaewiththesystemm odeledinthisscenario.Usingthesamequalityfactorsasdes cribedabovefortheexperimentalresults,thequalityadjusted EROI for the *Reduced Case* was determinedtobe0.013.

The growth and processing energy inputs for the *Highly* 

*Productive Case* are estimated to be 72.92 kJ/L, which isabout twice as much as that for the *Reduced Case*, and primarily due to increased indirect energy consumed

*Case*), while only consuming 2.7% of the experimental energy consumption. The *Literature Model* estimates CO<sub>2</sub> consumption to be 0.200 g/(L-day), which corresponds to

2.29 kg of CO<sub>2</sub>/kg of algae (compared to 36 kg/kg in

the Experimental Case and 8 kg/kg in the Reduced and

Using the same quality factors as described above for the experimental results, the quality-

adjustedEROIforthe*Highly Productive Case* was determined to be 0.36. ThequalityadjustedEROIsgreaterthanthenon-adjustedresult because 78% of the energy input is associated withCO<sub>2</sub>, *ReducedCase*,whereelectricity(withhighquality)wasthep rimaryenergyinput.

references for each data point. The majority of literaturesources report energy consumption and production data

as rates for a continuous system (e.g., MJ/(ha-

year)).Alloftheenergy data was converted into units of J/(L-day) and thenon-energy input data were similarly converted into unitssuchasmL/(Lday)ormg/(L-

day). Inthese<br/>units, L<br/>represents<br/>litersof<br/>growth<br/>volume and<br/>aninverted<br/>apostropheaccent( $\chi$ 

)isusedtorepresentdatainunitsofJ/(L-

day).Inordertocomparedirectlywiththeexperimentalr esults, the analytical results would need to be converted fromunits of J/(L-day) to J/L by multiplying by the cultivationduration. However, the multi-scale growth scenario and batchprocessingmethodsusedatUTmakethisapproac haninconsistent comparison. Furthermore, the UT results includeburdensassociatedwithstart-

energyformsofthe *Literature Model* inputs are not specified, aquality-adjusted EROI was not calculated.

# Discussion

This study presents the first known experimental results with end-to-end measurements for determining the

EROIforanintegratedalgalbiocrudefacility. AlthoughtheE ROIwas significantly less than 1 for the biocrude productionprocess evaluated here, it is the result for a single, researchsystem that was not designed to optimize EROI. However, the less - thanunity EROI results for the *Reduced Case*, *Highly Productive Case*, and the *Literature Model* also support the need to develop alternative, energy-efficient production bynutrientstoproducemorealgalbiomass.Basedontheno menclature defined in [33], the direct energy output forthe*HighlyProductiveCase*iscalculatedas,

# HighlyProductiveCases).

Usingenergyproductionandconsumptionrates(inunits of J/(L-day)), rather than amounts (in units of J/L), theEROIfortheanalyticaldatacanbecalculatedas,

which has a relatively low quality factor of 2.1, while the energy outputs have relatively high quality factors.

This resultisin contrast with the *Experimental Case* and the where  $P_{BC}$  is the bio crude productivity and  $P_{BS}$  is the bio massing lurry productivity. The bio crude productivity is calculated according to, h **i** 

upoperationsrequiredtoscale-

upalgalgrowthfrom the flask volume to apond volume, where each of these terms is listed in Table 3 (and defined in [33], except for  $\varphi_{\text{seps}}$ 

,whichisthealgalbiomass(inslurry)separationsefficiency. Thistermisdefinedasthe

mass of algal biomass in the post-extraction slurry divided by the lysed mass). These parations efficiency,  $\varphi_{sep}$ , contains the LF and the ULF. The refining energy inputs (per liter of growth volume per day) include the bio-oil refining,  $\tilde{E}_{R_{EG}}$ , and biomass fuel refining,  $\tilde{E}_{R_{EG}}$ , as,

$$\hat{\vec{E}}_{R} = (\vec{E} D_{in} + \sum_{k} \gamma_{k} \vec{I}_{k})_{R} = \hat{\vec{E}}_{R_{BO}} + \hat{\vec{E}}_{R_{BMF}}$$

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

ð28Þ

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

 $0:006^{g} | v_{BO} | 0:013^{g} | v_{BMF}$ 

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 demonst rated at similar scales (e.g., 0.08 g/(L-

day))[2].Similarly,basedonchromatographyanalysis(nots hown),theneutrallipidfractionofthealgaeprocessedinBatc hes1–5wasamere0.02(i.e.,2%ofdrycellweight). As shown above, for the *Highly Productive Case* the energyoutputis16.6kJ/Lofgrowthvolume.Therefore,forasy stemoperatingundertheseconditions,thetotalenergyinputf orgrowth,processing,andrefiningmustbelessthan16.6kJ/ LtoobtainanEROIthatisgreaterthan1.Thisresultillustratest he challengefor profitablealgal biofuel productionand theneedforultra-low-

energymethods, as event hespeculative

ReducedCaseenergyinputwasestimatedtobe32kJ/L.

The energy used for processing (harvesting, cell lysing, and separations),  $\dot{E}_{p}$ , was measured to be 118 kJ/L, on average. This amount is sevent imesgreater than the theoreti calvalue

fortheenergyproductionofthegrowthvolumeinthe*Highly ProductiveCase*(16.6kJ/L).Thecentrifugeitselfconsume dnearlyasmuchenergyperliterofgrowthvolumeprocesse d(14.0kJ/L)asthe*HighlyProductive* Case output(16.6kJ/L).Furthermore,theenergyrequiredtopum palgaeroughly10mfromthepondforharvestingwas1.8kJ/ L,onaverage,whichisnearly11%ofthe*HighlyProductive* Caseenergyproductionofthatvolume(16.6kJ/L).Specific analysis of those steps had already led the UT team todevelop low-energy alternatives to centrifugation and tofocusontheminimizationofpumping.Inthe*HighlyProd* 

growth systems. However, the  $NEC_{GV}$  is preferred in this study so as not to confuse it with an end-to-

endenergy ratiofor biofuel production (i.e., the EROI). For the EROI to be greater than 1 and assuming an ideal process (all efficiencie sin Eq. 22 being equal to  $1, v_L = v_{BO}, and v_{BM} = 14 \text{ MJ/kg})$ , Eqs. 16 and 30 can be combined and manipulated to be

Therefore, for energy to be produced from algae, assuming an ide alprocess (fr.e.), for the second s

 $therefore allowing a greater energy input while a chieving an ERO \\Iofl. As a theoretical case, the photosynthetic limit for the$ 

 $\label{eq:maximumalgalbiomassproductivity} $P_{\rm GM}$, can be estimated to be $$\sim$184g/(m^2-day), which is $$\sim$0.92g/(L-day) in a 0.2-m deeppond(cf.[10,57]). As optimistic assumptions, the LF $$LF$$ 

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,

 $\dot{ED}_{aur} = 0.92$ 

*uctive Case*, the energy consumption for processing and refining,  $\hat{E}_{n}$ 

,wasmodeledtobe3.58kJ/L,which

isonly22% of the theoretical energy production (16.6 kJ/L). Therefore, if growth could be accomplished for less than

13.03kJ/Lofgrowthvolume,thesecond-

orderEROIwouldbegreaterthan1.

The volume tricnet energy content of the growth volume,

 $N \dot{E} C_{GV}$ , is the energy contained in the growth volume per lite r,  $\dot{E} C_{GV}$ , minus the energy inputs for growth per liter,

 $\dot{\tilde{E}}_{c}$ , and can be expressed as,

ð30Þ

where  $v_L$  is the energy content of the lipids,  $v_{BM}$  is the energy content of the non-lipid biomass, and the other terms are defined above. The  $NEC_{GV}$  is a similar metric as the

"NetEnergyRatio" defined by Jorquera et al. [14] to evaluate

$$+ \hat{E}_R$$
 b

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2

Toachievethisbiomassproductivity,additionalcarbon, nitrogen,andphosphoruswouldberequired.Foreachkilogr am of algae, the minimum possible CO<sub>2</sub>, nitrogen,andphosphorusconsumptioncanbeapproximate das1.8 kg, 70 g, and 8 g, respectively [3, 12, 13, 18, 19, 58].Using these data, and the energy equivalent values for eachnutrient as listed in Table 2, the energy input for nutrientscanbecalculatedas,

]]Therefore, the embedded energy expense in  $CO_2$  and nutri ents would require more energy than the total energy produced (Eq. 33). This result can be calculated as the ratio f Eqs. 32 and 34, and is therefore independent of

thebiomassproductivity, but is dependent on production efficiencies (including the lipid fractions). This result demonst rates 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 embed ded in  $CO_2$  and nutrients of any real algal production system will depend on the specific method sused to produce and acquire those materials. Using at mospheric construction of the specific method suse of the specific method subscription of the specific method subscription.

arbondioxide could also reduce the indirect energy input, butwouldlikelyreducethebiomassproductivity.

Theseresultshighlightthereasonwhythenascentindust ryisfocusingonthedevelopmentoflow-energyinput,highenergyoutputalgalgrowthandprocessingmethods. While the discussion in this section considers abreak-even scenario in which the EROI is equal to 1 (cf.Eq. 31), for algal fuels to be economically competitive, theEROI must be comparable to that of current energy sources(i.e.,fossilfuels,nuclear,wind,andsolar).Waystoi mprove the EROI (beyond the *Reduced Case* and *HighlyProductive Case* scenarios) include: (1) using waste formsof nitrogen and phosphorus (e.g., wastewater and animalwaste)[12, 15, 40] (2)usingwastebeatandflu

animalwaste)[12,15,40],(2)usingwasteheatandflugasCO $_2$ 

fromindustrialplants[17],(3)minimizingpumping[65],(4) employinglessenergy-

intensiveharvestingmethods[21,66,67],and(5)avoidings eparationmethodsthatrequire distillation. However, Lundquist et al. determinedthatrelyingoncheapwastematerialsasfeedsto cksrelegatesalgalbiofuelproductiontorelativelylowlevel sofproduction(afewpercentofUSdemand)[40].

typical of even the full UT process, as some of the UTprocessesarelicensedtoacompanyandcouldnotbediscl osedinthisinvestigation.

Also, these results are limited to the operating energybalance, and donot include capital energy expenses. C learly, 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 costsfor a similar algal biofuel production system, which areroughly 50% of the total cost for the biofuel production cas espresented in that study (cf. Case 5) [40]. Finally, the growth scenario evaluated here includes scale-

upburdensassociated with cultivating algae from small-scale (flasks) to large-scale (2,500-

Lpond), and commercial production is envisioned as a continuous, large-scale process.

The value of this study, in our opinion, is to provide aninitial result for the operating EROI associated with algalbiofuel production and to outline many of the importantparameters that need to be included in such an analysis. Asproduction is scaled-up, algal biofuels have the potential to experience exponential improvements in energy

efficiency, analogous to the advances made insolar and wind technology over the last several decades.

# Limitations

Itisimportanttore-

statethelimitationsofthisstudy.Firstofall,thisworkfocuse dondevelopingandassessingaprocessto determine the EROI for algal biofuels. There was not asystem available for study that provided а future representativesurrogate for commercial processes. So. this studycharacterizedtheEROIforafunctionalresearchproce ss.Itisexpected that technology improvements, biology improve-ments, and industrial synergies (e.g., the use of wastewaternutrients or CO<sub>2</sub> from power plants) will algal enable biofuelproductionwithamorefavorableEROI.

Inaddition, for avariety 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 no t

# Conclusion

Withsignificantrigorandeffortitispossibletoexperimental lyassesstheenergyreturnonenergyinvestmentforalgalbiof uelproduction.Suchassess-

mentsonoperatingfacilitieswilllikelyremainproprie-tary for an extended time, because making them publicrequires revealing significant information about what

aregenerallyperceivedasproprietaryprocesses.Suchasses smentsarecritical,however,tohelpidentifyand

eliminateprocessinefficiencies. This assessment of a research facility shows an approach and the information required.

Theresultsofthefourcasespresented in this study are su mmarizedinTable6. As shown, the EROI for all four cases was determined to be less than unity. Furtherm ore, the quality-adjusted EROI, which parallelsa partial FROI analysis, was also less than unity for allcases. Several other studies have presented hypotheticalenergy analyses of algal biofuel production, and although these opeands ystems evaluated vary, each of these studieshavealsodemonstratedthatwithoutdiscountedinp uts (e.g., nutrients and water from waste water, excessheat from a power plant,  $CO_2$  from flue gas), the energyreturn on investment is not competitive with conventionalfuels[12, 13, 15, 20, 40]. However, it ismost important that the cumulative EROI for an entire energy profile isgreaterthanunity, including the contributions from all ene

rgysources(e.g.,fossilfuels,solarenergy,windenergy,bio fuels,etc.),whileprovidingthenecessaryfuels for essential services (i.e., transportation, industry,defense,etc.).Therefore,althoughtheEROIforal galfuels might remain less than one in the foreseeable future,algae represent one of the most promising petroleum fuelsubstitutes,particularlyforhighenergydensityfuels,suchasaviationfuel.Therefore,althou ghlarge-scalealgal biofuel production remains quite challenging,

algal fuel shave the potential to satisfy some of the senichem

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