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# Evaluating the relative impacts of operational and financial factors on the competitiveness of an algal biofuel production facility

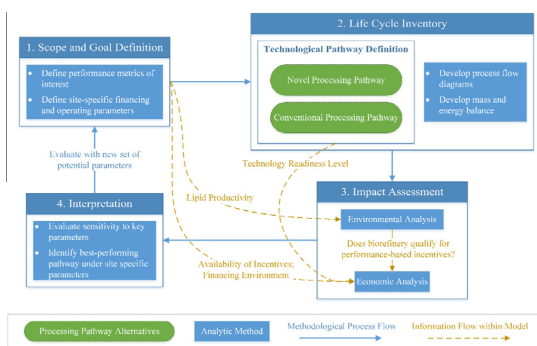
Adam M. Hise [a,*], Gregory W. Characklis [a], Jordan Kern [b], Robin Gerlach [c], Sridhar Viamajala [d], Robert D. Gardner [e], Agasteswar Vadlamani [d]

[a] Department of Environmental Sciences and Engineering, University of North Carolina, Chapel Hill, NC 24060, United States
[b] Institute for the Environment, University of North Carolina, Chapel Hill, NC 24060, United States
[c] Department of Chemical and Biological Engineering, Center for Biofilm Engineering, Montana State University, Bozeman, MT 59717, United States
[d] Department of Chemical and Environmental Engineering, The University of Toledo, Toledo, OH 43606, United States
[e] Department of Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, MN 55108, United States

## HIGHLIGHTS

- Algal biofuel processes evaluated relative to operational and financing scenarios.
- Lipid productivity and conversion method affect the value of novel techniques.
- Investment incentives promote pathways with greater capital intensity.
- Operating and financing assumptions affect choice of cost-competitive pathway.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Algal biofuels are becoming more economically competitive due to technological advances and government subsidies offering tax benefits and lower cost financing. These factors are linked, however, as the value of technical advances is affected by modeling assumptions regarding the growth conditions, process design, and financing of the production facility into which novel techniques are incorporated. Two such techniques, related to algal growth and dewatering, are evaluated in representative operating and financing scenarios using an integrated techno-economic model. Results suggest that these techniques can be valuable under specified conditions, but also that investment subsidies influence cost competitive facility design by incentivizing development of more capital intensive facilities (e.g., favoring hydrothermal liquefaction over transesterification-based facilities). Evaluating novel techniques under a variety of operational and financial scenarios highlights the set of site-specific conditions in which technical advances are most valuable, while also demonstrating the influence of subsidies linked to capital intensity.



## 1. Introduction

Producing biofuels from microalgae offers the potential to mitigate many of the challenges faced by crop-based biofuels, thanks to advantages conferred by efficient microbial processes and an

* Corresponding author.
*E-mail address:* ahise@live.unc.edu (A.M. Hise).

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increasingly closed-loop production system. Microalgae can produce 30–100 times more energy per hectare than terrestrial feedstocks (Kirrolia et al., 2013) as a result of a highly efficient photosynthesis pathway (Brennan and Owende, 2010) and the significant mass fraction of readily-convertible lipids in oleaginous algal strains (Chisti, 2007). In contrast to agriculturally produced terrestrial biofuels feedstocks, algal biofuel production can occur in a highly engineered and resource efficient biorefinery, encompassing biomass cultivation, harvesting, and conversion to fuels and coproducts (Rawat et al., 2013). Such processing can occur on non-arable land (further reducing competition with food crops) and allows for high levels of water, nutrient, and energy recycling, a necessary component for sustainable, commercial-scale algal biofuel production (Chowdhury et al., 2012).

Relative to agriculturally-based 1st and 2nd generation biofuels production systems, integrated algal biorefineries are both material and capital intensive (Collet et al., 2013). The substantial upfront capital expenses for developing commercial scale facilities require financing, which has been impeded by the use of processing techniques unproven at scale and the commensurate uncertainty in long-term system performance (Kirrolia et al., 2013). Systems analysis methodologies, especially techno-economic analysis (TEA) and life cycle analysis (LCA), can be used to provide forecasts of facility economic competitiveness (Zhu et al., 2013) and life cycle environmental impacts (Klöpffer, 1997), elucidating the production risks and thereby barriers to investment (Miller et al., 2013).

These methods have been widely utilized to evaluate the performance improvements achievable through incorporation of novel techniques for algal cultivation, harvesting/dewatering, extraction/conversion, and recycling (Quinn and Davis, 2014). Process (i.e. unit operation) decisions have systems-level (i.e. biorefinery) implications, since process-specific constraints dictate input and output flow characteristics which impact up- and downstream operations (Richardson et al., 2014). The benefits of incorporating a novel technique will therefore vary with the pathway in which the technique is incorporated (Resurreccion et al., 2012). Uncertainty surrounding operational parameters known to affect these benefits is generally not addressed in feasibility analyses, thereby limiting the applicability of the associated findings. Modeled performance of algal biofuel facilities has proven particularly sensitive to assumed algal growth rates (Liu et al., 2013) and lipid content (Clarens et al., 2011; Resurreccion et al., 2012), as well as the algae-to-biofuel conversion method (López Barreiro et al., 2013; Ríos et al., 2013; Torres et al., 2013).

The cost-competitiveness of a given pathway is, however, impacted by both technical advances (i.e. decreasing capital and operating expenses) and project financing assumptions, though only recently has uncertainty in the financial factors embedded in economic analyses been addressed (Beal et al., 2015; Gerber et al., 2016; Resurreccion et al., 2012; Richardson et al., 2012; Rogers et al., 2014; Stephens et al., 2010). Often, these factors are not only uncertain but affected by facility design and the site-specific financing environment. The technological readiness level (TRL), a measure of the maturity of a production pathway, increases as a process advances from concept to the commercial scale level (Mankins, 2009); higher TRL increases confidence in facility performance. This confidence is in turn felt by investors, reducing their perceived risk of investment in the facility and thereby the return they require on construction capital. While advanced techniques may therefore provide many advantages (e.g., reduced environmental impact, energy demand, and capital and operating expenses), these must be weighed against the increase in financing costs resulting from their incorporation. Environmental impacts, dependent on the operating environment and production pathway techniques, also have the potential to significantly impact economic competitiveness by determining whether a facility qualifies for substantial performance-based subsidies (Resurreccion et al., 2012).

This work seeks to address previously unexplored interactions between technical advances and financing parameters, and examine how tradeoffs resulting from these interactions affect the cost competitiveness of optimal facility design. A TEA/LCA model has been developed to evaluate performance benefits arising from the use of novel techniques for (1) boosting lipid productivity with a bicarbonate amendment (Gardner et al., 2013; Lohman et al., 2015) and (2) lowering capital costs and energy inputs for dewatering by utilizing temperature-sensitive "hydrogels" (Vadlamani, 2014; Zhao, 2015). These techniques are evaluated in pathways using either transesterification or hydrothermal liquefaction (HTL) conversion techniques, and across a range of achievable algal lipid content and growth rates, in order to assess the influence of these operational factors on the relative benefits of novel technique incorporation.

The financing parameters embedded in the economic model are then varied to evaluate the impact of accelerated depreciation methods, production tax credits, federal loan guarantees, and a range of investment risk on these pathways. Variations from the base financing assumptions allow a comparison of the relative economic competitiveness improvements achievable from regulatory subsidies and how they vary based on the capital intensity of the processing pathway. Each technical and financial alternative is then modeled in combination to identify maximally cost-competitive production pathways in various plausible financing scenarios. Novel technology evaluation in this manner provides a means for identifying the conditions, both operational (e.g., achievable algal lipid production rate, conversion method) and financial (e.g., reduced interest rates and tax liability) in which proposed production pathways are most economically competitive.

## 2. Methods

Simultaneous evaluation of environmental, economic, and energetic metrics for algal biofuel production pathways composed of alternative sub-processes allows system designers to select pathways that increase aggregate life cycle benefits (Delrue et al., 2012). The methodology for performing LCA is well established (ISO 14040, 1997) and provides a useful framework for an integrated and dynamic techno-economic and environmental analysis of novel techniques (Fig. 1).

### 2.1. Scope and goal definition

A systems model has been developed to examine the performance of an algal biorefinery producing a "functional unit" of 10 million gallons of biofuel (either biodiesel or renewable diesel) annually. The system boundary includes biofuels combustion (i.e. a "well-to-wheels" scope) to facilitate comparisons with conventional fuel life cycles, highlighting systems-level tradeoffs resulting from process-level decisions (Decicco, 2014).

Environmental impact analysis has, similar to previous analyses (Bennion et al., 2015; van Boxtel et al., 2015), focused on the characterization of biorefinery global warming potential (GWP) and energy balance in a "partial LCA" as designated by international standards (ILCD, 2012). The energy and emissions associated with system construction are excluded, assumed to be similar for all the considered pathways and relatively small when evaluated over the facility lifetime (Frank et al., 2011). The benefits of an increasingly closed-loop production system (e.g. efficiently recycling material and energy inputs as well as reducing emissions) are weighed against the increased capital expense required to achieve this state.

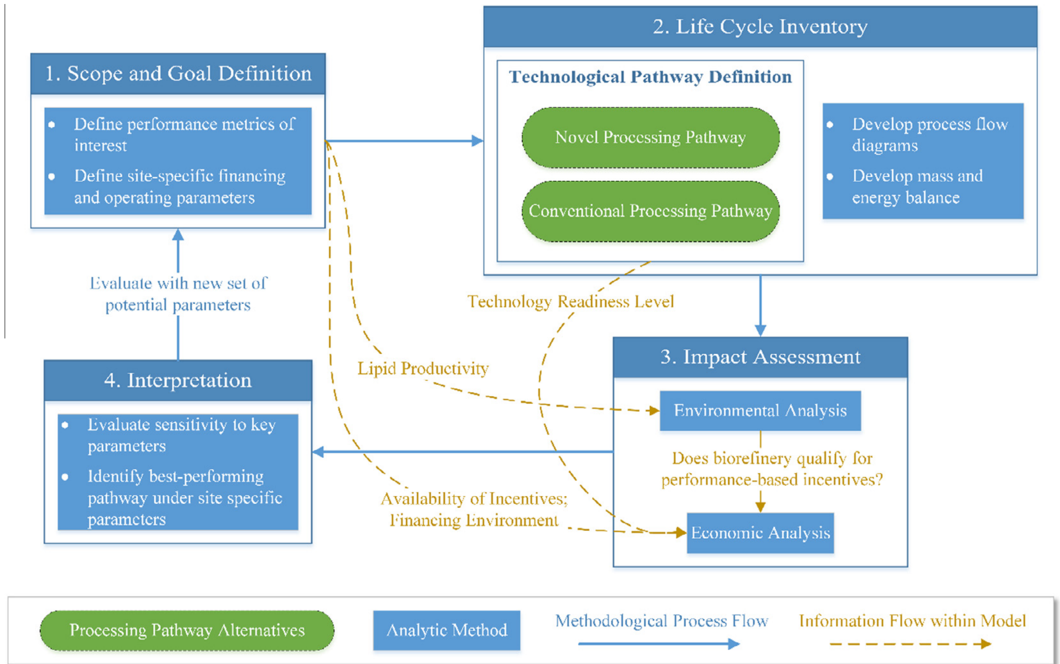


**Fig. 1.** Schematic of the integrated LCA/TEA modeling approach.

The cumulative energy ratio (CER), calculated as the sum of direct energy inputs and embodied energy (i.e. primary energy required to produce materials, thermal and electric energy) of inputs and divided by the output fuel energy is used as the primary energetic measure of the biofuel pathways (Collet et al., 2013). Using the methodology of Hill et al. (2006), biofuels produced are assumed to displace fossil fuels based on the pathway CER; a credit for avoided fossil emissions is subtracted from direct emissions from the biofuel production pathway. Life cycle petroleum diesel fuel emissions (i.e. including combustion) are multiplied by biorefinery CER to determine avoided emissions; summing with pathway emissions and further dividing by diesel emissions calculates the relative GWP of produced biofuels (Eq. (1)). Since the $CO_2$ supplied to supplement algae growth is assumed captured from industrial flue gas (at significant energy expense), biofuel combustion is “carbon neutral,” as emitted $CO_2$ was recovered from an atmospheric waste stream (Liu et al., 2013). The emissions and energy associated with process inputs are obtained from GREET (GREET, 2011), other analyses, and industrial sources (see SI).

$$GWP\ [\%\ of\ Diesel] = \frac{Diesel\ Emissions \left[\frac{g\ CO_2\ eq}{MJ}\right] \times \left(1 - \frac{Energy\ Out}{Energy\ In}\right) + Pathway\ Emissions \left[\frac{g\ CO_2\ eq}{MJ}\right]}{Diesel\ Emissions \left[\frac{g\ CO_2\ eq}{MJ}\right]} \quad (1)$$

The minimum fuel selling price (MFSP) represents the breakeven selling price of each gallon of biofuel produced, such that the net present value of the facility equals zero (i.e. Present Value of Costs = Present Value of Revenues). This metric is calculated by summing manufacturing and financing costs over the plant’s lifetime and dividing by the total volume of biofuel produced. In order to compare fuels of different energy contents, MFSP is converted to dollars per gallon gasoline (energy) equivalent ($\$\ gge^{-1}$) by multiplying by the ratio of gasoline energy content to biofuel energy content.

### 2.2. Inventory and impact assessment

The algal biomass-to-biofuel pathway consists of four general stages: algae cultivation, harvesting and dewatering, conversion to fuels, and recycling of nutrients and energy. A baseline pathway, composed of commercially viable unit operations, was initially developed and used to evaluate relative performance benefits achieved via incorporation of novel techniques. Details of the conventional processes included in baseline pathways are provided in the SI.

### 2.3. Novel techniques

#### 2.3.1. Bicarbonate-induced lipid productivity boost

Efforts to boost oil production from algae have largely focused on nutrient stressing, as nitrogen depletion can halt cell growth and induce energy storage via accumulation of lipids (Sheehan et al., 1998). However, boosting lipid content at the expense of growth rate can actually decrease the total lipid productivity (grams lipid produced $m^{-2}\ d^{-1}$) and thereby the biofuel production potential, making this tradeoff undesirable (Quinn and Davis, 2014).

Alternatively, recent work has shown that gains in total lipid productivity can be achieved through controlled additions of sodium bicarbonate (Gardner et al., 2011, 2012, 2013).

Low-grade sodium bicarbonate additions during growth increases the rate of dissolved inorganic carbon uptake (Markou et al., 2014), boosting the specific growth rate by up to 69% and leading to an increase in overall biomass productivity of 27% (Lohman et al., 2015). A second, higher concentration addition of $NaHCO_3$ occurs as nitrogen is depleted, inducing further lipid accumulation to increase the achievable biodiesel content by 8%. Together with the increased biomass productivity, total lipid productivity can be increased 37% over that achievable by conventional growth techniques (see SI). Unlike the biogenic $CO_2$ recovered from flue gas, sodium bicarbonate represents a source of sequestered carbon, and thus combustion of biofuel from algae grown with this inorganic carbon addition incurs a corresponding GWP penalty.

#### 2.3.2. Hydrogel dewatering

Hydrogels synthesized to respond to temperature changes by rapidly absorbing or releasing water have been tested as an algal dewatering technique (Vadlamani, 2014) and proven capable of concentrating algal slurries from 0.1 wt% up to 10 wt% with less than 1% biomass loss (Zhao, 2015). Fairly dilute algal cultures flow to a tank containing the "hydrogels" where swelling occurs at room temperature; the algae-hydrogel mixture is then passed through a sieve, where swollen gels are trapped and sent to a de-swelling tank in which a 10 °C temperature increase causes the gels to shrink (see SI for schematic). Given that this temperature shift can occur between 32 °C and 35 °C, waste heat captured via heat exchangers is utilized to reduce de-swelling energy demands (Zhao, 2015).

### 2.4. Growth scenarios

Widely disparate values for achievable algal growth rates and lipid content are reported in the literature and known to significantly affect predictions of biorefinery performance (Collet et al., 2013; Quinn and Davis, 2014). Lipid productivity affects the modeled performance of sub-process alternatives, impacting the choice of optimal growth reactor type (Richardson et al., 2014) and conversion method (Clarens et al., 2011). The impact of incorporating a bicarbonate-induced lipid productivity boosts and hydrogel dewatering in production pathways is therefore evaluated under two growth scenarios.

The "Ave. Growth" scenario is defined by the national average areal productivity for open pond systems, calculated as $13.2\ g\ m^{-2}\ day^{-1}$ (Davis et al., 2012), and an average extractable lipid content of 25% of dry algae by weight (henceforth referred to as wt%). In regions with higher insolation and less annual temperature variation, areal productivity can be significantly greater, with various analyses showing growth rates of up to $40.6\ g\ m^{-2}\ d^{-1}$ (Clarens et al., 2010). Additionally, species selection for biofuels production has shown that certain algae are capable of accumulating up to 50 wt% lipids (Collet et al., 2013). A "High Growth" scenario is therefore developed with an areal productivity of $32\ g\ m^{-2}\ d^{-1}$ and a lipid content of 45 wt%. To reflect the increased insolation and reduced temperature variability, the average ambient temperature in this scenario is increased from 23 °C (assumed for the "Ave. Growth" scenario) to 28 °C (reflective of conditions in the US Gulf Coast, Central America, the Middle East, and Southeast Asia). A selection of key model inputs are presented in Table 1; the full list of modeling parameters is provided in the SI.

**Table 1**
Select Model Parameters (capital and operating expenses adjusted to 2014 dollars).

| Parameter | Value | Units | References |
|---|---|---|---|
| *Algae cultivation* | | | |
| Land Cost | 3150 | \$/acre | Davis et al. (2011) |
| Algal Productivity | 13.2 | $g/m^2/d$ | Davis et al. (2012) |
| Operational Days | 330 | days/year | Davis et al. (2012) |
| Lipid Content | 25% | | Davis et al. (2012) |
| Pond Outlet Conc. | 0.5 | g DWB/L | Frank et al. (2011) |
| Pond CapEx | 3.40E+04 | \$/ha | Lundquist et al. (2010) |
| Nitrogen Demand | 7.70E−02 | g N/g algae | Frank et al. (2011) |
| Ammonia Cost | 427.35 | \$/ton $NH_3$ | Davis et al. (2011) |
| Phosphorous Demand | 8.10E−03 | g P/g algae | Frank et al. (2011) |
| DAP Cost | 464.1 | \$/ton DAP | Davis et al. (2011) |
| $CO_2$ Cost | 42 | \$/kg | Davis et al. (2011) |
| *Bicarbonate-induced lipid productivity boost* | | | |
| $HCO_3$ Demand | 55 | mM | Gardner et al. (2013) |
| $NaHCO_3$ Cost | 0.55 | \$/kg | Industrial Quote |
| *Dewatering* | | | |
| Autofloc. CapEx | 82 | $\$/m^3$ | Delrue et al. (2012) |
| DAF CapEx | 5.14E+06 | \$ | CapCost® Calculation |
| *Hydrogels* | | | |
| Temp Change | 10 | °C | Vadlamani (2014) |
| Retention Efficiency | 98% | | Vadlamani (2014) |
| CapEx | 2.30E+06 | \$ | CapCost® Calculation |
| OpEx | 4.61E+03 | \$ | CapCost® Calculation |
| *Dry hexane extraction* | | | |
| CapEx | 119 | \$/ton DWB | Chauvel et al. (2001) |
| *Transesterification* | | | |
| Capital Expense | 506.94 | \$/ton CL/yr | Chauvel et al. (2001) |
| *Hydrothermal liquefaction* | | | |
| CapEx | 6.07E+07 | \$ | Jones et al. (2014) |
| *Anaerobic digestion* | | | |
| CapEx | 190 | \$/ton residue/yr | Davis et al. (2011) |

### 2.5. Financing parameters

Financial assumptions embedded in feasibility analyses represent a significant source of uncertainty (Quinn and Davis, 2014), with parameters affected by external market conditions as well as linked to regulatory policies and facility design/operation (Gerber et al., 2016). The maturity of a facility's technology, as typified by the technology readiness level (TRL), affects the perceived investment risk of the facility, which impacts the interest rate for debt financing (Mankins, 2009). Choosing higher TRL pathways or employing managerial strategies to mitigate exposure to market, technology, and operational risks decreases overall investment risk, thereby reducing financing costs (Lamers et al., 2015).

By guaranteeing the repayment of loans offered to developers of innovative technologies, federal loan guarantees, such as those offered by the Department of Energy for advanced biofuel producers (Yacobucci, 2011), accelerate innovative technology development and deployment by allowing low-TRL facilities access to lower-cost capital. As per Jones et al. (2014), the facility is here is assumed to be financed 60% with debt (the other 40% from equity), with the MFSP calculated under three financing scenarios. The baseline financing scenario assumes an interest rate (IR) of 8%; an IR of 6% represents a "mitigated risk" scenario, wherein higher TRL or managerial actions reduce risk exposure; and an IR of 4% represents a case in which the facility qualifies for a DOE Loan Guarantee.

The depreciation method used for the MFSP calculation is impacted by regulatory policies designed to support renewable fuels. The depreciation charge is used to account for the loss in value of capital assets over time, and is a percent of total capital expenses that is deducted from the firm's taxable income (IRS, 2015). Straight line depreciation, used for the baseline financial analysis, is calculated by dividing the total depreciable capital expenses by the asset lifetime, such that an equal charge is applied annually until the end of its useful life, at which point it is considered valueless. Accelerated depreciation methods allow larger

**Table 2**
Growth scenarios, processing advances, and financing parameters composing scenarios in which each production pathway is evaluated.

| | | |
|---|---|---|
| Growth Scenarios | Average Growth | 13.2 g $m^{-2}$ $d^{-1}$ Areal Productivity, 25% Lipid Content |
| | High Growth | 32 g $m^{-2}$ $d^{-1}$ Areal Productivity, 45% Lipid Content |
| Processing Pathways | Conventional Transesterification | Open raceway pond, autoflocculation, dissolved air flotation, natural gas drum drying, hexane extraction, transesterification, anaerobic digestion of lipid extracted algae |
| | Conventional HTL | HTL replaces transesterification; no natural gas drum dryers are required; hydrotreating produces renewable diesel from biocrude |
| | Novel Tech. | Two-phase addition of $NaHCO_3$ during cultivation to boost lipid productivity; Dissolved air flotation is replaced by temperature sensitive hydrogels |
| Financing Scenarios | Base Financing | Straight line depreciation over 12 year recovery period; 40% of capital financed through equity, with debt repaid at 8% interest over 10 years |
| | MACRS Depreciation | 7-year MACRS depreciation schedule replaces straight line depreciation |
| | Bonus Depreciation | 50% of depreciable capital is deductible in the first year of operations, followed by 7-year MACRS |
| | Production Tax Credit (PTC) | Pathways with life cycle GWP < 50% of conventional diesel receive a \$1.01 $Gal^{-1}$ tax credit, which directly reduces the tax liability; deferred tax assets accrue if credits are greater than current liabilities |
| | 6%/4% Interest Rate | Interest rate reduction to 6% from 8%, represents actions taken to mitigate project risks; reduction to 4% represents guarantee of project loans (e.g., DOE Loan Guarantee) |

taxable income deductions early in the life of certain types of assets (e.g., biofuels production equipment); using a standard discount rate to account for the time value of money, the ability to defer tax liability to later in a facility's operational life increases a project's present value (US PREF, 2014). The 7-yr Modified Accelerated Cost Recovery System (MACRS) depreciation and Bonus depreciation, respectively currently and previously allowed for advanced biofuel facilities (Mendelsohn, 2012) methods can provide a significant subsidy to such facilities (see SI). These accelerated depreciation methods have been substituted for the straight line method to evaluate the impact on MFSP calculations for all production pathways and growth scenarios.

The updated Renewable Fuel Standard sets minimum volumes of biofuels which must be blended by refineries, supporting both biofuel demand and market value (Yacobucci, 2011), thereby helping producers mitigate offtake risk and secure financing (Miller et al., 2013). This policy further established a \$1.01 $Gal^{-1}$ production tax credit (PTC) for biomass-based diesel fuel with life cycle GWP less than 50% that of petroleum diesel (enacted in 2007 and sporadically extended since (Yacobucci, 2011)). Evaluating production pathways in an integrated LCA/TEA highlights how pathway design decisions affect a facility's environmental performance, which determines eligibility for performance based incentives, which affect the economic competitiveness of facility outputs. The relative benefits of these financing improvements (i.e. interest rate reductions, accelerated depreciation methods, and the PTC) are then compared for each proposed production scenario, to examine interactions between pathway design and subsidy benefits.

### 2.6. Economic assumptions

Equipment costs have been calculated using CapCost™ (Turton et al., 2008) or scaled from published analyses; details of technical operations, capital and operating expenses for production pathway equipment are included in the SI. Recent design reports have outlined economically competitive HTL production pathways for producing renewable fuels from either whole-cell (Jones et al., 2014) or lipid extracted algae (Davis et al., 2014); capital costs for the HTL pathway have been scaled from these reports. The methodology of these reports was further utilized for calculating initial and non-equipment operating expenses; these factors, as well as the baseline parameters used for the MFSP calculation, are outlined in the SI.

### 2.7. Interpretation

Transesterification produces biodiesel, lipid extracted algae (LEA), and glycerol in proportions based on the algal cellular composition. LEA is utilized onsite via anaerobic digestion (AD), where organic matter is converted to biogas and nutrients (primarily nitrogen and phosphorous) are recoverable from the aqueous phase. Catalytic hydrothermal gasification (CHG) of the nutrient-rich aqueous phase from HTL reactions reduces nitrogen to ammonia and produces biogas from aqueous carbon (Liu et al., 2013). Nutrients recovered from AD and CHG are recycled within the biorefinery to reduce net fertilizer demands; biogas is sent to a combined heat and power system to reduce natural gas and electricity inputs.

Any coproducts generated by the system that are not recycled within the facility displace conventionally produced goods, with the emissions avoided from displaced production processes credited to the facility (Chowdhury et al., 2012). Rather than considering the uncertainties surrounding on-site uses for glycerol, this coproduct of the transesterification reaction is substituted for biomass co-fired for bioelectricity offsite, generating a credit based on its energetic content (Koutinas et al., 2014; Ponnusamy et al., 2014). Integrating recycling processes has the potential to provide economic, environmental, and energetic benefits to biorefineries by reducing external resource demands. Assigning a credit to the avoided virgin resources effectively double-counts these benefits when comparing different systems and was therefore avoided in this work.

### 2.8. Limitations

The nascent stage of the cultivation and conversion technology often necessitates the use of data extrapolated from the bench scale for use in commercial scale feasibility assessments, reducing certainty in modeled performance estimates (Collet et al., 2013). While extrapolated data should be treated with caution, the National Algal Biofuels Technology Roadmap (DOE, 2010) notes that qualitative trends emerging from modeling efforts can be highly useful for guiding technical, economic and policy decisions. For example, HTL modeling has been developed using processing parameters from Frank et al. (2013) with hydrotreating parameters as well as capital and operating expenses scaled from Jones et al. (2014) to match the functional unit of this analysis. Inclusion of this conversion method is intended not to develop high resolution economic, energetic, or environmental results, but rather to examine the potential differences in the impact of incorporating novel sub-processes into pathways based around different conversion methods.

Exclusion of energy and emissions related to construction should be noted when drawing comparisons with other energy production pathways, as this omission may assign too little impact

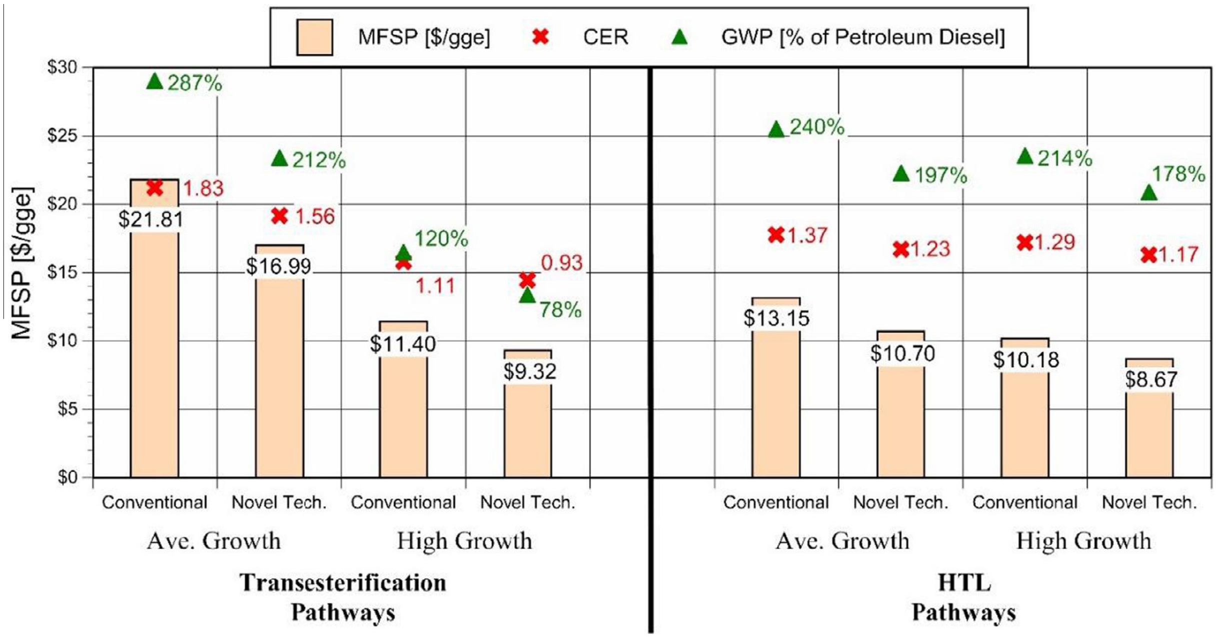


**Fig. 2.** Impacts from novel technique incorporation on minimum fuel selling price (MFSP), cumulative energy ratio (CER), and global warming potential (GWP); performance with conventional and novel growth and dewatering techniques are compared under average and high growth (i.e. lipid productivity) scenarios for transesterification and HTL-based pathways.

**Table 3**
Changes in performance metrics and key operating parameters resulting from incorporation of both bicarbonate triggers and hydrogel-based dewatering (i.e. novel techniques).

| | Transesterification pathways | | HTL pathways | |
|---|---|---|---|---|
| | Ave. Growth | High Growth | Ave. Growth | High Growth |
| CER | −15% | −16% | −10% | −9% |
| GWP | −23% | −21% | −18% | −17% |
| Algae demand | −13% | −16% | −6% | −6% |
| Pond CapEx | −33% | −33% | −27% | −25% |
| MFSP | −22% | −18% | −19% | −16% |
| Capital intensity ratio | +4% | +9% | +14% | +19% |

to algal biofuels (Clarens et al., 2010). The limited scope of environmental impact assessment, while appropriate for the goals of this analysis, may also skew comparisons with other fuel cycles. Comparing environmental impacts with terrestrial biofuel production systems, which have considerable land use change, water use, and eutrophication impacts (Clarens et al., 2011), would require further evaluation of algal pathway performance in these impact categories.

## 3. Results

### 3.1. Pre-screening and analysis overview

Novel techniques (i.e. bicarbonate amendment and hydrogel dewatering) were evaluated, separately as well as in combination, under both growth scenarios and with cumulative changes to the financing parameters. Replacing conventional growth with bicarbonate-induced lipid productivity boosting and dissolved air flotation with hydrogel dewatering each separately yield economic, environmental, and energetic benefits. As the benefits from incorporating these two novel techniques in tandem dominate those from incorporation of either alone, results are presented for "Novel Tech." pathways which include both the bicarbonate treatment as well as hydrogel dewatering. A summary of the growth scenarios, processing advances, and financing parameters that make up the examined production scenarios is provided in Table 2.

### 3.2. Novel technique incorporation

Pathways incorporating novel techniques are compared against conventional operations under the average ("Ave. Growth") and high ("High Growth") achievable lipid productivity growth scenarios and in pathways using either the transesterification or HTL conversion process (Fig. 2). In the Ave. Growth scenario, novel techniques reduce the MFSP 22%, the CER by 15%, and GWP by 26% in the transesterification pathway, compared to reductions of 19%, 10%, and 18% (respectively) in HTL pathways. Though unable to compete economically with HTL pathways in the Ave. Growth scenario, under High Growth conditions the transesterification pathway with novel techniques has a lower MFSP than the conventional HTL pathway, while also achieving a net energy output (0.93 kWh energy input per kWh energy output) and reducing GWP 22% relative to petroleum diesel. No pathway reaches the 50% GWP reduction required to qualify for the PTC.

Several trends are highlighted by the relative impacts of novel technique incorporation under different operating scenarios (Table 3). The energetic, environmental, and economic benefits of incorporating these novel techniques are greater in transesterification than HTL-based pathways. Our model assumes that biocrude yield from HTL is unaffected by cellular composition (see SI), while biodiesel yield from transesterification is directly linked to lipid content (Frank et al., 2011). By increasing the lipid productivity (grams lipid produced per $m^2$ per day) above that otherwise achievable (e.g., based on algal strain and growth conditions), bicarbonate additions increase the biodiesel produced per gram of transesterified algae as well as the rate at which algae is produced.

Combined with the decreased algae loss during processing with hydrogel dewatering (2% of throughput) relative to dissolved air flotation (10%), these novel techniques together significantly decrease the total algae required for the annual production of 10 MM gallons of biofuel. This in turn decreases the pond area required for the facility, with a commensurate decrease in capital costs. However, novel technique incorporation increases pathway capital intensity, the ratio of total capital investment to annual operating costs, as greater initial expenses increase the efficiency of biofuel production and decrease operating expenses. Further details regarding the performance benefits arising from novel technique incorporation are available in the SI.

### 3.3. Combining novel techniques and financing improvements

Policy-derived incentives for investment (i.e. interest rate reductions, accelerated depreciation of equipment) in biorefineries and production (i.e. tax credits) of biofuels are evaluated to assess their impact on the economic competitiveness of the considered production pathways. As none of the pathways in either growth scenario qualify for the federal production tax credit (PTC), only investment incentives impact economic competitiveness. The relative impacts of novel technique incorporation, higher achievable lipid productivity, and cumulative improvements from base financing assumptions for transesterification and HTL pathways are illustrated in Fig. 3.

Relative reductions in MFSP, CER, and GWP from novel technique incorporation and operating under "High Growth" conditions are far greater for transesterification than HTL-based pathways. Conversely, interest rate reductions and the availability of MACRS depreciation allowances offer greater MFSP reductions for the more capital intensive HTL-based pathways (Bonus depreciation offered no significant change in the MFSP for these pathways and has therefore been omitted).

A strong positive correlation exists between the capital intensity ratio and the MFSP reduction achieved via financing improvements, with these investment incentives offering greater MFSP reductions to pathways with a greater fraction of costs from capital expenses (Fig. 4). Incorporating novel techniques increases the capital intensity, as does the use of HTL, while capital expense reductions realized from operating under the "High Growth"

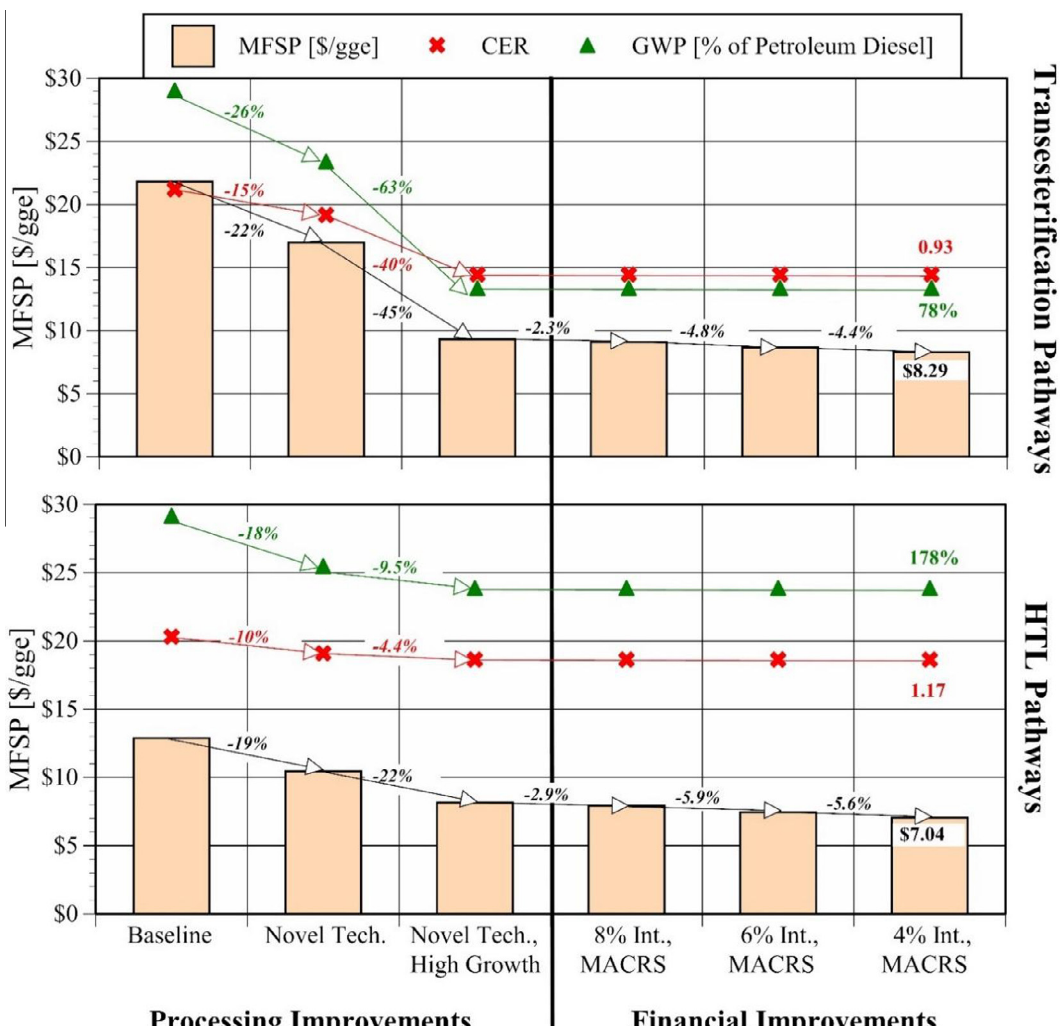


**Fig. 3.** Processing and financing improvements for transesterification and HTL-based facilities; processing advances include incorporating both novel techniques and operating under "High Growth" conditions; financing improvements include utilizing MACRS accelerated depreciation allowances and iterative interest rate reductions.

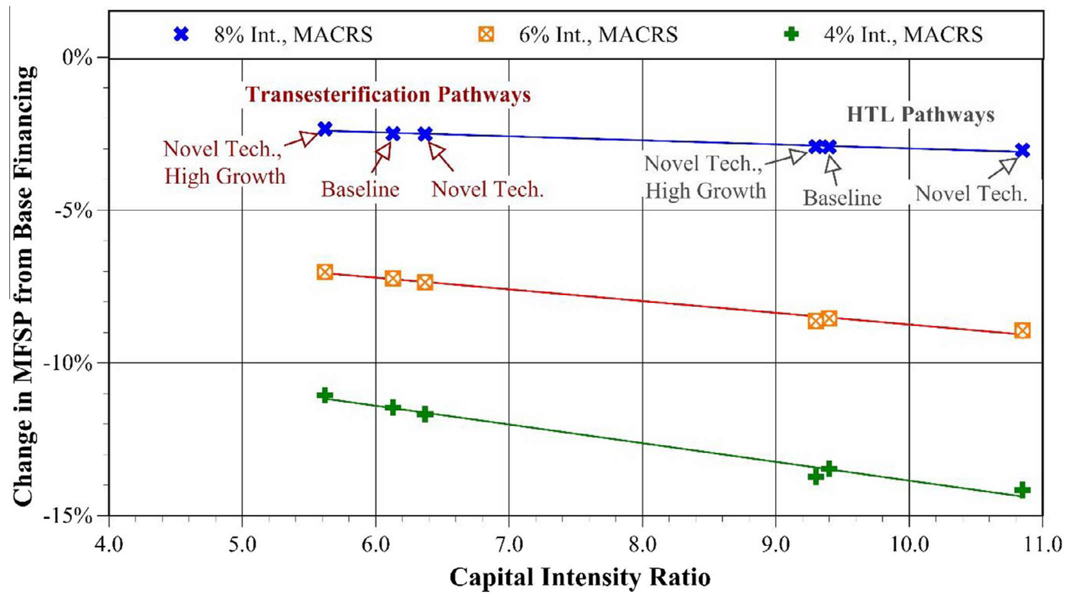


**Fig. 4.** Process choices affect the capital intensity ratio (fixed capital investment/annual operating expenses), which is correlated with the change in MFSP resulting from financing improvements; this is shown for HTL (which have a higher capital intensity ratio) and transesterification-based pathways as accelerated depreciation methods and lower interest rates replace baseline financing assumptions.

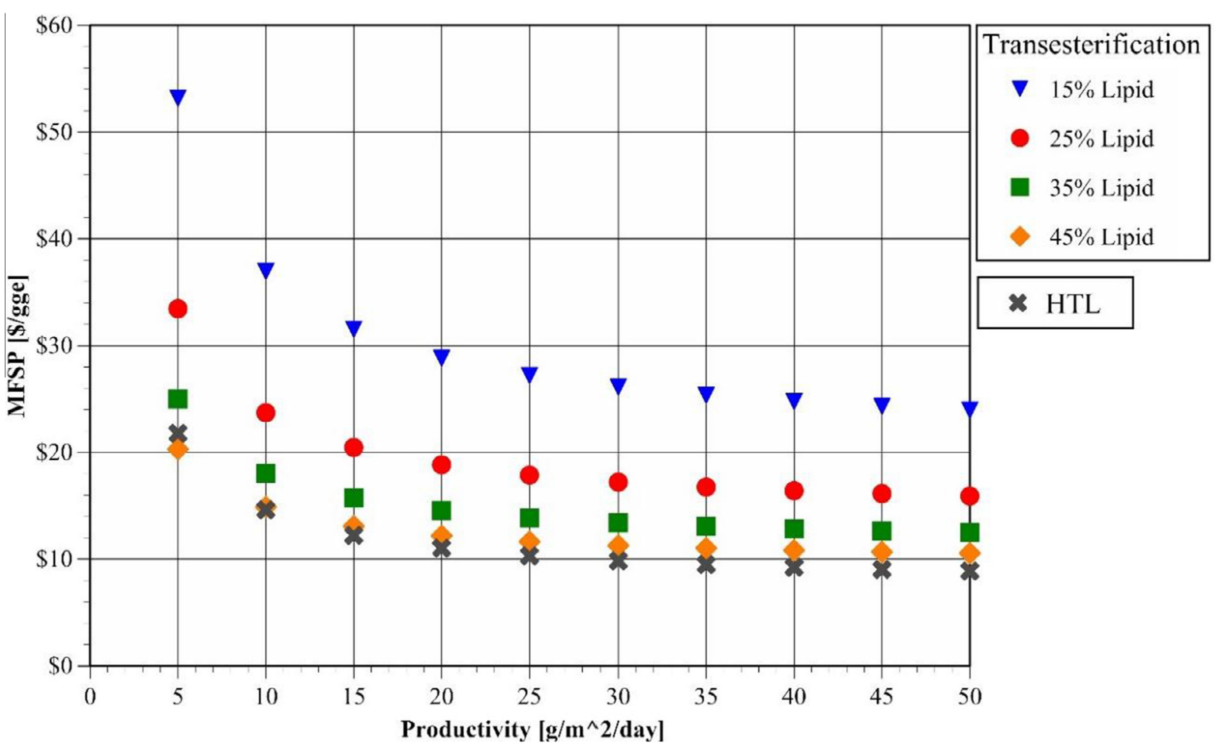


**Fig. 5.** Sensitivity of transesterification and HTL pathways to biomass productivity rates; transesterification-based pathways are evaluated across a range of achievable (i.e. based on algal strain, not growth treatment) lipid contents; HTL performance is modeled as independent of lipid content (see SI for details).

scenario decrease the capital intensity, with proportionate changes in MFSP reductions.

HTL-based systems are between 1.5 and 1.7 times more capital intensive than transesterification-based pathways and realize MFSP reductions between 17% and 24% greater when investment incentives are available. This relationship follows from the way these parameters affect facility financing: interest rate reductions decrease payments on capital financed through debt, while accelerated depreciation allowances decrease taxable income by a larger fraction of capital expenses early in the asset's life. Pathways with higher capital intensity will therefore achieve greater reductions in MFSP when these financing improvements are available. This link between the capital intensity of a facility and the economic benefit of regulatory financing improvements suggests that

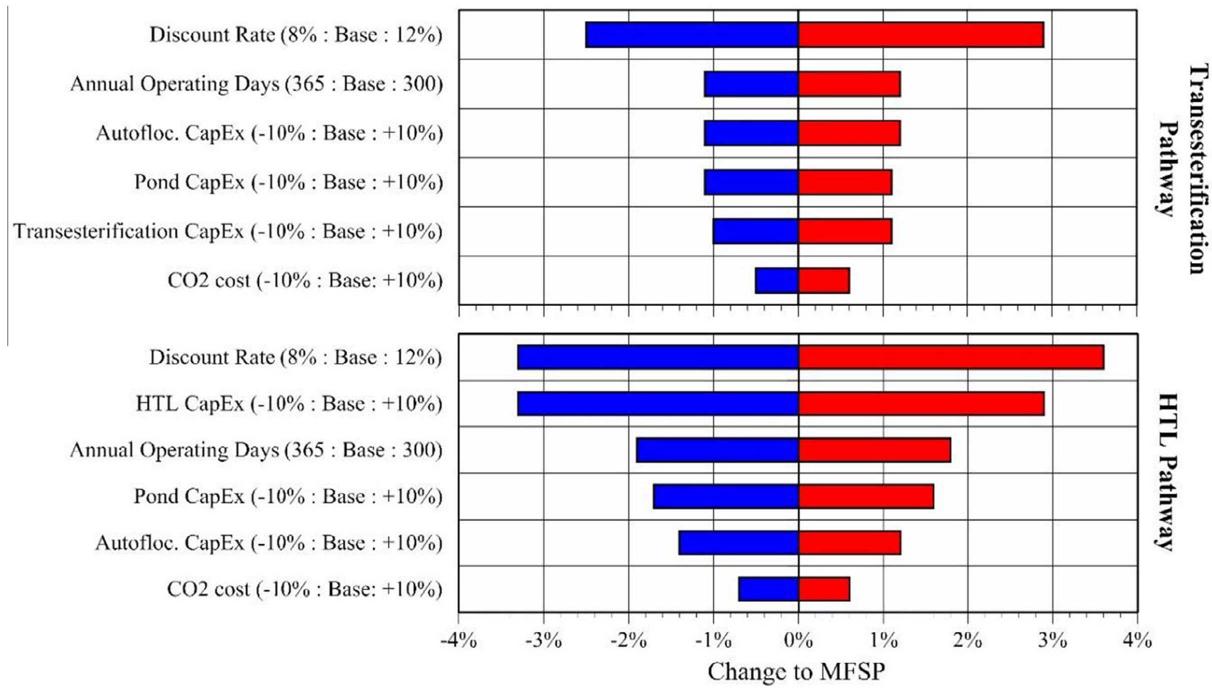


**Fig. 6.** MFSP sensitivity of transesterification and HTL-based novel technique pathways in the "High Growth" scenario; input ranges taken from literature (see SI).

relevant, site-specific policies need to be considered in the design of optimally competitive pathways.

### 3.4. Local sensitivity analysis

Increasing lipid content and biomass productivity via selection of optimal algal strain and cultivation site has a greater impact on the performance of transesterification-based pathways than on HTL-based pathways. Examining the performance impacts from varying lipid content and productivities for transesterification pathways (Fig. 5) shows diminishing returns from increased productivity at higher lipid content. While HTL pathway performance is unaffected by lipid content, low lipid content makes transesterification less economically attractive at even the highest productivity levels. At higher lipid content, transesterification pathways are able to compete economically with HTL pathways, illustrating that site specific growth rates and achievable lipid content must be considered carefully when designing production pathways.

The impact of single parameters embedded in the TEA/LCA model was analyzed by varying inputs over a range encompassing literature estimates and evaluating the MFSP sensitivity of transesterification and HTL-based production pathways (Fig. 6). The model is most sensitive to the specified discount rate for both conversion processes; decreasing the discount rate to 8% induces a 2.5% and 3.3% reduction in transesterification and HTL-based pathway MFSPs, respectively. After the discount rate, HTL-based systems are next most sensitive to the capital expense of the conversion equipment, while variations in transesterification reactor costs have a relatively smaller impact. The HTL pathway model is more sensitive than the transesterification model to annual operating days, capital expenses for the autoflocculation tank and open raceway pond, and $CO_2$ procurement costs.

Overall, the transesterification pathway is less sensitive to uncertainty in input parameters. It should be noted that the algal lipid transesterification model has been adapted from a standard model of commercial scale soy-oil transesterification (Frank et al., 2011) while the HTL parameters are based on lab and pilot scale testing (Frank et al., 2013); such extrapolation from a low TRL system may further increase HTL performance uncertainty.

### 3.5. Perspectives

Several useful insights can be derived from this analysis. From a modeling perspective, the finding that the benefits of novel techniques are closely linked to operational assumptions infers that technique suitability analyses ought to be performed across a range of plausible scenarios. From a financial perspective, results characterizing the greater value of investment incentives to pathways with higher capital intensity suggest these incentives are encouraging the development of facilities with greater upfront costs. This artifact of the current policies should be given consideration as policymakers consider how to effectively promote the development of liquid fossil fuel alternatives.

## 4. Conclusions

The novel techniques examined provide greater benefit to transesterification than HTL-based production pathways. Investment incentives are more valuable to pathways with a higher capital intensity, encouraging development of more efficient facilities with greater upfront expenses when policies make such incentives available. Evaluation of alternative techniques in a variety of operational and financing scenarios provides a more accurate representation of the exact conditions in which sub-processes dominate alternatives, accelerating the development of energetically positive, environmentally beneficial and economically competitive algal biorefineries.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2016.08.050.

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