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

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AbstractThis studyis an experimentaldetermination ofthe energy return on investment (EROI) for algal biocrudeproduction at a research facility at the University of Texasat Austin (UT). During the period of this assessment, algaeweregrownatseveralcultivationscalesandprocessedusing centrifugation for harvesting, electromechanical celllysing,andamicroporoushollowfibermembranecontactorfor lipid separation. The separated algal lipids represent abiocrude product that could be refined into fuel and thepost-extraction biomass could be converted to methane. TodeterminetheEROI,asecond-orderanalysiswasconducted,whichincludesdirectandindirectenergyflows,butdoesnotincludeenergyexpensesassociatedwithcapitalinvestments. The EROI for the production process evaluatedherewassignificantlylessthan1,however,themajorityoftheenergyconsumptionresultedfromnon-optimizedgrowthconditions.Whiletheexperimentalresults do not represent an expected typical case EROI foralgalfuels,theapproachandend-to-endexperimentaldeterminationofthedifferentinputsandoutputsprovidesa useful outline of the important parameters to consider insuchananalysis.The*ExperimentalCase*resultsarethefirst known experimental energy balance for an

KeywordsAlgae· Energyreturnoninvestment · Energybalance·Netenergyratio·Biofuel·Biodiesel

Introduction

Algae are a potential biofuel feedstock that have received agreatdealofresearchinterest.Theoretically,algaearepromising 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),whichissimilar to the net energy ratio (NER), and can be used toassess the feasibility and sustainability of an energy source.Inbrief,theEROIistheamountofenergyproduceddividedbytheamountofenergyrequiredforthatproduction,andithasbeenusedtocharacterizemanyresources.Forexample,theEROIforproductionofconventionaloilandgas,coal,wind energy,andcorn

ethanol has been estimated to be ∼ -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.Therelationshipbetweenthe

EROI and FROI is considered in this study, and character-izedmorethoroughlyelsewhere[10,11].

When calculating the energy balance for algal biofuel,researchersareleftwithtwochoices:(1)tocalculate energyflows for theoretical systems, which risk incorporatingunrealistic assumptions, or (2) to characterize productionbasedonresearch

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scaleprocesses,whichareoftenknownapriori to be uneconomical. In this study, both approachesare explored. Several studies have evaluated the energyrequirementsforgrowingalgae[2,4,12–20]andmany have also considered the energy required to process algaeintoacommercialproduct(i.e.,foodorfuel)[4,13,15–21]. Many of these analyses rely on rough estimates andsometimes omit necessary inputs because there is nocommercial algal biofuel industry to serve as a reference.This work describes initial attempts at a clearly definedmodel for the second-order EROI of algal fuels (whichincludes direct and indirect energy inputs) and the use ofend-to-endexperimentaldatatopopulatethemodel.

Thescopeofthisstudyislimitedtoevaluatingoperatingenergyexpenses(includingdirectandindirectenergyflows, but omitting capital energy expenses) according tothe EROI framework provided by Mulder and Hagens [22].A quality-adjusted EROI value is also presented, whichconsiders the impact of using high quality fuels (i.e., highvaluefuels,mainlyelectricity)forproductionoflowerquality fuels (i.e., lower value fuels, bio-oil and methane).Theexperimentalresultsreportedinthisstudyare notrepresentativeofacommercial-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 afunctionalresearchfacilitytodeveloptheexperimentalapproachfordeterminingtheEROIforalgalbiocrudeproduction. This type of analysis will be important for thealgalfuelsindustry,asithasbeenforcurrentbiofuelindustries[8,23–28].ItisexpectedthattheEROIwillbe improvedforoptimizedgrowthconditions,refinedprocessing methods, and with the application of future 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 algalgrowthwasintegratedwithseveralcriticalprocessingsteps.The research focus is on processing; growth is done toprovide material to process. The growth facilities at UTwerebuilttobalancecapitalcostswithoperationalcostsforlow-volume production on a research budget. Consequently,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 processingsteps,albeitforrelativelyshorttimes.Todate,nearly20 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 sameenergy outputs as obtained in the experiments. The *HighlyProductive Case* uses similar assumptions for the energyinputs as the *Reduced Case* and assumes greater energyoutputproductivity.Inaddition,the*LiteratureModel*provides 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*, whicharelargelycomprisedoftheoreticaldata.

MethodsandMaterials

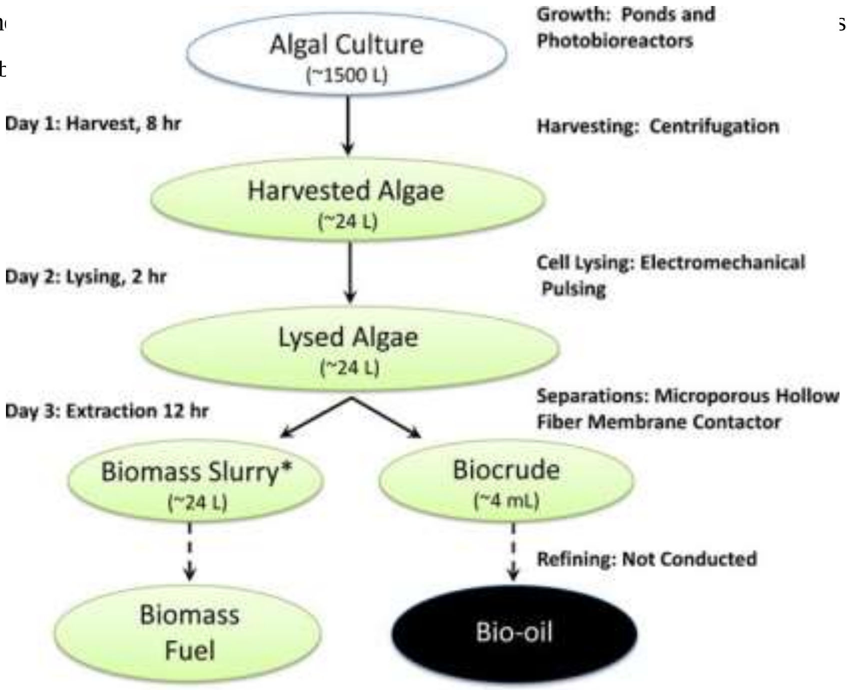
ProductionPathway

There are several energy carriers that can be produced fromalgae, including renewable diesel (such as biodiesel fromlipids), ethanol (from carbohydrates), hydrogen producedphotobiologically,methane(viaanaerobicdigestionorgasification),andelectricityviadirectcombustion[17,29–36].Biodieselisthemostcommonlystudiedalgal biofuel, and can be produced by transesterification of algallipids [33]. However, additional refining technologies existthatcanproducearangeofrefinedfuelsfromlipidsdependingonthelipidcomposition(e.g.,hydrocracking [37] and gasification). Algal lipids include neutral lipidsand polar lipids and the proportion of each type is highlyvariable [1, 2, 38, 39]. As a result, it is not clear 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 associatedwith upgrading the biocrude into a refined fuel product. Inotherwords,thisisa“strain-to-refinerydoor”analysis.However, the energy requirement of refining, noted as E_R,willbeincludedintheanalysisinsymbolicnotation(accordingtoaconventionestablishedinapriorpublication[33])andestimatedvalueswillbeusedwhennecessary.

Figure 1 presents the production pathway used at UT inthis investigation. In this approach, algae were grown inoutdoor “raceway” ponds (∼0.2 m deep), which are similartothosediscussedinpreviousstudies[2– 4,40]andthe

ponds were in sandtheresultsofthis

Fig. 1The algal b



TheEROIanalysisusedinthisstudyisbasedontheframeworkprovidedbyMulderandHagens[22].Specifically,thesecond-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$_{out}$þ P $_j v_j o_j$

in

crude)andbiomassfuel(producedfromthebiomassslurry) . Thus, the direct energy output includes the bio-oilenergy,ED$_{BO}$,andthebiomassfuelenergy,ED$_{BMF}$,as,

ED$_{out}$¼ED$_{BO}$þED$_{BMF}$

ð2Þ

Ifthebiomassisusedtoproducenon-energyproducts(e.g.,protein,nutritionalsupplements,orcosmetics),thenitcouldberepresentedasanindirectenergyf

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

Where P is the price (in \$/kg), EE is the energy equivalent(withunitsofMJ/kg),andEP$_{coal}$istheenergyprice forcoal(\$1.4/GJ). By using quality factors that are based on price,thequality-adjustedEROIanalysisisequivalenttothepartialFROIanalysisthatiscalculatedusingthesameinputs and outputs (i.e., excluding capital expenses,

low.InEq.1,indirectenergyflowsincludematerialinputsthatcontainembeddedenergy(e.g.,theembeddedenergyinnitrogenfertilizer) and material outputs. Specifically, the quantity ofthe*k*thnon-energyinputis$I_k$andtheper-unitenergyequivalentvalueforthatinputisdenotedasγ_k.Similarly,thequantityofthe*j*thnon-energyoutputis$O_j$andtheper-unitenergyequivalentvalueforthatoutput isdenotedasv_j.However,inthisstudy,therearenoindirectenergyoutputs.Aquality-adjustedEROI(analogousto apartialFROI[10,41]) was also determinedfor allof the casesexcept forthe*LiteratureModel*bymultiplyingeachoftheinputand outputflowsbyacorrespondingqualityfactor.Forenergyflows,thequalityfactors(QF) werecalculated accordingtotheenergyprice(EP),whichisthepriceofeachenergysource per joule, which correlates the relative value of eachfuel[42].Settingcoalasthestandardwithaqualityfactor

thepercentageofthesmallervolumethatwastransferred.The

laborcosts,regulatoryfees,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]). The alga processed in these batches was a marine species of *Chlorella* (KAS 603, provided by Kuehnle AgroSystems, Inc.) and was grown in four different growth stages: flasks, airlift photobioreactors, greenhouse tanks, and covered raceway ponds (cf. Fig. 3). In general, the larger growth volumes were inoculated from the smaller growth volumes, and all of the algae transfers are illustrated in a flow diagram in [10] (cf. Appendix 4A in [10]). Energy consumption for growth and processing equipment was either measured with energy meters or estimated according to the manufacturer specifications. When algae were transferred from a smaller growth volume to a larger one, batches, hereafter referred to by batch numbers 1–5, 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 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.

CellLysing

Theelectromechanicalcelllysingprocesswasconductedbyapplying 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 severalparallelcapacitorsthatarechargedonathree-phase,480V,ACcircuit.Theelectricityconsumedduringeachpulsewasdeterminedtobe480J,onaverage(cf.[10]).

LipidSeparation(Extraction)

Amicroporoushollow fiber membrane contactor(MHFcontactor)wasusedtoseparatethealgallipidsfromtheotherbiomassintoheptane.Duetothespecificresearchthatwas 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.Thealgallipidswererecoveredvia 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*).Theelectricityconsumedduringtheseparationprocesses was either measured directly with energy metersor estimated from the equipment manufacturer specifications.The energy-consuming equipment included: (1) an algaefeedpumpforthecontactor,(2)asolventfeedpumpforthecontactor,(3)adistillationperistalticsolvent/oilfeedpump, (4)adistillationvacuumpump,and(5)twoelectricalheatersfordistillation.Inaddition,theamountofchilledwaterusedto condensetheheptanedistillatewasmeasured.ForBatch3only, 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.

ReducedCaseandHighlyProductiveCase

Thepurposeofthe*Reduced(Inputs)Case*and*HighlyProductive Case* is to provide a more realistic model foroperatingenergyexpensesthatareexpectedinacontinuous,commercial-scaleproductionfacility.Theenergyoutputsforthe*Reduced Case*areassumedtobethesameasthoseintheexperiments,whilethe*HighlyProductiveCase*assumeda greaterbiomassproductivity(0.08g/Ld,∼16g/m^{2}d)andahigherneutrallipidfraction(30%),whichyieldsagreater 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 Productive Case* models usethe same basic production pathway that was used for theexperimental results (cf. Fig. 2), but substitute bioreactorsfor growth and an advanced flocculation technique in placeof centrifugation. Several modifications are implemented toimproveenergyefficiency.

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(ratherthanpumping).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.Asintheexperiments,aMHFcontactorseparationprocessandsubsequent distillation are used for the *Reduced Case* and*HighlyProductiveCase*.However,bymodelingproper equipmentsizeandassumingcontinuousoperation,theenergyconsumedduringseparationsinthesecasesissignificantly less than that of the experiments. With properdesign,asinglepumpcanbeusedtomovealgalconcentratefromharvesting,throughlysing,andthroughthelipid separation contactor. Thus, only one additional pump isrequiredforpassingsolventthroughthecontactor.

Results

SummaryofBatches

Table 1 summarizes processing efficiency data obtained foreachofthefivebatchesinthisstudy.Tocalculatethesedata,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].Theefficienciesarecalculatedasthemassratiooftheoutputofaproductionstep 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 is embeddedinthisefficiency).Therefore,thesetermsdonotrepresenttheeffectivenessofeachstep(exceptfortheharvestingefficiency, which also represents the harvesting effectiveness).Similarly,theoverallprocessingefficiencyisthemassof 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 by HPLC analysis (Poenie,personalcommunication),datanotshown)thatwererecoveredasbiocrude.Thereareseveralvariablesthatinfluencetheneutrallipidrecovery,includingeachprocess-ing efficiency and changes in the neutral lipid 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.,theenergyequivalentofureais 26.30 MJ//kg). Since the volume that was processed foreachbatchwasdifferent,thedataarenormalizedperliter ofgrowth volume processed and reported in units of kJ/L.Table3liststheaveragevalueforeachinputandoutput across the five batches. In addition, the percentage of thetotal energy consumption/production, the uncertainty, and thestandarddeviationarelisted.

There are three types of uncertainties associated withusingtheexperimentaldatapresentedinthisstudyforevaluatingtheEROIofalgalbiofuelsingeneral:measurement error, artifacts associated with sub-optimalresearch-scaleproduction,andbatch-to-batchvariations.Adetailederroranalysisisprovidedin[10]thataddressesmeasurementerror,andtheuncertaintyresults are tabulated for each input and output in Tables 2 and 3.The*ReducedCase*and*HighlyProductiveCase*areprovidedbelowinanattempttoaddressresearch-scaleartifacts by estimating the EROI for an optimal commer-cial-scaleoperationofasimilarproductionpathway.Finally,batch-to-batchvariationsinthegrowthandprocessingmethodsarecharacterizedbythestandarddeviation (cf. Table 3). For example, the average (indirect)energyconsumptionforureawas11.18±2.55kJ/Lwithastandarddeviationof8.9kJ/L.Theuncertaintyinthismeasurementistheaveragemeasurementerrorfortheenergyconsumptionbyureaofthefivebatches.Thestandarddeviationishighbecausedifferentnutrientfeeding schedules were implemented throughout the year,resulting in different nutrient consumption for each batch.Similarvariabilityexistsformanyinputs.

Onaverage,theenergyconsumedforgrowth,harvesting, celllysing,andlipidseparationsaccountfor96.23%,0.89%, 0.15%,and2.73%,ofthetotalrequirement,respectively.Theenergyrequirementsaredominatedbygrowthinputs,andofthese inputs, mixing, lighting, air compression, and CO_2consumption represent the parameters with the most signif-icantcontributions,asshowninFig.4.Mixinginthepond wasaccomplishedbyanoversizedpump(∼1,130W,operated 24 h/day and 7 days/week); the use of a paddle-wheelorpumpdutycyclewouldsignificantlyreducethis consumption. Artificial lighting of the airlift photobioreactorswas used to enable stable growth conditions, but could bereplaced by the use of sunlight. Air compression require-mentsandCO_2consumptioncouldbereducedbyemployingmoreefficientCO_2deliverymethods(toimproveCO_2uptakerates,thereforereducingtheamountofCO_2/airneeded) and using an appropriately sized compressor. Theamountofwaterusedforeachbatchwascalculatedtobe 1.91Lforeveryliterprocessed(duetoevaporationfromthe growth volumes). About 98% of the water processed isrecoveredafterharvestingandcouldberecycled,butwouldlikelyrequireadditionaltreatment.Althoughnorecycling isincludedinthisstudy,if100%recyclingwereaccomplished,thewaterconsumptionwouldbereducedto0.91L/L(limitedtojusttheevaporationduringgrowth)andtheenergyrequiredtotreattherecycledwaterwouldneedtobeadded(cf.[10,41]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_2, etc., account for 5.8%of the total energy consumed. The energy equivalent valuesofthenon-energyinputsrepresentthetotalembeddedenergy for their production, and are therefore much greaterthanthechemicalenergycontentofeachinput.For example,theembeddedenergycontentofCO_2(g_{CO_2} ,whichresultsfromcollectionandcompression)isestimatedat7.33MJ/kg[12,19].Themostsignificantnon-energy inputs are CO_2 and heptane, which accounted for 2.7% and1.6% of the total energy consumption on average, respec-tively.Approximately36kgofCO_2wereconsumedperkg

whereM_{BMF}isthemassofbiomassfuelproducedfromanassociatedamountofalgalmassinthepost-separa-tions slurry, M_{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 ð$\varphi_{\mathrm{refBMF}}$¼ 0:25Þ [46]andmethanecontains~55MJ/kg(v_{BMF}=55MJ/kg).Althoughnotconsideredinthisstudy, 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~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,onaverage,is,

ð16Þ

If the biomass slurry is converted to methane (biomassfuel)usingtheCHGprocessdescribedabove,itisspeculated that the refining efficiency ð$\varphi_{\mathrm{refBMF}}$ Þ and biomassfuelenergycontent(v_{BMF})wouldbe0.25and55MJ/kg, respectively, yielding $\acute{E}D_{\mathrm{BMF}}$=2.31 kJ/L [46]. The energyrequired for the CHG process is estimated to be 0.23 kJ/L.Usingthesespeculativeestimates,andiftheotherun-known terms in Eq. 16 are estimated by optimistic values(φ_{refBO} ¼1,v_{BO}=40MJ/kg,and$\acute{E}_{R\,BO}$(using=.6J/L 2.21MJforrefiningperkgofbio-oil[15]appliedto2.1mgof biocrude)), the average EROI for all five batches in thisstudywouldbe9:2×10^{-4}3:310^{-4}.×

Thequality-adjustedEROIwascalculatedbyapplying thequalityfactorslistedinTable4 to each input andoutputflow.AdjustingforqualityyieldedanEROI of9.2 × 10^{-5}.Duetohighqualityfactorsforelectricityinputsandmaterialinputs,thequality-adjustedtotal energy input was 31 times greater than the non-adjustedtotal. The quality-adjusted total energy output was threetimesgreaterthanthenon-adjustedtotalenergyoutput,reflecting the bio-oil and biomass fuel (methane) qualityfactors.

ReducedCaseandHighlyProductiveCaseResults

carbondioxide;[46]).Combiningtheseterms(andneglectingthe energyrequiredtoconcentratethepost-extractionbio-massfrom~15to~150g/L),roughly13.8MJofmethaneenergycouldbeproducedperkgofpost-extractionalgae.Theseroughestimatesdonotconsidertheeffectofextractinglipidsfromalgaepriortoconversion or the dependence of conversion performanceon algal species. Other studies have suggested that (dry)algalbiomasshasaheatingvaluebetween17.5and26 MJ/kg[12,13,17,57].Theenergyrequirementsto operatethisprocessareestimatedtobe~10%ofthemethaneenergyproduced(~1.4MJ/kg;[46]).

The*ReducedCase*and*HighlyProductiveCase*modelestimates the EROI for a configuration that uses closedbioreactors,chemicalflocculationforharvesting,andoptimizedlysingandseparationsprocesses.Theenergyflow data are presented in Table 4. Using closed growthcontainerscouldnearlyeliminateevaporation(aresultobserved for the indoor bioreactors), which would reducethewaterconsumptionto1L/L,onaveragewithout recycling,and0.05L/Lwith95%recycling(equivalentto 0.07kJ/Lprocessed).TheamountofCO_2requiredtoproduce 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% conversionefficiency,thisgrownmasswouldrequireabout 0.52 g/L of CO_2. However, for the indoor bioreactors, theamount of CO_2 supplied was roughly 4× the amount thatwas absorbed. Applying this rate of absorption to 0.52 g ofCO_2required/Lofgrowthvolumeprocessed,theCO_2consumptionforthe*ReducedCase*ismodeledasbeing 2.08 g/L (with 7.33 MJ/kg of energy equivalent), which is22%oftheCO_2consumedperliterforBatches1–5,onaverage. The same assumptions are used to calculate theCO_2 required in the *Highly Productive Case*, except for analgal concentration of 1 g/L, resulting in CO_2 consumptionof8g/L.

Nutrientrequirementsmodeledinthe*Reduced Case*are estimated from averaged literature data to be ~70 g ofnitrogen/kg of grown mass and ~8 g of phosphorus/kg ofgrownmass[12,13,18,19].Althoughitisacknowledged thatthese nutrientrequirements arenear the theoreticalminimum[10],specific uptake ratesare notconsideredhere.Forthe*ReducedCase*withanalgalconcentrationof 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] 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

where: density (ρ) is 1 kg/L, elevation (Δz) is 3 m, friction factor (f) is 0.03 (for a Reynolds number of ~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 $8 ¼ \frac{1}{65}$ 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 ($8 ¼ \frac{1}{1}$ 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 ($8 ¼ \frac{1}{1{,}300}$ 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, $8 ¼ \frac{1}{1{,}300}$ V_G, and a heat loss of 10%). Commonly, the energy required to establish a vacuum during distillation is less than 2% of the heat of vaporization, and it is therefore modeled as being 3.3 J/L for the *Reduced Case*

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

required for the chilled water (9.4°C). Per liter, 39.4 kJ are required for chilling (9.4°C, 4.18 kJ/(kg-K)) and an ideal vapor-compression refrigeration cycle is assumed to remove the heat from the water (coefficient of performance of 3.97), resulting in a compressor energy requirement of 9.9 kJ/L of chilled water. The embedded energy in the chilled water includes the energy to provide the water (1.33 kJ/L [47]) and the energy consumed for chilling (9.9 kJ/L). The total energy embedded in the chilling water is therefore 48.6 J per L of processed volume (the product of 4.3 mL of water consumed and 11.23 kJ/L of embedded energy).

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

If the unknown terms in Eq. 20 are estimated with the same values as for Eq. 16 (φ_{refBO} ¼1, v_{BO}=40 MJ/kg, =4.6 J/L, φ_{refBMF} ¼0:25, v_{BMF}=55 MJ/kg, and , the EROI for the *Reduced Case* would be 0.074. This result indicates that the energy productivity needs to be increased by more than an order of magnitude or the energy inputs need to be further reduced by more than an order of magnitude to have net positive energy production from algae with the system modeled in this scenario. Using the same quality factors as described above for the experimental results, the quality-adjusted EROI for the *Reduced Case* was determined to be 0.013.

The growth and processing energy inputs for the *Highly*

and *Highly Productive Case*. Finally, the amount of chilled water needed per liter processed, $\dot{M}_{CW}$, is estimated to be 4.3 g (4.3 mL) per liter of processed volume according to, *Productive Case* are estimated to be 72.92 kJ/L, which isabout twice as much as that for the *Reduced Case*, andprimarily due to increased indirect energy consumed

Case),whileonlyconsuming2.7%oftheexperimentalenergy consumption. The *Literature Model* estimates CO_2consumptiontobe0.200g/(L-day),whichcorrespondsto 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

Usingthesamequalityfactorsasdescribedabovefortheexperimentalresults,thequality-adjustedEROIforthe*Highly Productive Case* was determined to be 0.36. Thequality-adjustedEROIisgreaterthanthenon-adjustedresult because 78% of the energy input is associated withCO_2, *ReducedCase*,whereelectricity(withhighquality)wastheprimaryenergyinput.

references for each data point. The majority of literaturesources report energy consumption and production data asratesforacontinuoussystem(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/(L-day)ormg/(L-day).Intheseunits,Lrepresentslitersofgrowthvolume andaninvertedapostropheaccent($\grave{X}$)isusedtorepresentdatainunitsofJ/(L-day).Inordertocomparedirectlywiththeexperimentalresults, 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 batchprocessingmethodsusedatUTmakethisapproachaninconsistent comparison. Furthermore, the UT results includeburdensassociatedwithstart-

energyformsofthe*LiteratureModel*inputsarenotspecified, aquality-adjustedEROIwasnotcalculated.

Discussion

This study presents the first known experimental resultswith end-to-end measurements for determining the EROIforanintegratedalgalbiocrudefacility.AlthoughtheEROIwas 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,theless-than-unityEROIresultsforthe*ReducedCase*,*HighlyProductive Case*,andthe*LiteratureModel*alsosupport the need to develop alternative, energy-efficientproduction

bynutrientstoproducemorealgalbiomass.Basedonthenomenclature 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, whiletheenergyoutputshaverelativelyhighqualityfactors. Thisresultisincontrastwiththe*ExperimentalCase*andthe

whereP_{BC}isthebiocrudeproductivityandP_{BS}isthebiomassinslurryproductivity.Thebiocrudeproductivityiscalculatedaccordingto, h i

upoperationsrequiredtoscale-upalgalgrowthfromtheflaskvolumetoapondvolume, where each of these terms is listed in Table 3 (and definedin[33],exceptfor$\varphi_{sep_{BS}}$,whichisthealgalbiomass(inslurry)separationsefficiency. Thistermisdefinedasthe mass of algal biomass in the post-extraction slurry dividedbythelysedmass).Theseparationsefficiency,φ_{sep}, contains the LF and the ULF. The refining energy inputs(per liter of growth volume per day) include the bio-oilrefining,$\grave{\dot{E}}_{R_{BO}}$,andbiomassfuelrefining,$\grave{\dot{E}}_{R_{BMF}}$,as,

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

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

$$0{:}006^{g}\,|\nu_{BO}\,þ\,0{:}013^{g}\,|\nu_{BME}$$

methods. As noted, the majority of the energyconsumptioninallfourcalculationsisfromgrowth.

In addition to reducing many of the high energy inputs, it isreasonabletoexpectalgalproductivityandlipidyieldstobeincreased.ForBatches1–5,thegrownmassproductivitywas roughly0.002g/(L-day),whichis40timeslessthanyieldsthathavebeendemonstratedatsimilarscales(e.g.,0.08g/(L-day))[2].Similarly,basedonchromatographyanalysis(notshown),theneutrallipidfractionofthealgaeprocessedinBatches1–5wasamere0.02(i.e.,2%ofdrycellweight). As shown above, for the *Highly Productive Case* the energyoutputis16.6kJ/Lofgrowthvolume.Therefore,forasystemoperatingundertheseconditions,thetotalenergyinputforgrowth,processing,andrefiningmustbelessthan16.6kJ/LtoobtainanEROIthatisgreaterthan1.Thisresultillustratest he challengefor profitablealgal biofuel productionand theneedforultra-low-energymethods,aseventhespeculative *ReducedCase*energyinputwasestimatedtobe32kJ/L.

The energy used for processing (harvesting, cell lysing, andseparations), $\acute{\hat{E}}_P$, was measured to be 118 kJ/L, on average.Thisamountisseventimesgreaterthanthetheoreticalvalue fortheenergyproductionofthegrowthvolumeinthe*Highly ProductiveCase*(16.6kJ/L).Thecentrifugeitselfconsumednearlyasmuchenergyperliterofgrowthvolumeprocessed(14.0kJ/L)asthe*HighlyProductive Case* output(16.6kJ/L).Furthermore,theenergyrequiredtopumpalgaeroughly10mfromthepondforharvestingwas1.8kJ/L,onaverage,whichisnearly11%ofthe*HighlyProductive Case*energyproductionofthatvolume(16.6kJ/L).Specific analysis of those steps had already led the UT team todevelop low-energy alternatives to centrifugation and tofocusontheminimizationofpumping.Inthe*HighlyProductive Case*, the energy consumption for processingandrefining,$\acute{\hat{E}}_P$,wasmodeledtobe3.58kJ/L,which isonly22%ofthetheoreticalenergyproduction(16.6kJ/L). Therefore,ifgrowthcouldbeaccomplishedforlessthan 13.03kJ/Lofgrowthvolume,thesecond-orderEROIwouldbegreaterthan1.

Thevolumetricnetenergycontentofthegrowthvolume, $N\acute{E}C_{GV}$,istheenergycontainedinthegrowthvolumeperliter,$\acute{E}C_{GV}$,minustheenergyinputsforgrowthperliter, $\acute{\hat{E}}_G$,andcanbeexpressedas,

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where v_L is the energy content of the lipids, v_{BM} is the energycontent of the non-lipid biomass, and the other terms aredefined above. The $N\acute{E}C_{GV}$is a similar metric as the "NetEnergyRatio"definedbyJorqueraetal.[14]toevaluate growth systems. However, the$N\acute{E}C_{GV}$is preferred in thisstudysoasnottoconfuseitwithanend-to-endenergyratiofor biofuel production (i.e., the EROI). For the EROI to begreaterthan1andassuminganidealprocess(allefficienciesinEq.22beingequalto1,v_L=v_{BO},andv_{BM}=14MJ/kg), Eqs.16and30canbecombinedandmanipulatedtobe

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

2

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3

$$\dot{E}D_{max} = 150\left[\frac{kJ}{L-d}\right]$$

3

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Therefore,forenergytobeproducedfromalgae,assuminganidealprocess(i.e.,100%efficiencythroughout),thevolumetricnetenergycontentofthegrowthvolumemustbegreaterthan theprocessingandrefiningenergyrequirementsperliterof growth volume. For energy production in real pathways,thenetenergycontentofthegrowthvolumemustbesignificantly greater than the processing and refining energyrequirements to compensate for processing inefficiencies anduseful product fractions (cf. Eq. 22). Increasing the biomassproductivity, lipid content, and processing efficiencies ofEq. 22 would result in a greater energy output, thereforeallowingagreaterenergyinputwhileachievinganEROIof1.Asatheoreticalcase,thephotosyntheticlimitforthe maximumalgalbiomassproductivity,P_{GM},canbeestimatedtobe∼184g/(m^2-day),whichis∼0.92g/(L-day)ina0.2-mdeeppond(cf.[10,57]).Asoptimistic assumptions,the LF andULFcanbeestimatedas0.3and1,respectively.Insertingthese data into a modified form of Eq. 22 (omitting thecultivationtime(t_c),whichresultsinunitsofJ/(L-day))yields,

$$\dot{E}D_{sur} = 0.92$$

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3

Toachievethisbiomassproductivity,additionalcarbon, nitrogen,andphosphoruswouldberequired.Foreachkilogram of algae, the minimum possible CO_2, nitrogen,andphosphorusconsumptioncanbeapproximatedas1.8 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,theembeddedenergyexpenseinCO$_2$andnutrients would require more energy than the total energyproduced (Eq. 33). This result can be calculated as the ratioof Eqs.32 and34, and is thereforeindependentof thebiomassproductivity,butisdependentonproductionefficiencies(includingthelipidfractions).Thisresultdemonstrates the need to acquire usable waste forms ofcarbon,nitrogen,andphosphorus,whichhaveenergyequivalent values near zero (because little or no energy isrequiredtoobtainthenutrients).Theactualenergyembedded in CO_2 and nutrients of any real algal productionsystemwilldependonthespecificmethodsused toproduceandacquirethosematerials.Usingatmosphericc arbondioxide could also reduce the indirect energy input, butwouldlikelyreducethebiomassproductivity.

Theseresultshighlightthereasonwhythenascentindustryisfocusingonthedevelopmentoflow-energyinput,high-energyoutputalgalgrowthandprocessingmethods. 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).Waystoimprove 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)usingwasteheatandflu-gasCO_2 fromindustrialplants[17],(3)minimizingpumping[65], (4) employinglessenergy-intensiveharvestingmethods[21,66,67],and(5)avoidingseparationmethodsthatrequire distillation. However, Lundquist et al. determinedthatrelyingoncheapwastematerialsasfeedstocksrelegatesalgalbiofuelproductiontorelativelylowlevelsofproduction(afewpercentofUSdemand)[40].

Limitations

Itisimportanttorestatethelimitationsofthisstudy.Firstofall,thisworkfocusedondevelopingandassessingaprocessto determine the EROI for algal biofuels. There was not asystem available for study that provided a representativesurrogate for future commercial processes. So, this studycharacterizedtheEROIforafunctionalresearchprocess.Itisexpected that technology improvements, biology improve-ments, and industrial synergies (e.g., the use of wastewaternutrients or CO_2 from power plants) will enable algal biofuelproductionwithamorefavorableEROI.

Inaddition,foravarietyofreasonsrelatedtotheresearch goals of the project, UT did not incorporate itsmostefficientprocessesintothisinvestigation.Consequently, the experimental data are a reflection of energyconsumptionduringthesespecifictests.Theyarenot typical of even the full UT process, as some of the UTprocessesarelicensedtoacompanyandcouldnotbedisclosedinthisinvestigation.

Also, these results are limited to the operating energybalance,anddonotincludecapitalenergyexpenses.Clearly,direct capital energy expenses (earthworks, water supply, etc.)and materials (pond liners, processing equipment, etc.) willsignificantly 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 areroughly50%ofthetotalcostforthebiofuelproductioncasespresentedinthatstudy(cf.Case5)[40].Finally,thegrowth scenarioevaluatedhereincludesscale-upburdensassociatedwithcultivatingalgaefromsmall-scale(flasks)tolarge-scale(2,500-Lpond),andcommercialproductionisenvisionedasacontinuous,large-scaleprocess.

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 toexperience exponential improvements in energy efficiency,analogoustotheadvancesmadeinsolarandwind technologyoverthelastseveraldecades.

Conclusion

Withsignificantrigorandeffortitispossibletoexperimentallyassesstheenergyreturnonenergyinvestmentforalgalbiofuelproduction.Suchassessmentsonoperatingfacilitieswilllikelyremainproprie-tary for an extended time, because making them publicrequires revealing significant information about what aregenerallyperceivedasproprietaryprocesses.Suchassessmentsarecritical,however,tohelpidentifyand eliminateprocessinefficiencies.Thisassessmentofaresearch facility shows an approach and the informationrequired.

Theresultsofthefourcasespresentedinthisstudyaresummarizedin Table6. As shown, the EROI for allfourcaseswasdeterminedtobelessthanunity.Furthermore,thequality-adjustedEROI,whichparallelsa partial FROI analysis, was also less than unity for allcases. Several other studies have presented hypotheticalenergy analyses of algal biofuel production, and althoughthescopeandsystemsevaluatedvary,eachofthesestudieshavealsodemonstratedthatwithoutdiscountedinputs (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 importantthat the cumulative EROI for an entire energy profile isgreaterthanunity,includingthecontributionsfromallene 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,particularlyforhigh-energydensityfuels,suchasaviationfuel.Therefore,althou ghlarge-scalealgal biofuel production remains quite challenging, algalfuelshavethepotentialtosatisfysomeofthesenichemarkets.

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References

HuQ,SommerfeldM,JarvisE,GhirardiM,PosewitzM,Seibert M et al (2008) Microalgaltriacylglycerols as feedstocksfor biofuel production: perspectives and advances. Plant J 54(4):621–639

Sheehan J, Dunahay T, Benemann J, Roessler P (1998) A LookBackattheU.S.DepartmentofEnergy'sAquaticSpeciesProgram, Biodiesel from Algae. NREL and U.S. Department ofEnergy'sOfficeofFuelsDevelopment(NREL/TP-580-24190)

Schenk P, Thomas-Hall S, Stephens E, Marx U, Mussgnug J,Posten C et al (2008) Second generation biofuels: high-efficiencymicroalgaeforbiodieselproduction.BioEnergyRes1(1):20–43

BenemannJ,OswaldW(1996)Systemsandeconomicanalysisofmicroalgaepondsforconversionof CO2tobiomass.In:DepartmentofEnergy

Wijffels RH, Barbosa MJ An outlook on microalgal biofuels.Science329:796–799

ClevelandCJ(2005)NetenergyfromtheextractionofoilandgasintheUnitedStates.Energy30:769–782

Kubiszewski I, Cleveland CJ, Endres PK (2010) Meta-analysis ofnet energy return for wind power systems. Renewable Energy35:218–225

FarrellAE,PlevinRJ,TurnerBT,JonesAD,O'HareM,KammenDM (2006) Ethanol can contribute to energy and environmentalgoals.Science311:506–508

Shapouri H, Duffield J, Wang M (2002) The energy balance ofcorn ethanol: an update. In: USDA Agricultural Economic ReportNo.814

BealCM(2011)Constraintsonalgalbiofuelproduction.In:MechanicalEngineering.DoctoralDissertation,UniversityofTexasatAustin,AustinTX

King CW, Zarnikau J, Henshaw P (2010) Defining a StandardMeasure for Whole System EROI Combining Economic "Top-Down" and LCA "Bottom-up" Accounting. In: ASME ES2010.Phoenix,AZ

ClarensAF,ResurreccionEP,WhiteMA,ColosiLM(2010)Environmental life cycle comparison of algae to other bioenergyfeedstocks.EnvironSciTechnol44(5):1813–1819

Lardon L, Helias A, Sialve B, Steyer J, Bernard O (2009) Life-cycleassessmentofbiodieselproductionfrommicroalgae.EnvironSciTechnol43(17):6475–6481

Jorquera O, Kiperstok A, Sales EA, Embiruçu M, Ghirardi ML(2010)Comparativeenergylife-cycleanalysesofmicroalgalbiomass production in open ponds and photobioreactors.Bio-resourTechnol101(4):1406–1413

Batan L, Quinn J, Willson B, Bradley T (2010) Net energy andgreenhouse gas emission evaluation of biodiesel derived frommicroalgae.EnvironSciTechnol44(20):7975–7980

Collet P, Helias A, Lardon L, Ras M, Goy R, Steyer J (2011) Life-cycleassessmentofmicroalgaeculturecoupledtobiogasproduction.BioresourTechnol102:207–214

KadamKL(2002)Environmentalimplicationsofpowergenerationviacoal-microalgaecofiring.Energy27(10):905–922

Campbell PK, Beer T, Batten D (2010) Life cycle assessment ofbiodieselproductionfrommicroalgaeinponds.BioresourTechnol102 (1):50–56

Murphy C (2010) Analysis of innovative feedstock sources andproduction technologies for renewable fuels: chapter 6. Algal OilBiodiesel, EPA: XA-83379501-0. In: Allen D, Hebner R (eds)UniversityofTexasatAustin

Xu L, Brilman DWF, Withag JAM, Brem G, Kersten S (2011)Assessmentofadryandawetroutefortheproductionofbiofuelsfrommicroalgae:energybalanceanalysis.BioresourTechnol102:5113–5122

MolinaGrimaE,BelarbiEH,AciénFernándezFG,RoblesMedinaA, Chisti Y (2003) Recovery of microalgal biomass and metabolites:processoptionsandeconomics.BiotechnolAdv20:491–515

MulderK,HagensNJ(2009)Energyreturnoninvestment:towardaconsistentframework.AMBIO:JHumEnviron37:74–79

1. KimS,DaleBE(2005)Lifecycleassessmentofvariouscroppingsystems utilized for producing biofuels: bioethanol and biodiesel.BiomassBioenergy29:426–439
2. PatzekT(2006)AFirst-lawthermodynamicanalysisofthecorn–ethanolcycle.NatResourRes15:255–270
3. Pimentel D, Patzek TW (2005) Ethanol production using corn,switchgrass, and wood; biodiesel production using soybean andsunflower.NatResourRes14:65–76
4. PoldyF(2008)Netenergyandstrategicdecision-making.Biofuels,BioprodBiorefin2:389–392
5. Ponton JW (2009) Biofuels: thermodynamic sense and nonsense.JCleanerProd17:896–899
6. SchmerMR,VogelKP,MitchellRB,PerrinRK(2008)Netenergy of cellulosic ethanol from switchgrass. ProcNatlAcadSci105:464–469
7. BerbergogluH,BarraN,PilonL,JayJ(2008)Growth,CO$_2$consumption and H$_2$ production of *Anabaena variabilis*ATCC29413-U under different irradiances and CO$_2$ concentrations. JApplMicrobiol104:105–121
8. Tsukahara K, Sawayama S (2005) Liquid fuel production usingmicroalgae.JJpnPetInst48:251
9. Sialve B, Bernet N, Bernard O (2009) Anaerobic digestion ofmicroalgaeasanecessarysteptomakemicroalgalbiodieselsustainable.BiotechnolAdv27:409–416
10. Posten C, Schaub G (2009) Microalgae and terrestrial biomass assourceforfuels—aprocessview.JBiotechnol142:64–69
11. BealC,SmithC,WebberM,RuoffR,HebnerR(2011)Aframeworktoreporttheproductionofrenewabledieselfromalgae.BioEnergyRes4:36–60
12. Melis A, Melnicki MR (2006) Integratedbiological hydrogenproduction.IntJHydrogenEnergy31:1563–1573
13. AminS(2009)Reviewonbiofueloilandgasproductionprocesses frommicroalgae.EnergConversandManag50:1834–1840
14. DemirbasA(2010)Useofalgaeasbiofuelsources.EnergConversandManag51:2738–2749
15. Hillen LW, Pollard G, Wake LV, White N (1982)

Hydrocrackingof the oils of *Botryococcusbraunii*to transport fuels. BiotechnolBioeng24:193–205

16. Guschina IA, Harwood JL (2006) Lipids and lipid metabolism ineukaryoticalgae.ProgLipidRes45:160–186
17. TornabeneTG,HolzerG,LienS,BurrisN(1983)Lipidcompositionofthenitrogenstarvedgreenalga Neochlorisoleoabundans.EnzymeMicrobTechnol5:435–440
18. Lundquist TJ, Woertz IC, Quinn NWT, Benemann JR (2010) ARealistic technology and engineering assessment of algae biofuelproduction
19. BealCM,HebnerRE,WebberME,RuoffRS,SeibertAF,King CW (In Review) Constraints on algal biofuel production.EnvironmentalScience&Technology
20. Cleveland CJ, Kaufmann RK, Stern DI (2000) Aggregation andtheroleofenergyintheeconomy.EcolEcon32:301–317
21. (2010)AnnualEnergyOutlook2010.In:EnergyInformationAgency
22. Beal CM, Hebner RE, Romanovicz D, Mayer CC, Connelly R (InReview)Progressionoflipidprofileandcellstructureinaresearchproductionpathwayforalgalbiocrude.RenewableEnergy
23. Poenie M (2009) Personal Communication, Beal C.M., HPLCAnalysis
24. Oyler J (2010) Personal Communication, Beal C.M., Genifuel:CatalyticHydrothermalGasification
25. King CW, Holman AS, Webber ME (2008) Thirst for energy. NatGeosci1(5):283–286
26. GoldsteinR,SmithW(2002)Water&Sustainability(Vol.4):U.S. ElectricityConsumptionforWaterSupply&Treatment.PaloAlto, CA:EPRI#1006787
27. RamírezCA,WorrellE(2006)Feedingfossilfuelstothesoil:Analysis of energy embedded and technological learning in thefertilizerindustry.ResourConservRecycl46(1):75–93
28. Sheehan J, Camobreco V, Duffield J, Shapouri H, Graboski M,Tyson KS (2000) An overview of biodiesel and petroleum diesellifecycles.In:NREL/TP-580-24772
29. WuH,FuQ,GilesR,BartleJ(2007)Productionofmalleebiomass in western Australia. Energy Balance Anal Energy Fuels22(1):190–198
30. (2008) U.S. Life-Cycle Inventory Database. August 16, 2008 ed:NREL
31. Worrell E, Phylipsen D, Einstein D, Martin N (2000) Energy useand energy intensity of the U.S. chemical industry. Report nrLBNL–44314.40p.
32. FeldmanSR(2005)SodiumChloride.Kirk-OthmerEncyclopediaofChemicalTechnology:JohnWiley&Sons,Inc.
33. Capello C, Fischer U, Hungerbuhler K (2007) What is a greensolvent?Acomprehensiveframeworkfortheenvironmental assessmentofsolvents.GreenChem9(9):927–934
34. YenHW,BruneDE(2007)Anaerobicco-digestionofalgalsludgeandwastepapertoproducemethane.BioresourTechnol98:130–134
35. Weyer K, Bush D, Darzins A, Willson B Theoretical maximumalgaloilproduction.BioEnergyResearch3:204–213
36. ChistiY(2007)Biodieselfrommicroalgae.BiotechnolAdv25:294–306
37. BenemannJ,OswaldW(1996a)SystemsandeconomicanalysisofmicroalgaepondsforconversionofCO2tobiomass.DepartmentofEnergy,Citing1987Study
38. Benemann J, Oswald W (1996b) Systems and economic analysisofmicroalgaepondsforconversionofCO2tobiomass.Department of Energy, Citing Study by Weissman and Goeble,1982
39. PruvostJ,VanVoorenG,CogneG,LegrandJ(2009)Investigationofbiomassandlipidsproductionwith*Neochlorisoleoabundans*inphotobioreactor.BioresourTechnol100(23):5988–5995
40. Miao X., Wu Q (2006) Biodiesel production from heterotrophicmicroalgaloil.BioresourTechnol97(6):841–846
41. MengX,YangJ,XuX,ZhangL,NieQ,XianM(2009)Biodieselproduction from oleaginous microorganisms. Renewable Energy34(1):1–5
42. Yang J, Xu M, Zhang X, Hu Q, Sommerfeld M, Chen Y (2010)Life-cycleanalysisonbiodieselproductionfrommicroalgae:waterfootprintandnutrientsbalance.BioresourTechnol102(1):159–165
43. Bolhouse A, Ozkan A, Berberoglu H (2010) Rheological study ofalgae slurries for minimizing pumping power. In: ASME-IMECE2010.Vancouver,BCCanada
44. Henderson R, Parsons S, Jefferson B (2008) The impact of algalpropertiesandpre-oxidationonsolid–liquidseparationofalgae.WaterRes42:1827–1845
45. PoelmanE,DePauwN,JeurissenB(1997)Potentialofelectrolytic flocculation for recovery of micro-algae. ResourConservRecycl19:1–10