Check for updates

Modeling and Analysis

Biofpr
Biofuels Bioproducts & Biorefining

Algae to HEFA: Economics and potential deployment in the United States

Swaroop Atnoorkar[†], Strategic Energy Analysis Center, National Renewable Energy Laboratory, Golden, CO, USA
Matthew Wiatrowski[†], Catalytic Carbon Transformation and Scaleup Center, National Renewable Energy Laboratory, Golden, CO, USA
Emily Newes, Strategic Energy Analysis Center, National Renewable Energy Laboratory, Golden, CO, USA
Ryan Davis, Catalytic Carbon Transformation and Scaleup Center, National Renewable Energy Laboratory, Golden, CO, USA
Steve Peterson, Independent contractor

Received January 2 2024; Revised February 27 2024; Accepted March 11 2024;
View online 26 April 2024 at Wiley Online Library (wileyonlinelibrary.com);
DOI: 10.1002/bbb.2623; *Biofuels, Bioprod. Bioref.* 18:1121–1136 (2024)

Abstract: To reach the goals set by the US Department of Energy's Sustainable Aviation Fuel (SAF) Grand Challenge, currently available feedstocks may be insufficient. Giving priority to developing, prototyping and reducing the cost of algal feedstock before investing and lining up locations is important. As the production of algal feedstocks advances, a simplified conversion approach using more mature technologies can help reduce the investment risk for algae-based fuels. Reducing process complexity to the steps described here [namely, conversion of lipids to HEFA (hydroprocessed esters and fatty acids) fuels and relegating the remainder of the biomass to anaerobic digestion or food/feed production] enables the near-term production of algal SAF but presents challenging economics depending on achievable cultivation costs and compositional quality. However, these economics can be improved by present-day policy incentives. With these incentives, the modeled algae-to-HEFA pathway could reach a minimum fuel selling price as low as $4.7 per gasoline gallon equivalent depending on the carbon intensity reduction that can be achieved compared with petroleum. Uncertainty about algal feedstock production maturity in the current state of technology and the future will play a large role in determining the economic feasibility of building algae-to-HEFA facilities. For example, if immaturity increases the feedstock price by even 10%, SAF production in 2050 is about 58% of the production which could have been achieved with mature feedstock. Additionally, growth in this conversion pathway can be notably boosted through the inclusion of subsidies, and also through higher-value coproducts or higher lipid yields beyond the scope

---

Correspondence to: Swaroop Atnoorkar, National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80215, USA.
E-mail: swaroop.atnoorkar@nrel.gov

[†]These authors contributed equally.

SCI where science meets business

of the process considered here. © 2024 Alliance for Sustainable Energy, LLC. *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Supporting information may be found in the online version of this article.

Key words: algal fuel; biofuel; bioenergy scenario model; hydroprocessed esters and fatty acids; system dynamics; techno-economics

Introduction

The Intergovernmental Panel on Climate Change has stressed the importance of reaching net-zero emissions by 2050 to limit global warming to 1.5°C.[1] In 2019, the civil aviation sector accounted for around 3% of US greenhouse gas (GHG) emissions. As the United States looks to deep decarbonization scenarios, aviation is a sector that is consistently highlighted as one that is difficult to decarbonize owing to jet fuel's properties. Even then, the US Federal Aviation Administration expects most GHG emission reductions in the aviation sector in 2050 to come from sustainable aviation fuels (SAF).[2] In recognition of this need, the US Department of Energy, US Department of Transportation and US Department of Agriculture jointly announced the Sustainable Aviation Fuel Grand Challenge, with the goal of reducing the cost and increasing the sustainability and production of SAF. Specifically, the goal is to achieve full decarbonization for the aviation sector by achieving a 50% reduction in life-cycle GHG emissions for SAF compared with conventional jet fuel and meeting 100% of aviation fuel demand by 2050. This translates to supplying 35 billion gallons of SAF annually and achieving a near-term goal of 3 billion gallons of annual SAF supply by 2030.[3,4].

As of September 2021, total biofuel production capacity was at around 17 billion gallons for ethanol, 2.5 billion gallons for biodiesel and 900 million gallons for renewable diesel and other biofuels, of which SAF contributed around 4.5 million gallons.[3,5] Some of the current biofuel capacity could shift to produce SAF, but significant production expansion will also be needed over the next 30 years to reach the SAF Grand Challenge goal, which requires more than 1000× production in 2050 compared with 2021. This expansion will require greater availability of a diverse set of feedstocks for conversion to SAF. Up to 2030, fats, oil and greases (FOG) are expected to be the major feedstock for SAF production, supplemented by smaller shares of waste, forest or agricultural residues and alcohols. However, the availability of these feedstocks is not enough to meet projected SAF needs.[6] Current FOG production in the US is about 5.37 Tg per year and is constrained by population growth. If all FOG is *via* the hydroprocessed esters and fatty acids (HEFA) pathway, 0.53 billion gallons of SAF can be produced annually, using literature estimates of FOG availability[7] and FOG to HEFA yield.[8]

Algal biomass is attractive as a feedstock for biofuel production; it contains lipids that are suitable for SAF production through the HEFA or alternative upgrading processes;[9–11] it can be grown on marginal and non-arable land in inhospitable conditions, and thus does not compete for agricultural land;[12,13] it can be grown using saline water or wastewater;[12,14,15] and it is currently not a major fuel source. However, despite notable demonstration projects for algal biofuels in the previous decade, algal lipids are not commonly used commercially for the purpose of fuel production. One reason for this is the high cost of algae production relative to other sources of biomass. Cultivation of algal biomass in open raceway ponds is one of the most cost-efficient ways of growing purpose grown algae; however, the inherent costs of building and operating the cultivation system necessitates achieving high biomass productivity and lipid content to enable economically feasible biofuels.[16] A key challenge is that these two economic drivers of algal biofuels have contrary correlations to the nutrient conditions of biomass cultivation; lipid content increases in nutrient-deplete conditions, but biomass productivity is maximized in a nutrient replete environment.[17,18] Pilot-scale research has made significant progress toward achieving biomass productivity goals, but has thus far been unable to demonstrate concurrently high lipid production.[19] However, recent research using engineered algae strains has shown progress in overcoming these challenges, demonstrating a lipid productivity (combining biomass productivity and lipid content) in the range of 8–9 g m^{-2} per day, a substantial increase over the current state of technology published elsewhere.[20,21]

In optimal locations where seasonal productivity variations could be minimized, this demonstrated progress focused on maximizing lipid productivity has been estimated to achieve fuel selling prices approaching commercial viability when paired with other high-value coproducts;[22] nevertheless, further advancements toward demonstrating favorable lipid production alongside cost reductions are needed to de-risk early commercial facilities and enable a wider range of potential site locations. Other key uncertainties and risks for algae cultivation include mitigating culture contamination (*via* hyper-saline tolerant strains, the use of biological crop protection measures such as fungicides, strain engineering and other measures), the degree to which pond liners are required (liners add considerable cost but may be required depending on local regulations or soil conditions to withstand erosion/pond drainage), processing requirements for dewatering (the selection of dewatering operations is often highly strain-dependent) and the utilization efficiency of delivered CO_2 (minimizing CO_2 outgassing/uptake losses through optimal media/pH conditions and proper pond design at scale).[23,24] Commercial algae facilities may take a variety of approaches toward managing these risks while maximizing lipid productivity; thus, assessing realistic cost estimates of algae oil is difficult. A review of studies found a range of 0.22–297 \$ L^{-1} (0.83–1124 \$ gal^{-1}); however, the median cost was \$4.3 L^{-1}, suggesting that most of the distribution was on the lower side.[25] Traditionally, algal fuel has also required coproducts to be economically viable relative to more conventional feedstocks.[15,26–28]

Owing to these higher costs and the need for extensive research and development, policy would provide benefits to spur investment in algal biofuels. Cruce *et al.*[29] found that short-duration incentives consistent with historical levels [maximum of \$2 per gasoline gallon equivalent (GGE) for 6 years] and carbon pricing scenarios improved algal biofuel attractiveness but did not make them competitive with existing biofuels (i.e. corn ethanol) or petroleum-based fuels. Employing a Bayesian network probabilistic framework, Gambelli *et al.*[30] found that favorable supply-side policy conditions alone were insufficient to spur algal biofuel investment with conversion technologies that are not commercially available. According to Gambelli, the most relevant factors included having a clear demand signal for algal biofuels and developing markets for coproducts (e.g. food-feed). Using results from a stochastic automata network model they created, Ribeiro *et al.*[31] concluded that investment in research and development for nascent algae technologies is important for their adoption and there would be no uptake of algal biofuels in scenarios without policy support.

HEFA processing represents a possible alternative to less commercially established conversion technologies for lipid feedstocks including algae. Approved by the ASTM in 2011, HEFA is commercially available, and can be blended up to 50% with conventional jet fuel, while meeting stringent performance criteria.[32] HEFA is at a high technology maturity level;[33] several companies are already producing HEFA at commercial scales from non-algae feedstocks,[34] and the use of algae HEFA SAF has been recently demonstrated.[35] Hydrodeoxygenation, a similar option for upgrading algal lipids to hydrocarbons, has been shown to be possible in a single reactor, but it results in a higher fraction of heavier components more suited for replacing diesel fuels.[36,37] In contrast, HEFA uses an additional cracking step to shorten hydrocarbon chain lengths and produce satisfactory cold flow properties for jet fuel[38] at the expense of a reduced overall fuel yield and increased production of naphtha-range fuels (C5–C8) and lighter.[33,39] The economic feasibility of HEFA fuels can vary significantly by feedstock; Tao *et al.* examined more than 20 oil feedstocks and their suitability as HEFA feedstocks based on techno-economic analysis (TEA) and resource assessment.[32] Of the five feedstocks selected for TEA, the minimum jet fuel selling price ranged from \$3.8 to 11 gal^{-1}. In all cases, the oil feedstock cost drove economics, accounting for 54–82% of the fuel cost. Other cost drivers for HEFA fuels included hydrogen and catalyst costs, although these were dwarfed by the cost of the feedstock implications. These correlations hold true and are amplified for algae HEFA, which incurs a higher lipid feedstock cost than terrestrial oils. Thus, the key challenges toward enabling algae HEFA are tied to minimizing feedstock cost, as discussed previously. For algae oil specifically, a higher degree of oil cleanup is also required.[40] While this is typically not a key cost driver,[36] this represents a technical challenge that must be met to avoid catalyst poisoning. An additional challenge associated with algal oils is the high content of free fatty acids, which may require specialized acid-resistant metallurgy for hydrotreatment.[41,42]

In this paper, we examine the TEA characteristics of the algae-to-HEFA pathway. We configure the pathway to reflect the most high-maturity processes using extracted solids as a source of energy via anaerobic digestion (AD) or (slightly less mature because of higher feedstock dependency) as an animal or fish feed coproduct,[43,44] and we report results for a selected set of suitable site locations taken from Davis *et al.*[15] More complex conversion approaches which include the production of high-value coproducts such as polyurethane[22,45] or bioplastics[27] may significantly improve the economics, but simultaneously introduce additional risk by adding additional unit operations and relying on less mature technology. By maximizing simplicity and technology maturity for the conversion process, only the feedstock cultivation process poses a more elevated risk for investors. We then use the TEA in the algae module of the Biomass Scenario Model (BSM),[46] a systems dynamics model of the US bioenergy supply chain to explore potential biofuel production trajectories, given varied assumptions about feedstock cost, process maturity and incentives.

Materials and methods

TEA

A detailed techno-economic model of a single algal biorefinery was developed to assess the economic feasibility of each pathway and to provide the necessary inputs to the BSM. The model used Aspen Plus[47] to generate rigorous mass and energy balance information for two design scenarios, detailed in Fig. 1. Each design scenario considered a conversion facility co-located with a 5000-acre algal biomass production facility. Costs associated with biomass production were included as a feedstock cost for the conversion facility, which can vary regionally based on differences in biomass productivity, pond evaporation rates and associated water blowdown handling, and carbon dioxide (CO_2) costs. To account for this variation, eight representative site groups suitable for algae farm siting were considered [shown in Fig. S2 in the Supplementary Information (SI), as identified by Davis *et al.*[15]], each with a corresponding minimum biomass selling price (MBSP) and average biomass production rate. From the above-cited study, regional factors influencing MBSP were most strongly driven by climate and resultant cultivation productivity (both annual average productivity and degree of seasonal variability), as documented elsewhere.[16,48] However, the costs associated with salt blowdown handling and disposal also contributed to substantial regional variability, adding between $21 and 88 per ton to overall MBSPs largely correlated with local evaporation rates and concomitant blowdown disposal rates (highest in the West/Southwest and lowest in the Southeastern United States), while CO_2 variability imparted minimal regional variations in MBSP albeit at higher absolute cost contributions (adding between $96 and 106 per ton to overall MBSPs).[15] The MBSP values for the saline site groups were adjusted to reflect a more optimistic assumption of a minimally lined cultivation pond consistent with other analyses[36,45] rather than the fully lined ponds considered in the original study.[15] The modeled biomass composition was obtained from a mid-stage harvested *Scenedesmus acutus* and applied consistently throughout the year; however, a single strain is not assumed, and several strains may be rotated into the ponds to maximize seasonal productivity. The biomass included a total lipid content of 30% [27% fatty acid methyl ester (FAME) lipids], reflecting a future target consistent with prior analyses,[36,45,49] although also representing a significant improvement compared with recent experimental demonstrations of approximately 14% (8% FAME lipids).[19] FAME lipids are exclusively used for fuel production, while polar lipid impurities are removed prior to HEFA upgrading.

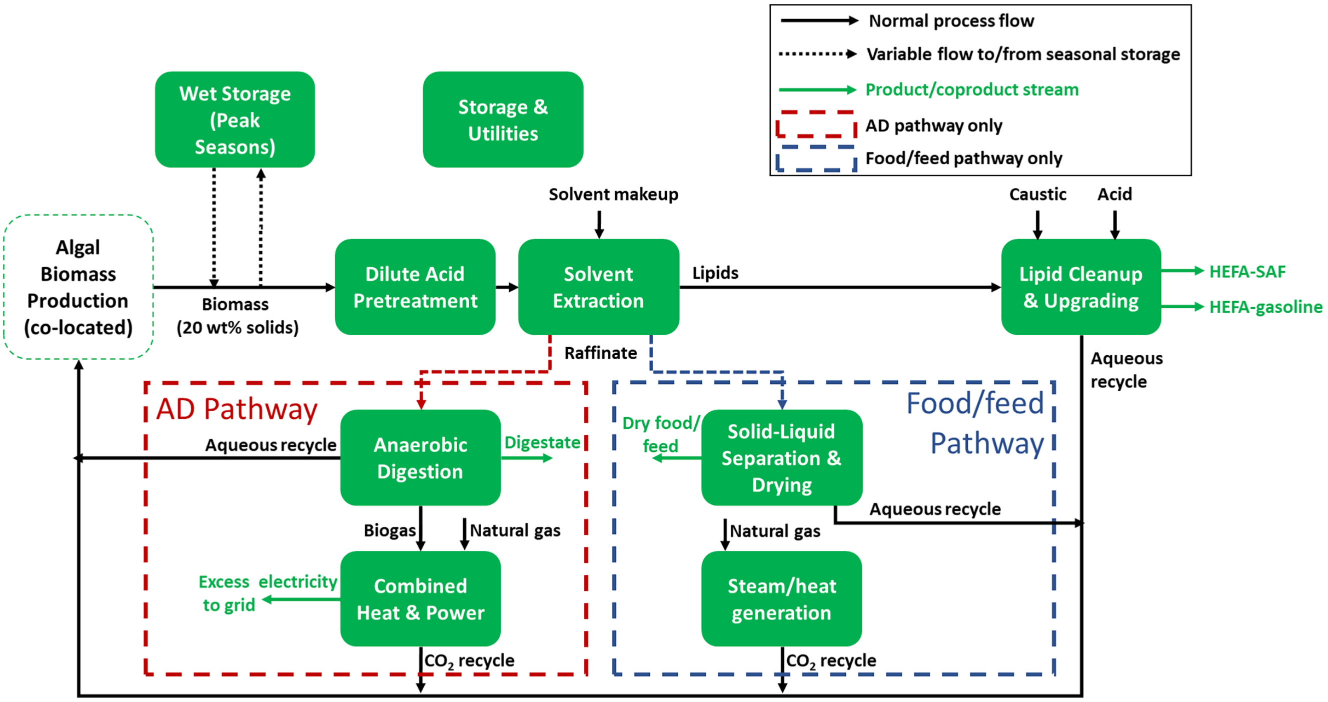

Figure 1. Process flow diagram for the anaerobic digestion (AD) and food/feed biorefinery designs.

Biofuels, Bioproducts and Biorefining published by Society of Industrial Chemistry and John Wiley & Sons Ltd.
| *Biofuels, Bioprod. Bioref*. **18**:1121–1136 (2024); DOI: 10.1002/bbb.2623

For the modeled conversion process, dewatered algae are fed to the conversion facility at a constant rate despite seasonal variations in productivity by use of wet anaerobic storage during peak seasons. Biomass undergoes a dilute acid pretreatment step followed by lipid extraction. Lipids are further purified *via* degumming, demetallization and bleaching operations to meet intake specification of the HEFA refinery, before being upgraded to HEFA fuels, which include hydrogenation and reforming steps. Residual solids from the lipid extraction step are either sent to an anaerobic digestor for generation of biogas (utilized on-site for combined heat and power generation) or dried for sale as a food/feed coproduct (the assumed value for feed is \$500 per dry ton). A summary of the process parameters used in the conversion model is supplied in Table S4; key assumptions include a fermentable sugar release of 80% in pretreatment, an overall lipid extraction yield of 96%, and a resulting product distribution of 75% SAF and 25% gasoline.

The biorefinery TEA was informed by the material and energy balances generated from the process models and consisted of a discounted cash flow rate of return analysis with a fixed internal rate of return. The primary metric used in the TEA was the minimum fuel selling price (MFSP) required to obtain a net present value of zero at an internal rate of return of 10%. Details on the TEA model and associated assumptions, which can be found in the SI, are generally consistent with those in other published works.[32,37,45]

System dynamics model and scenario design

For this analysis, we modified an existing system dynamics simulation model to explore the effect of policy, economic drivers and alternative assumptions regarding the production of algae and the development of algal SAF production. The model, which we call BSM-algae, was adapted from the BSM, which was developed by the National Renewable Energy Laboratory for the US Department of Energy's Bioenergy Technologies Office and is publicly available at https://github.com/NREL/bsm-public. The BSM was designed to explore the evolution of the bioeconomy within the United States.[50–54] Its extensible, modular structure supports analysis of interactions among the US agricultural system, bioenergy conversion, and downstream fuel uses.

The BSM divides the lower 48 US states into 10 regions corresponding to US Department of Agriculture farm production regions, and its interconnected modular structure represents physical and information flows in the US supply chain for bioenergy. The following modules are included in the BSM: Feedstock production, logistics and markets; Development and operation of conversion facilities; Downstream inventory, pricing, distribution, exports and domestic use of fuel ethanol; Vehicles; and Oil industry. Details of the model are available in previous publications.[46,55] An overall assumed maximum annual rate of investment in feedstock-to-bioenergy conversion facilities is allocated among different conversion options (including an assumed alternate investment) based on the relative net present value (NPV) of the marginal investment. For each conversion option, the NPV is determined by techno-economic considerations such as expected revenue, operating cost, plant scale, capital cost and process yield.

To explore dynamics specific to the algae-to-HEFA pathway, we made several model modifications. First, we deactivated non-algae-related modules and incorporated proxies for significant parameters from the full BSM (e.g. comparative attractiveness of and spillover industrial learning from pathways not using algal feedstock). Second, we incorporated TEA data for the algae-to-HEFA conversion pathway, accounting for the target algal lipid content and extraction efficiency consistent with the TEA model in determining process yield (see Table S6). Third, we implemented feedstock costs as regional supply schedules for saline cultivation, based on Davis *et al.*[15] While Davis *et al.* assume a mature feedstock process with 5000-acre ponds, we added structure in BSM-algae to enable industrial learning in the algal feedstock production system. The mature industry feedstock production cost for each site group is converted in BSM-algae into a feedstock production cost for the lipid component, based on lipid content and industry maturity. The feedstock maturity evolves based on doublings of cumulative production of biofuel. The feedstock maturity then can optionally impact feedstock cost and/or conversion facility scale factors (see the SI for more information). Finally, we added logic to the model to capture potential delays in the availability of feedstock production sites. This structure facilitates testing the scenarios in which varying degrees of potential sites are available for development at the outset of the simulation. In the simulations, we analyzed multiple scenarios around policy, feedstock maturity levels and facility growth. Multiple life cycle assessments (outside the scope of this work) have been performed on algal biofuel production. However, the carbon intensity (CI) of biofuel produced from algae has been found to have high variability.[56–58] In this study, we assumed cases with 0 and 50% reductions in CI of algae biofuel compared with the CI of petroleum fuels. See the SI for more information on the CI of algae biofuels and petroleum fuels. Factors that were varied in the analysis are described in Table 1.

Results and discussion

TEA single refinery results

The single-biorefinery TEA found that algal HEFA SAF would be produced at an MFSP of $8.70–10.08 per GGE spanning the various site groups considered without inclusion of policy incentives or high-value coproducts (Fig. 2). Using residual biomass solids for a food/feed application was slightly more economically favorable than using solids to generate biogas *via* AD, with MFSPs generally demonstrating a 3–5% improvement. Each biorefinery as modeled produced a liquid fuel yield of 65 GGE ton^{-1} of feedstock (ash-free dry weight, AFDW), which equates to 11.6–13.2 million GGE per year of total fuel production, with a fuel breakdown of approximately 75% HEFA SAF and 25% HEFA gasoline. These results are predicated on the modeled biomass composition, most notably the assumption of 27% FAME lipids (target lipid productivity of 6.8 g m^{-2} per day). Given the disparity between this compositional target compared with the recently demonstrated lipid content of 8% FAME lipids based on the composition as harvested in recent experimental trials (1.5 g m^{-2} per day lipid productivity), a sensitivity case was also considered at the compositions demonstrated today based on National Renewable Energy Laboratory state of technology data under nutrient-replete cultivation conditions.[19] This case showed more challenging economics, with an MFSP greater than $20 per GGE for all cases and a fuel yield of 23 GGE ton^{-1} (AFDW), highlighting

Table 1. Description of scenario components varied in the Biomass Scenario Model (BSM)-algae simulations.

Scenario component	Description	Values
Incentives	Total incentives for fuel production, including production tax credit, low carbon fuel standard and renewable identification numbers	Low, moderate, high (see the SI for more information)
Maximum plant construction limit	Maximum biorefinery facilities (including algae-to-HEFA and all other alternative biofuel conversion processes determined by competitiveness metric) that can be started per year	25 plants per year, 100 plants per year
Initial feedstock maturity	Commercial maturity of feedstock production systems in 2015 (initial year in BSM); signifies how close costs are to *n*th pond costs	50%, 100%
Precommercial feedstock cost multiplier	Multiplier applied to the *n*th plant feedstock cost when feedstock maturity is 0%	1 (no cost penalty for immature feedstock), 1.2 (implies a 20% higher cost for immature feedstock; 10% higher cost when feedstock has a 50% initial feedstock maturity)[1]
Feedstock facilities development delay	Initial fraction of sites targeted to produce algae – Allows the possibility for a delay in siting acquisition, permitting and development of non-targeted sites	0: No sites are available for algae production at the beginning of the simulation; sites become available at a maximum rate of 15% per year based on the economic viability of the algae-to-HEFA pathway 1: All sites are available for algae production at the beginning of the simulation
Relative attractiveness	• Based on the relative magnitude of an NPV metric for each potential investment, including an alternative (non-algal) investment • For potential algal investments, the metric is calculated as the NPV of the potential investment, normalized by expected annual output • For the alternative investment, assumed values are based on analysis conducted with full BSM	6.5: Lower value for alternate investment favors investment in algal biofuels. 10.5: Higher value for alternate investment reduces the relative attractiveness of algal investment
Carbon intensity reduction	Decrease in the carbon intensity of algal fuels as compared with petroleum	0%, 50%

[1] 1.2 was chosen after running a sensitivity around different values for the cost multiplier. Higher values precipitated the need for higher subsidies in order to spur SAF production.

HEFA, Hydroprocessed esters and fatty acids; NPV, net present value; SI, Supplementary Information.

the importance of meeting compositional targets in the future. Alternatively, others in industry have recently demonstrated a lipid productivity rate in the range of 8–9 g m^{-2} per day,[21] with a near-term target to increase up to 15 g m^{-2} per day (assumes 25 g m^{-2} per day biomass productivity with 60% total lipid content; all other biomass constituents are reduced proportionally from the base case);[59] taking the latter value as a more optimistic case, this could increase the fuel yield to 135 GGE ton^{-1} and reduce the MFSP to $4.6 per GGE without the inclusion of policy incentive credits.

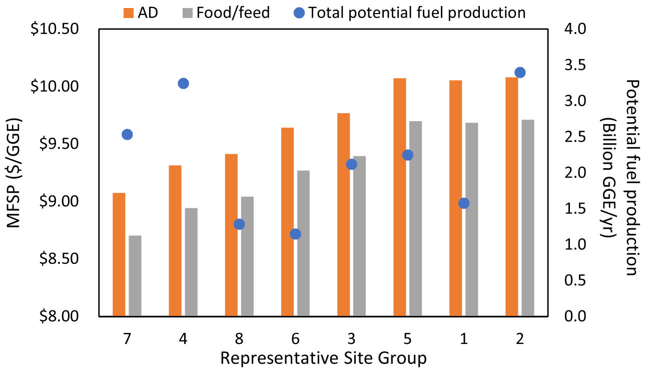

Figure 2. Minimum fuel selling price (MFSP; vertical bars, orange for AD and gray for food/feed), and total potential fuel production [blue circles, billion GGE (gasoline gallon equivalent) per year] for each saline site group. Locations of each site group are provided in Fig. S2 in the Supplementary Information (SI); more context can be found in Ref. [15].

The TEA results varied by the site group considered, with site group 7 (algae farms in the Florida region) exhibiting the most promising economics, in turn driven by the lowest biomass production cost attributed to high cultivation productivity, low seasonal variability and low evaporation/salt blowdown handling costs as discussed previously. High-level TEA results for site group 7 are supplied in Table 2. It should be noted that the TEA considers all HEFA fuel (including SAF and naphtha) in the MFSP calculation based on total energy-equivalent (GGE) fuel yield outputs. If naphtha-range fuels were instead assumed to be sold at a fixed price of $2.50 gal^{-1} (a value roughly equivalent to its recent historical market value[60]), HEFA SAF would require a higher selling price for profitability. Implementing this SAF-specific methodology would result in an MFSP increase of approximately $2 per GGE; for example, the MFSP of site group 7 for the AD case would increase to $11.06 per GGE, compared with $9.07 per GGE for the base case.

It is important to view these results in the context of the algae conversion approach, which was chosen based on maximizing process simplicity and technology maturity. Numerous studies have shown that the production of high-value coproducts alongside biofuels can significantly improve process economics. For example, diverting some algal lipids for polyurethane production has been shown to enable MFSPs of $2.50 per GGE or lower for the same algae composition modeled here,[22,45] and utilizing residual solids for producing bio-based thermoplastics can enable similar MFSPs for lower quality biomass which is elevated in proteins and deficient in

Table 2. High-level techno-economic analysis (TEA) results for site group 7 (Florida region) – excluding any carbon intensity (CI) policy credits.

	Anaerobic digestion	Food/feed	Units
MFSP	$9.07	$8.70	$ per GGE
Total fuel yield	65.1	65.1	GGE ton^{-1} biomass (AFDW)
SAF	50.1	50.1	GGE ton^{-1} biomass (AFDW)
Naphtha	15.1	15.1	GGE ton^{-1} biomass (AFDW)
Total fuel production	12.7	12.7	Million GGE per year
SAF	9.8	9.8	Million GGE per year
Naphtha	2.9	2.9	Million GGE per year
Feedstock cost	$495	$495	$ ton^{-1} (AFDW)
Biomass feed rate (seasonal average)	592	592	tons per day AFDW
Total capital investment	$144 720 000	$141 644 000	$
Variable operating costs	$105 378 000	$110 738 000	$ per year
Fixed operating costs	$5 406 000	$5 386 000	$ per year
Coproduct credits	$13 687 000	$23 406 000	$ per year
Fuel revenue	$115 436 000	$110 734 000	$ per year

AFDW, Ash-free dry weight; GGE, gasoline gallon equivalent; MFSP, minimum fuel selling price.

lipids.[27,61] Other coproducts such as omega-3 fatty acids for nutraceuticals may enable similar economics, although limited to much smaller markets.[62] The addition of coproducts can also improve the carbon intensity of the biofuels, because a portion of the required raw materials for biomass production and conversion is allocated to the coproduct; as a result, the potential for revenue from policy incentives may be higher, further enabling economic viability.[63]

A cost breakdown for the AD case is shown in Fig. S3 to show key cost drivers. Algae biomass cost is by far the largest cost driver, contributing \$7.54 per GGE to the MFSP. This is commonly seen in analyses of biofuels from purpose-grown algae, regardless of the conversion technology employed.[36,64] The cost of HEFA upgrading is the next largest contributor (\$1.10 per GGE), followed by lipid extraction (\$0.59 per GGE) and pretreatment (\$0.57 per GGE). These costs are somewhat offset by credits from generating electricity and recycling CO_2 and nutrients, amounting to a credit of \$1.09 per GGE.

Policy credit sensitivity analysis

An additional sensitivity analysis was performed to quantify the impact on single biorefinery HEFA SAF economics when considering additional revenue such as may be garnered from various present-day policy incentives. Policy incentives were applied to site group 7 as an example. The first incentive considered was the generation of renewable identification numbers (RINs; as specified in the US Renewable Fuel Standard) at an assumed RIN value of \$1.12 gal^{-1} when meeting the minimum GHG reduction threshold (50%). Additional credits were also considered as specified in California's low carbon fuel standard (LCFS), which allows a low-carbon fuel producer to generate credits based on a reduction of fuel CI compared with its analogous petroleum fuel. Low carbon fuel standard credit values of \$133 t^{-1} CO_2 and \$200 t^{-1} CO_2, which are in line with currently traded LCFS credit prices, were considered; they reflect the 6 year historical average and maximum credit prices respectively.[65] Both RIN and LCFS credits require a minimum of a 50% reduction in fuel carbon intensity for a fuel producer to be eligible, assumed to be applicable here for purposes of evaluating resultant impacts on MFSP although life cycle analysis is not conducted as part of the scope of this assessment to establish a specific CI value for this pathway. Additional policy incentives such as a blender's tax credit (for SAF) and an alternative fuel mixture credit (for naphtha) may also apply to algal biofuels but were omitted from this analysis. These credits are set to expire after a limited period of 5 years, while RIN and LCFS credits do not have explicitly defined expiration dates.

The impacts of the various policy incentive scenarios are shown in Fig. 3 for each pathway. Overall, it was shown that the generation of RIN credits, which only occurs after meeting the 50% GHG reduction threshold, reduced the MFSP by about \$1.7 per GGE for each pathway. Additional revenue from the generation of LCFS credits can lower the MFSP by an additional \$1.1–2.3 per GGE, reaching MFSP values as low as \$4.7 per GGE depending on the CI reduction compared with petroleum that can be achieved. Greenhouse gas reductions of up to 68% have been demonstrated,[66] and CI reductions

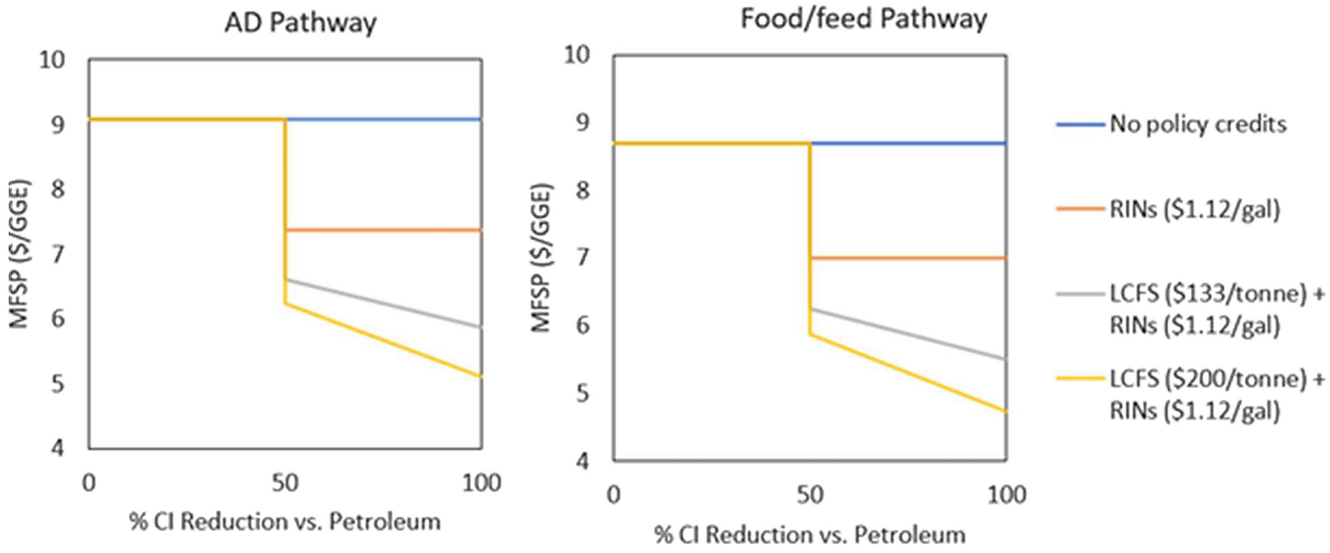

Figure 3. The MFSP of the AD and food/feed pathways at varying levels of policy incentives and process CI reductions relative to petroleum fuels. Renewable identification number (RIN) and low carbon fuel standard (LCFS) credits only apply when the CI reduction is greater than or equal to 50%.

have the potential to reach 100% in certain scenarios.[67] Alternatively, a 50% CI reduction relative to petroleum can still achieve MFSPs of \$6.2 per GGE and \$5.9 per GGE (AD and food/feed pathways, respectively). Although the impact of these policy incentives is substantial, additional improvements may need to be made for algal HEFA SAF to compete with petroleum fuels. These improvements could take various forms, including: (1) higher quality algal biomass compositions (i.e. higher lipid content resulting in increased fuel yields); (2) additional operations to increase fuel yields, such as fermentation and upgrading of carbohydrates; (3) new policy incentives that are not currently in place or included here; and (4) alternative coproduct scenarios. Many chemical coproduct options also enable the opportunity for long-term carbon sequestration mechanisms, which would improve the fuel carbon intensity relative to the process considered here (which does not include any carbon sequestration benefits as currently configured). In addition to MFSP and CI allocation benefits enumerated above for polyurethanes, thermoplastics and other chemicals that may be sourced from various algal biomass constituents, such coproducts also may serve a dual purpose as durable carbon sinks as a means of long-term biogenic carbon sequestration, which can further reduce the overall system carbon intensity.[15] In these cases, the combined revenue improvements from coproducts and policy incentives may enable algal biofuels to reach cost parity with petroleum fuels.

BSM-algae scenario analysis results

The BSM-algae simulations in Fig. 4 show the effects of the interactions of incentives, feedstock maturity and cost, the rate of investment in algal fuel conversion facilities and the limit on annual biorefinery growth on algal fuel production. In general, higher incentives, feedstock maturity and assumed maximum rates of biorefinery construction result in higher production of algal biofuel.

In Fig. 4, the columns show results for economic policy incentives (low, moderate, high). The rows show results for

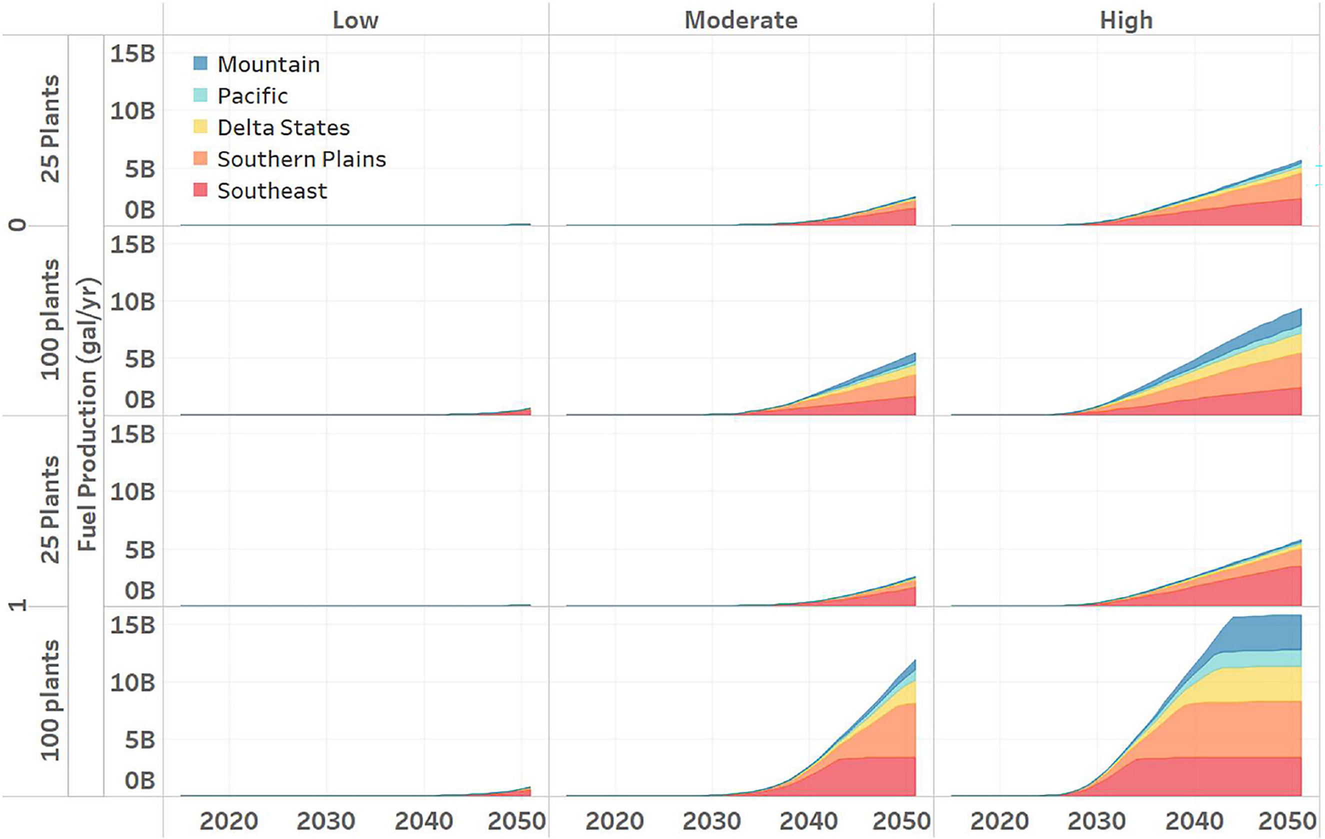

Figure 4. Algal fuel production by the HEFA pathway in the United States shown by scenario components of policy incentives (columns) and initial availability for algae production and annual maximum plant construction capacity (rows) (2015–2050). Results should not be interpreted as point estimates; rather, comparison of results in terms of magnitude and initial production is more appropriate.

the initial fractional availability (0 or 1) of sites for algae production and annual maximum plant construction capacity (25 plants per year or 100 plants per year). Algae production is at a maturity level of 50% in 2015 (beginning of the simulation), and there is a 10% cost multiplier for immature feedstock. Feedstock price then follows learning-curve dynamics to approach mature industry values with each doubling of production. The scenarios also assume limited availability of sites for producing algae in the first two rows. Here, based on the expected selling price of jet fuel, BSM-algae brings more sites into production, thus accounting for delays in acquisition, permitting and development of algae-producing sites. In the last two rows, the scenarios assume the availability of all sites for producing algae.

The take-off of fuel production in different US regions depends on the biomass feedstock cost (MBSP) in the region, which is differentiated based on Davis *et al.*[15] The Southeast Region, where the MBSP is the lowest, starts producing algal biofuel earliest, followed by the Southern Plains and the Delta States, while the Pacific and Mountain regions (with highest MBSP) begin producing biofuel only in later years (Fig. 4). As a result, lowest-cost regions will be the first to invest, but as production develops in those regions, production costs in other regions will fall, potentially stimulating investment.

In the scenarios displayed in Fig. 4, the progression of incentives along the columns shows increasing algal fuel production. Under the assumption of high oil prices (consistent with the Annual Energy Outlook[68]), low incentives are insufficient to stimulate investment in algae-to-HEFA facilities owing to a low NPV. When the annual construction limit for biorefineries is increased and all algae-producing sites are available for use (last row), low incentives still limit fuel production to half a million gallons in 2050. Thus, a set of moderate (column 2) to high (column 3) economic incentives consisting of a production tax credit, RINs, LCFS credits and other incentives would significantly support increasing fuel production from algae. Cruce *et al.*[29] agrees that short-duration incentives consistent with historical levels and carbon pricing scenarios improved algal biofuel attractiveness but did not make them competitive with existing biofuels or petroleum-based fuels. In addition, Gambelli *et al.*[30] also found that favorable supply-side policy conditions alone were insufficient to spur algal biofuel investment with conversion technologies that are not commercially available. In this case, we have a commercially available converstion technology (HEFA), yet modeled incentive levels necessary to spur SAF production are still higher than historically observed levels.

An increase in incentives results in a more attractive NPV, which encourages higher levels of investment in the algae-to-HEFA pathway. Investment in the algae-to-HEFA pathway increases the production of feedstock and may decrease feedstock price (as fuel production encourages learning for the feedstock production process). This in turn increases investment attractiveness for algae facilities, which results in the takeoff of algal fuel production earlier in the simulation. In the 2040s, algae from the regions with higher MBSP can also be used for fuel production, especially when high incentives are present. For all scenarios in Fig. 4, an increase in the annual maximum biorefineries constructed from 25 plants (each coupled with a 5000-acre production farm) per year (row 1) to 100 plants per year (row 2) increases algal fuel production and allows an earlier takeoff. When fewer biorefineries can be constructed per year, the availability of algal farm sites does not affect the total fuel production, as the number of biofuel facilities able to start construction is the limiting constraint. However, the initial availability of algal farm sites constrains the rate of biofuel production growth when 100 biorefineries per year can be constructed. A combination of higher availability of algae farms at the beginning of the simulation and 100 biofuel facility construction starts per year is required to reach maximum fuel production, which in the most optimistic scenario is 15 billion gallons per year in 2050 (Fig. 4, row 4 column 3).

Figure 5 shows the effect of cost multipliers for an initial maturity of 50% in 2015 in the feedstock production process for algae-to-HEFA fuel production. Background assumptions include high oil prices, moderate economic policy incentives, and delayed availability of algae production. Here, the initial cost of feedstock is 10% higher than that of mature feedstock. As the feedstock production process matures, the feedstock costs reduce and trend toward the feedstock costs associated with a 100% mature feedstock production process. The last column assumes no effect on the initial price of feedstock owing to a lower maturity. BSM-algae models the maturity level of feedstock to increase with each doubling of total feedstock production, thereby creating a learning curve (see the SI for more information). For high oil prices, moderate incentives and a delayed availability of algae production sites, if the feedstock cost increases by 25%, no significant algal fuel production from algae can be observed. There is insufficient incentive to stimulate investment. Ribeiro *et al.*[31] also concluded that investment in research and development for nascent algae technologies, effectively reducing their cost, is important for their adoption. Uncertainty around the current cost for large-scale algae production and what incentives would be needed to make it more economically attractive has broad implications for the production potential of the algae-to-HEFA pathway. For a biorefinery construction limit of 25 plants per year, if the price of immature feedstock increases by even a modest 10%, SAF production in 2050 is just over half

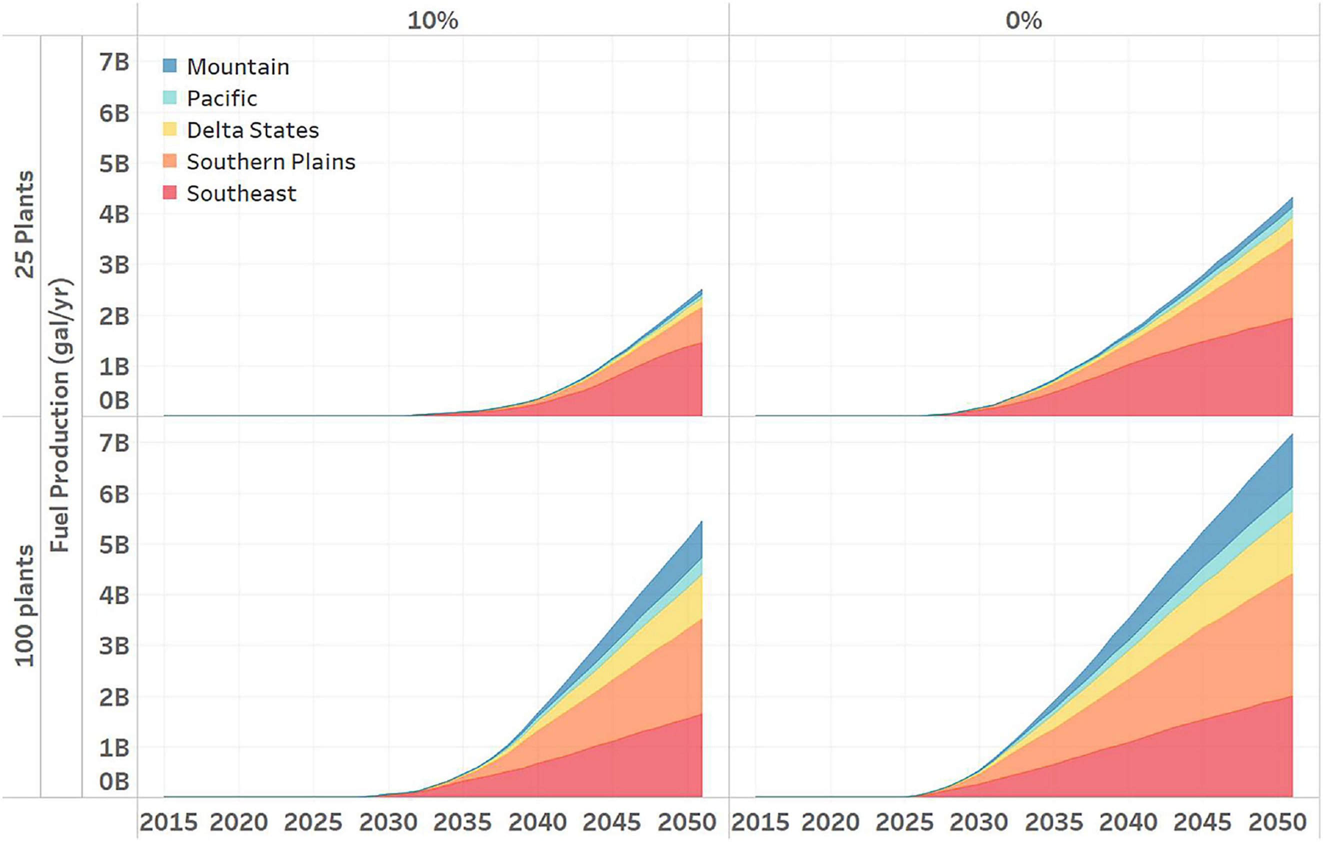

Figure 5. Algae fuel production by the HEFA pathway in the United States shown by scenario components of cost penalties for immature feedstock (columns) and annual maximum plant construction capacity (rows) (2015–2050). Results should not be interpreted as point estimates; rather, comparison of results in terms of magnitude and initial production is more appropriate.

of the production levels which could have been achieved with mature feedstock (Fig. 5, row 1, column 2 *versus* column 3).

Again, an increase in the annual maximum biorefinery construction counts increases fuel production (Fig. 5, row 2). This effect is stronger when there is a 10% higher initial price for immature feedstock, and the production in the 100 plants per year scenario (row 2, column 1) is more than twice that in the 25 plants per year scenario (row 1, column 1). The additional construction starts allows for this case to build production later in the simulation, as the investment is less attractive at the beginning. A higher annual plant construction capacity, which implies more investment per year allowed in biofuel facilities, thus strengthens the positive feedback as shown in Fig. 6 and can counter the suppression of fuel production by expensive and price-uncertain feedstock.

Another area of uncertainty in the biofuels industry is the economic competitiveness of algal fuels relative to biofuels produced from other feedstocks. Figure 7 shows the comparison of total biofuel production for high (orange) and low (blue) economic viability as represented by NPV of other biofuel pathways (e.g. SAF produced from cellulosic feedstocks *via* gasification) relative to algae-to-HEFA. A low relative NPV (blue) for other fuel pathways makes investment in algae HEFA more favorable. The higher algal fuel production for scenarios with a low relative NPV for other fuels (blue) is constrained only by the availability of algae-producing sites. When investment in other fuels is

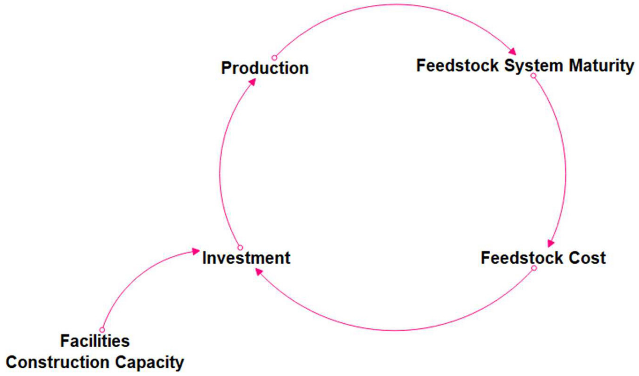

Figure 6. Loop diagram describing the positive feedback strengthening effects of constructing more facilities per year.

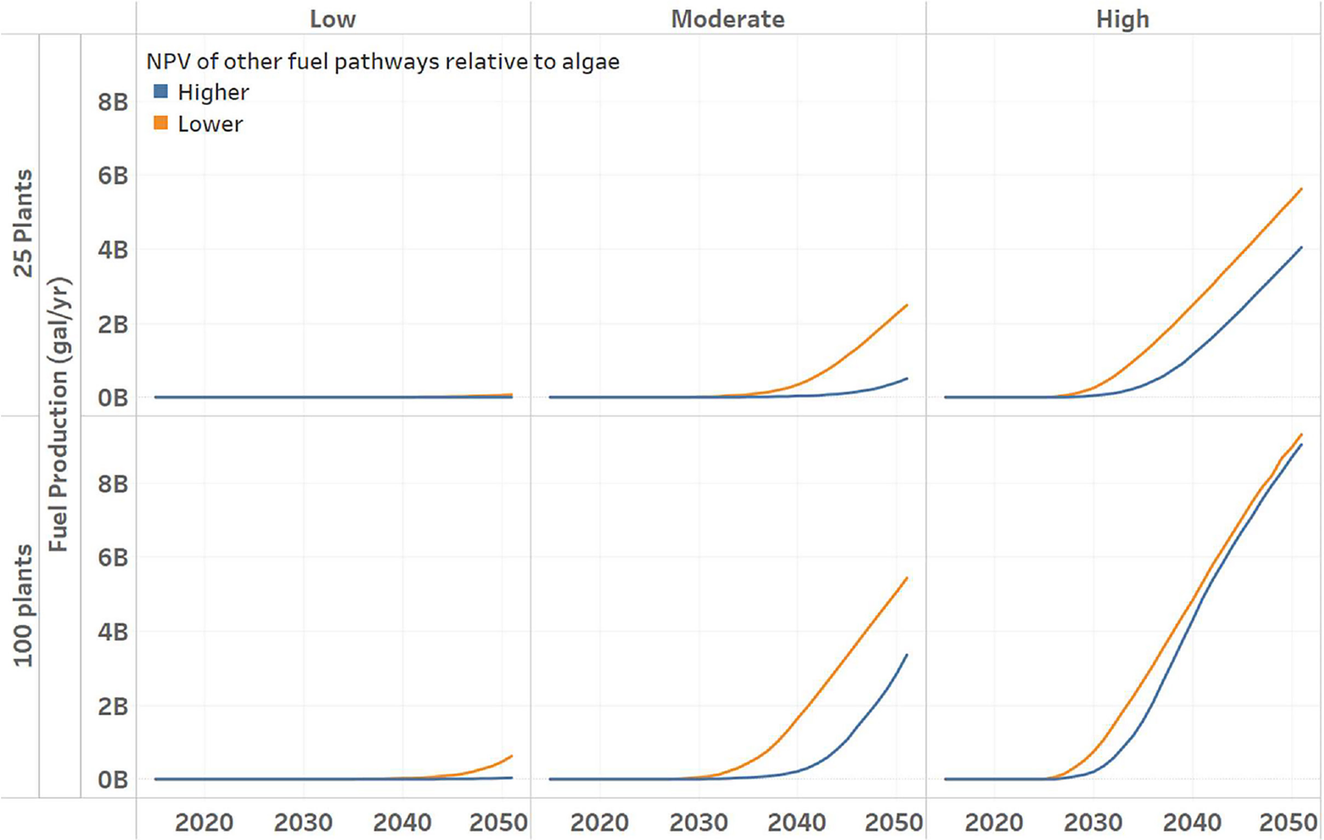

Figure 7. Algal fuel production by the HEFA pathway in the United States shown by scenario component (2015–2050). The columns show results for different levels of economic policy incentives. The rows show results for the maximum plant construction capacity. Scenarios with a low NPV (economic viability) of other fuels compared with algae are shown in blue, and those with a high NPV of other fuels compared with algae are shown in orange. Background assumptions include delayed availability of algae production, algae production at a maturity level of 50% in 2015 (beginning of the simulation), and a cost penalty for immature feedstock is 10%. Results should not be interpreted as point estimates; rather, comparison of results in terms of magnitude and initial production is more appropriate.

more economically favorable (orange), algal fuel production is lower and delayed. However, higher incentives and plant construction limits can overcome the effects of the algae pathway receiving a lower share of investments among biofuels. In this case, because investment in algae is lower, the maturity of algae rises more slowly than in the case where algae is a favorable investment opportunity, and the resulting slower learning curve delays the takeoff of fuel production.

The BSM-algae model is an approximation of how a real-world system could evolve over time, but it cannot exactly replicate this complex system. There will always be limitations owing to necessary system boundaries and assumptions. For example, we have approximated the relative attractiveness of other technologies in comparison with the algae-to-HEFA pathway. In reality, these other technologies are also evolving dynamically and could have future advantages/disadvantages compared with algae-to-HEFA that are currently not even considered. Another limitation is the lack of any algal feedstock production (or conversion pathway) available at a demonstration or commercial scale, which makes it impossible to calibrate the model with real-world algae-related data. Instead, we must use proxies, such as other more mature biofuel pathways (e.g. biodiesel, ethanol). Future research will expand upon these results using the full BSM model to see how the algae-to-HEFA pathway could contribute to overall SAF production goals in concert with other SAF-generating pathways.

Additionally, the BSM-algae model relies on inputs from the single biorefinery TEA model, which has its own set of similar limitations. The parameters used in the biorefinery model are based on achievable targets supported by experimental data, but in most cases these parameters have not been demonstrated simultaneously in an integrated system nor beyond bench scale. As discussed, a prime example of this is the modeled biomass productivity and lipid composition, which when paired together represent a target scenario that has not yet been fully demonstrated in an outdoor open pond setting (although recent data achieved by others has approached similar levels in more limited growth trials).[22] Other process assumptions, such as the modeled CO_2 utilization efficiency and the dewatering approach applied in cultivation, have been similarly achieved in specific cases, but must be demonstrated concurrently and scaled up significantly to enable the commercial deployment scenarios considered here. The modeled conversion approach is better understood and thus carries less risk to achieve process parameter targets, but likewise needs to be demonstrated with algae biomass at scale and across different strains. Experimental work in these areas to date has shown progress; the biorefinery considered here extrapolates and relies on the continuation of that progress.

Conclusion

To reach the goals of producing 3 and 35 billion gallons per year by 2030 and 2050 respectively set by the Sustainable Aviation Fuel Grand Challenge, availability of feedstock will be essential. The current preferred feedstock for the HEFA pathway is FOG, since it has a lower CI than soy. However, domestic supply of FOG is not enough to fulfill demand for SAF.[6] Currently, only 0.53 billion gallons of SAF production is possible from all available FOG in the United States *via* the HEFA pathway. Oil crops also have other competing uses, along with concerns about food supply. Therefore, algae could play an important role in supplying a sustainable lipid feedstock for HEFA. Giving priority to developing, prototyping and reducing the cost of algae as a fuel-feedstock before investing and lining up locations is important.

As the production of algal feedstocks continues to advance, there are a variety of strategies for accelerating development timelines for SAF production.

- Using more mature technologies for conversion can help reduce the investment risk for algae-based fuels.
- Reducing process complexity (e.g. conversion of lipids to HEFA fuels and relegating the remainder of the biomass to AD or food/feed production) enables the near-term production of algal SAF.
- Implementing subsidies can provide substantial incentives toward the development of a mature industry for algae feedstock production and conversion of algae to biofuel.
- Continued developments to improve cultivation performance through enhanced lipid productivity rates at lower costs can further improve the outlook for algal biofuel deployment.
- Further reducing the carbon intensity of the algae-to-HEFA process can ensure the process is eligible for policy credit scenarios modeled in this analysis.

Challenges remain regarding the economics of the algae-to-HEFA process. Higher-value coproducts often considered for algal biorefinery systems are not included in the TEA presented in this analysis, which decreases investment attractiveness. Even though present-day policy incentives improve these economics, meeting price parity with petroleum fuels still requires additional revenue streams. Prior works have shown that high-value algae products such as polyurethane have the potential to meet such revenue drivers. However, they require additional research and development to advance toward the technology readiness levels of the processes presented in our analysis, while incurring additional processing complexity. Simulation results using BSM-algae show that two additional factors will play a large role in determining the economic feasibility of deploying algae-to-HEFA facilities at scale: (1) uncertainty in the current and future maturity of algae feedstock production; and (2) the achievable reduction in carbon intensity of the algal biofuel production, which determines the applicable policy incentive credits.

Abbreviations

AD	anaerobic digestion
AFDW	ash-free dry weight
BSM	Biomass Scenario Model
CI	carbon intensity
CO_2	carbon dioxide
FAME	fatty acid methyl ester
FOG	fats, oils and greases
GGE	gasoline gallon equivalent
GHG	greenhouse gas
HEFA	hydroprocessed esters and fatty acids
LCFS	low carbon fuel standard
MBSP	minimum biomass selling price
MFSP	minimum fuel selling price
NPV	net present value
RIN	renewable identification numbers
SAF	sustainable aviation fuel
TEA	techno-economic analysis
Tg per year	tergram per year

Acknowledgements

We would like to thank Alicia Lindauer, Dan Fishman, Andrea Bailey and Michael Shell of the US Department of Energy (DOE) Bioenergy Technologies Office for their support of this work in addition to Lieve Laurens and Dan Bilello for reviewing versions of this paper. This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the DOE under contract no. DE-AC36-08GO28308. Funding was provided by US DOE Office of Energy Efficiency and Renewable Energy Bioenergy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the US Government. The US Government retains and the publisher, by accepting the article for publication, acknowledges that the US Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for US Government purposes.

References

1. Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V *et al.*, Mitigation pathways compatible with 1.5°C in the context of sustainable development (2018 [cited 2022 Dec 8].). Available: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf.
2. U.S. Federal Aviation Administration, *United States 2021 Aviation Climate Action Plan*. [Internet]. U.S. Federal Aviation Administration, Washington, DC (2021 [cited 2022 Dec 8].). Available: https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf.
3. The White House. Briefing Room, FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation (2021 [cited 2022 Sep 26].). Available: https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/.
4. U.S. Department of Energy. Energy.gov, Sustainable Aviation Fuel Grand Challenge (2021 [cited 2021 Dec 29].). Available: https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge.
5. U.S. Energy Information Administration. Petroleum & Other Liquids, Monthly Biofuels Capacity and Feedstocks Update with Data for September 2021 (2021 [cited 2022 Sep 26].). Available: https://www.eia.gov/biofuels/update/archive/2021/2021_09/biofuels.php.
6. Holladay J, Abdullah Z and Heyne J, *Sustainable Aviation Fuel: Review of Technical Pathways [Internet]*. U.S. Department of Energy, (2020 [cited 2022 Dec 8].). Available: https://www.energy.gov/sites/default/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf.
7. Skaggs RL, Coleman AM, Seiple TE and Milbrandt AR, Waste-to-energy biofuel production potential for selected feedstocks in the conterminous United States. *Renew Sustain Energy Rev* **82**:2640–2651 (2018).
8. Bhatt AH, Zhang Y, Milbrandt A, Newes E, Moriarty K, Klein B *et al.*, Evaluation of performance variables to accelerate the deployment of sustainable aviation fuels at a regional scale. *Energ Conver Manage* **275**:116441 (2023).
9. Martinez-Villarreal S, Breitenstein A, Nimmegeers P, Perez Saura P, Hai B, Asomaning J *et al.*, Drop-in biofuels production from microalgae to hydrocarbons: microalgal cultivation and harvesting, conversion pathways, economics and prospects for aviation. *Biomass Bioenergy* **1**(165):106555 (2022).
10. Ağbulut Ü, Sirohi R, Lichtfouse E, Chen WH, Len C, Show PL *et al.*, Microalgae bio-oil production by pyrolysis and hydrothermal liquefaction: mechanism and characteristics. *Bioresour Technol* **1**(376):128860 (2023 May).
11. Hoang AT, Sirohi R, Pandey A, Nižetić S, Lam SS, Chen WH *et al.*, Biofuel production from microalgae: challenges and chances. *Phytochem Rev* **22**(4):1089–1126 (2023).
12. Wiley PE, Campbell JE and McKuin B, Production of biodiesel and biogas from algae: a review of process train options. *Water Environ Res* **83**(4):326–338 (2011).
13. Ng KS, Farooq D and Yang A, Global biorenewable development strategies for sustainable aviation fuel production. *Renew Sustain Energy Rev* **150**:111502 (2021).
14. Wollmann F, Dietze S, Ackermann JU, Bley T, Walther T, Steingroewer J *et al.*, Microalgae wastewater treatment: biological and technological approaches. *Eng Life Sci* **19**(12):860–871 (2019).
15. Davis R, Coleman A, Wigmosta M, Markham J, Kinchin C, Zhu Y *et al.*, *Algae Harmonization Study: Evaluating the Potential for Future Algal Biofuel Costs, Sustainability, and Resource Assessment from Harmonized Modeling* [Internet]. National Renewable Energy Laboratory, Golden, CO (2017) 2018 [cited 2021 Dec 29]. Report No.: NREL/TP-5100-70715. Available: https://www.nrel.gov/docs/fy18osti/70715.pdf.
16. Davis R, Markham J, Kinchin C, Grundl N, Tan ECD and Humbird D, Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion [Internet]. 2016 Feb [cited 2020 Dec 15] p. NREL/TP-5100-64772, 1239893. Report No.: NREL/TP-5100-64772, 1239893 Available: http://www.osti.gov/servlets/purl/1239893/.
17. Williams PJLB and Laurens LML, Microalgae as biodiesel & biomass feedstocks: review & analysis of the biochemistry, energetics & economics. *Energy Environ Sci* **3**(5):554–590 (2010).
18. Laurens LML, Van Wychen S, McAllister JP, Arrowsmith S, Dempster TA, McGowen J *et al.*, Strain, biochemistry, and cultivation-dependent measurement variability of algal biomass composition. *Anal Biochem* **452**:86–95 (2014).
19. Klein B and Davis R, *Algal Biomass Production Via Open Pond Algae Farm Cultivation: 2021 State of Technology and Future Research* [Internet]. National Renewable Energy Laboratory, Golden, CO (2022 [cited 2022 Dec 8].). Available: https://www.nrel.gov/docs/fy22osti/82417.pdf.
20. Ajjawi I, Verruto J, Aqui M, Soriaga LB, Coppersmith J, Kwok K *et al.*, Lipid production in Nannochloropsis gaditana is doubled by decreasing expression of a single transcriptional regulator. *Nat Biotechnol* **35**(7):647–652 (2017 Jul).
21. Klein B and Davis R, *Algal Biomass Production via Open Pond Algae Farm Cultivation: 2022 State of Technology and Future Research*. National Renewable Energy Lab. (NREL), Golden, CO (2023).
22. Wiatrowski M and Davis R, *Algal Biomass Conversion to Fuels via Combined Algae Processing (CAP): 2022 State of Technology and Future Research*. National Renewable Energy Lab, Golden, CO (2023) Jun p. 38. Report No.: NREL/TP-5100-85662.
23. Huesemann M, Edmundson S, Gao S, Dale T, Negi S, Laurens L, et al. Development of integrated screening, cultivar optimization, and verification research 2023.
24. Huntley ME, Johnson ZI, Brown SL, Sills DL, Gerber L, Archibald I *et al.*, Demonstrated large-scale production of marine microalgae for fuels and feed. *Algal Research.* **10**:249–265 (2015).
25. Carriquiry MA, Du X and Timilsina GR, Second generation biofuels: economics and policies. *Energy Policy* **39**(7):4222–4234 (2011).

26. Stephens E, Ross IL, King Z, Mussgnug JH, Kruse O, Posten C *et al*., An economic and technical evaluation of microalgal biofuels. *Nat Biotechnol* **28**(2):126–128 (2010).
27. Wiatrowski M, Klein BC, Davis RW, Quiroz-Arita C, Tan ECD, Hunt RW *et al*., Techno-economic assessment for the production of algal fuels and value-added products: opportunities for high-protein microalgae conversion. *Biotechnol Biofuels Bioprod* **15**(1):8 (2022).
28. Kruger JS, Wiatrowski M, Davis RE, Dong T, Knoshaug EP, Nagle NJ *et al*., Enabling production of algal biofuels by techno-economic optimization of Co-product suites. *Frontiers in Chemical Engineering* [Internet] **3** (2022 [cited 2022 Mar 7]) Available: https://www.frontiersin.org/article/10.3389/fceng.2021.803513.
29. Cruce JR and Quinn JC, Economic viability of multiple algal biorefining pathways and the impact of public policies. *Appl Energy* **233–234**:735–746 (2019).
30. Gambelli D, Alberti F, Solfanelli F, Vairo D and Zanoli R, Third generation algae biofuels in Italy by 2030: a scenario analysis using Bayesian networks. *Energy Policy* **103**:165–178 (2017).
31. Ribeiro LA, Pereira da Silva P, Ribeiro L and Dotti FL, Modelling the impacts of policies on advanced biofuel feedstocks diffusion. *J Clean Prod* **142**:2471–2479 (2017).
32. Tao L, Milbrandt A, Zhang Y and Wang WC, Techno-economic and resource analysis of hydroprocessed renewable jet fuel. *Biotechnol Biofuels* **10**(1):261 (2017).
33. Wang WC and Tao L, Bio-jet fuel conversion technologies. *Renew Sustain Energy Rev* **53**:801–822 (2016).
34. Pearlson M, Wollersheim C and Hileman J, A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production. *Biofuels Bioprod Biorefin* **7**(1):89–96 (2013).
35. Honeywell, Honeywell technology enables jet flights with SAF from algal oil | Biomassmagazine.com. [cited (2022 Feb 8]). Available: http://biomassmagazine.com/articles/18484/honeywell-technology-enables-jet-flights-with-saf-from-algal-oil.
36. Davis R, Kinchin C, Markham J, Tan E, Laurens L, Sexton D *et al*., *Process Design and Economics for the Conversion of Algal Biomass to Biofuels: Algal Biomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products [Internet]*. National Renewable Energy Lab. (NREL), Golden, CO (2014 [cited 2022 Dec 8].). Available: https://www.osti.gov/biblio/1159351.
37. Wiatrowski M, Davis R. Algal biomass conversion to fuels via combined algae processing (CAP): 2020 state of technology and future research. National Renewable Energy Lab (NREL) Golden, CO; 2021 p. 36.
38. Pearlson MN, *A Techno-Economic and Environmental Assessment of Hydroprocessed Renewable Distillate Fuels* [Internet] [Thesis]. Massachusetts Institute of Technology, Cambridge, MA (2011) [cited 2021 Dec 20]. Available: https://dspace.mit.edu/handle/1721.1/65508.
39. Robota HJ, Alger JC and Shafer L, Converting algal triglycerides to diesel and HEFA jet fuel fractions. *Energy Fuel* **27**(2):985–996 (2013).
40. Kruger JS, Christensen ED, Dong T, Van Wychen S, Fioroni GM, Pienkos PT *et al*., Bleaching and hydroprocessing of algal biomass-derived lipids to produce renewable diesel fuel. *Energy Fuel* **31**(10):10946–10953 (2017).
41. van Dyk S, Su J, Mcmillan JD and Saddler J, Potential synergies of drop-in biofuel production with further co-processing at oil refineries. *Biofuels Bioprod Biorefin* **13**(3):760–775 (2019).
42. Marker TL, Opportunities for Biorenewables in Oil Refineries [Internet]. UOP LLC, Des Plaines, IL (United States); 2005 Dec [cited 2024 Feb 19]. Report No.: DOEGO15085Final Available: https://www.osti.gov/biblio/861458.
43. Ansari FA, Guldhe A, Gupta SK, Rawat I and Bux F, Improving the feasibility of aquaculture feed by using microalgae. *Environ Sci Pollut Res* **28**(32):43234–43257 (2021).
44. Lum KK, Kim J and Lei XG, Dual potential of microalgae as a sustainable biofuel feedstock and animal feed. *J Animal Sci Biotechnol* **4**(1):53 (2013).
45. Davis R, Wiatrowski M, Kinchin C and Humbird D, Conceptual Basis and Techno-Economic Modeling for Integrated Algal Biorefinery Conversion of Microalgae to Fuels and Products. 2019 NREL TEA Update: Highlighting Paths to Future Cost Goals via a New Pathway for Combined Algal Processing [Internet]. National Renewable Energy Lab. (NREL), Golden, CO (United States); 2020 Sep [cited 2020 Dec 15]. Report No.: NREL/TP-5100-75168 Available: https://www.osti.gov/biblio/1665822.
46. Peterson S, Newes E, Inman D, Vimmerstedt L, Hsu D, Peck C *et al*., An overview of the biomass scenario model, in *The 31st International Conference of the System Dynamics Society [Internet]*. Cambridge, Massachusetts (2013 [cited 2022 Dec 8].). Available: http://www.systemdynamics.org/conferences/2013/proceed/papers/P1352.pdf.
47. AspenTech, *Aspen Plus V10*. Aspen Technology, Inc, Bedford, MA (2017).
48. Quinn JC and Davis R, The potentials and challenges of algae based biofuels: a review of the techno-economic, life cycle, and resource assessment modeling. *Bioresour Technol* **184**:444–452 (2015).
49. Wiatrowski M, Davis R and Kruger J, Algal Biomass Conversion to Fuels via Combined Algae Processing (CAP): 2021 State of Technology and Future Research [Internet]. National Renewable Energy Lab. (NREL), Golden, CO (United States); 2022 Apr [cited 2022 Oct 19]. Report No.: NREL/TP-5100-82502 Available: https://www.osti.gov/biblio/1866075.
50. Peterson S, Bush B, Inman D, Newes E, Schwab A, Stright D *et al*., Lessons from a large-scale systems dynamics modeling project: the example of the biomass scenario model. *System Dynamics Review* **35**(1):55–69 (2019).
51. Newes EK, Bush BW, Peck CT and Peterson SO, Potential leverage points for development of the cellulosic ethanol industry supply chain. *Biofuels* **6**(1–2):21–29 (2015).
52. Vimmerstedt LJ, Bush B and Peterson S, Ethanol distribution, dispensing, and use: analysis of a portion of the biomass-to-biofuels supply chain using system dynamics. *PLoS ONE* **7**(5):e35082 (2012).
53. Vimmerstedt LJ, Bush BW, Hsu DD, Inman D and Peterson SO, Maturation of biomass-to-biofuels conversion technology pathways for rapid expansion of biofuels production: a system dynamics perspective. *Biofuels Bioprod Biorefin* **9**(2):158–176 (2015).
54. Newes E, Clark CM, Vimmerstedt L, Peterson S, Burkholder D, Korotney D *et al*., Ethanol production in the United States: the roles of policy, price, and demand. *Energy Policy* **161**:112713 (2022).
55. Newes E, Inman D and Bush B, Understanding the developing cellulosic biofuels industry through dynamic modeling, in *Economic Effects of Biofuel Production [Internet]*, ed. by dos Santos Bernardes MA. InTech, Rijeka, Croatia, pp. 373–404 (2011 [cited 2013 Jun 26]) Available: http://www.intechopen.com/books/economic-effects-of-biofuel-production/understanding-the-developing-cellulosic-biofuels-industry-through-dynamic-modeling.
56. Kendall A and Yuan J, Comparing life cycle assessments of different biofuel options. *Curr Opin Chem Biol* **17**(3):439–443 (2013).
57. Chamkalani A, Zendehboudi S, Rezaei N and Hawboldt K, A critical review on life cycle analysis of algae biodiesel: current

challenges and future prospects. *Renew Sustain Energy Rev* **134**:110143 (2020).

58. Carneiro MLNM, Pradelle F, Braga SL, Gomes MSP, Martins ARFA, Turkovics F *et al*., Potential of biofuels from algae: comparison with fossil fuels, ethanol and biodiesel in Europe and Brazil through life cycle assessment (LCA). *Renew Sustain Energy Rev* **73**:632–653 (2017).
59. McCarren J, Viridos: Harnessing the power of photosynthesis to mitigate climate change [Internet] (2023 [cited 2022 Dec 8].). Available: https://www.energy.gov/sites/default/files/2023-06/beto-04-energy-crops-saf-d2-3x5-june-2023-mccarren.pdf.
60. Petroleum & Other Liquids Data—U.S. Energy Information Administration (EIA) [Internet]. [cited (2022 Sep 21].). Available: https://www.eia.gov/petroleum/data.php.
61. Beckstrom BD, Wilson MH, Crocker M and Quinn JC, Bioplastic feedstock production from microalgae with fuel co-products: a techno-economic and life cycle impact assessment. *Algal Res* **46**:101769 (2020).
62. Manganaro JL, Lawal A and Goodall B, Techno-economics of microalgae production and conversion to refinery-ready oil with co-product credits. *Biofuels Bioprod Biorefin* **9**(6):760–777 (2015).
63. Cai H, Ou L, Wang M, Davis R, Dutta A, Harris K *et al*., Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Ex Situ Catalytic Fast Pyrolysis, Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2020 State-of-Technology Cases. Argonne National Lab.(ANL), Argonne, IL (United States); National Renewable … (2021).
64. Jones SB, Zhu Y, Anderson DB, Hallen RT, Elliott DC, Schmidt AJ *et al*., Process design and economics for the conversion of algal biomass to hydrocarbons: whole algae hydrothermal liquefaction and upgrading. Pacific Northwest National Lab. (PNNL), Richland, WA (United States) (2014).
65. California Air Resources Board, Monthly LCFS Credit Transfer Activity Reports [Internet] (2021 [cited 2022 Jul 20].). Available: https://ww2.arb.ca.gov/resources/documents/monthly-lcfs-credit-transfer-activity-reports.
66. Prussi M, Weindorf W, Buffi M, Sánchez López J and Scarlat N, Are algae ready to take off? GHG emission savings of algae-to-kerosene production. *Appl Energy* **15**(304):117817 (2021 Dec).
67. Vasudevan V, Stratton RW, Pearlson MN, Jersey GR, Beyene AG, Weissman JC *et al*., Environmental performance of algal biofuel technology options. *Environ Sci Technol* **46**(4):2451–2459 (2012).
68. U.S. Energy Information Administration, Annual Energy Outlook 2021 [Internet] (2021 [cited 2021 Dec 29].). Available: https://www.eia.gov/outlooks/aeo/.

Swaroop Atnoorkar

Swaroop Atnoorkar is a researcher at the National Renewable Energy Laboratory, specializing in life-cycle assessment, system dynamics modeling and data analysis. Her research focuses on evaluating the deployment and decarbonization potential of biofuels, industrial technologies and novel building materials using data-centric approaches.

Matthew Wiatrowski

Matthew Wiatrowski is a research engineer at the National Renewable Energy Laboratory, specializing in techno-economic analysis and life cycle assessment of biomass conversion technology pathways. His work focuses on evaluating the production of fuels and products from feedstocks such as microalgae, waste resources and woody biomass.

Emily Newes

Emily Newes is a group manager at the National Renewable Energy Laboratory. She specializes in system dynamics modeling and currently leads bioeconomy scenario analysis and modeling projects funded by the Bioenergy Technologies Office of the US Department of Energy, focusing on biofuel deployment in the aviation and maritime industries.

Ryan Davis

Ryan Davis is a group manager and senior research engineer at the National Renewable Energy Laboratory focusing on techno-economic analysis and life cycle assessment for biomass conversion technology pathways. Ryan coordinates analysis efforts for biochemical conversion strategies *via* lignocellulosic sugars as well as algal biomass projects.

Steve Peterson

Steve Peterson is an independent consultant and a Senior Lecturer at the Thayer School of Engineering at Dartmouth, where he teaches undergraduate courses in system dynamics and energy systems. His work over the past 20+ years has applied system dynamics modeling approaches in diverse topic areas in industry, government and non-profit settings.