Algal Biomass Conversion to Fuels via Combined Algae Processing (CAP): 2022 State of Technology and Future Research

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National Renewable Energy Laboratory

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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

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List of Acronyms

AD	anaerobic digestion
AFDW	ash-free dry weight
ASU	Arizona State University
BDO	2,3-butanediol
BETO	Bioenergy Technologies Office
CAP	combined algae processing
FA	Florida Algae (test bed site under ATP^3 consortium)
FY	fiscal year
GGE	gallon gasoline equivalent
HCSD	high-carbohydrate *Scenedesmus*
HDO	hydrodeoxygenation
HI	hydroisomerization
INL	Idaho National Laboratory
MBSP	minimum biomass selling price
MFSP	minimum fuel selling price
NIPU	non-isocyanate polyurethane
NREL	National Renewable Energy Laboratory
PU	polyurethane
SAF	sustainable aviation fuel
SOT	state of technology
TAG	triacylglyceride
TEA	techno-economic analysis
UCSD	University of California, San Diego

Executive Summary

The annual State of Technology (SOT) assessment is an essential activity for platform research conducted under the Bioenergy Technologies Office (BETO). It allows for the impact of research progress (both directly achieved in-house at NREL and furnished by partner organizations) to be quantified in terms of economic improvements in the overall biofuel production process for a particular biomass processing pathway, whether based on terrestrial or algal biomass feedstocks. As such, initial benchmarks can be established for currently demonstrated performance, and progress can be tracked toward out-year goals to ultimately demonstrate economically viable biofuel technologies.

NREL's algae SOT benchmarking efforts focus both on front-end algal biomass production and separately on back-end conversion to fuels through NREL's "combined algae processing" (CAP) pathway. The production model is based on outdoor long-term cultivation data, enabled by comprehensive algal biomass production trials conducted under Development of Integrated Screening, Cultivar Optimization, and Verification Research (DISCOVR) consortium efforts and driven by data furnished by Arizona State University's (ASU's) Arizona Center for Algae Technology and Innovation (AzCATI) test bed site. The CAP model is primarily based on experimental efforts conducted under NREL research and development projects, with some process parameters provided by partner organizations. Assumptions regarding the wet storage of algae use data provided by Idaho National Laboratory (INL), while parts of the polyurethane production process leverage BETO-funded research from collaborators at Algenesis and the University of California, San Diego (UCSD).

This report focuses on back-end conversion of algal biomass through the CAP pathway, highlighting the 2022 updates to minimum fuel selling price (MFSP). This update incorporates improvements to fermentation performance for two biological pathways through carboxylic acid and 2,3-butanediol (BDO) intermediates, as demonstrated through parallel research on the biochemical conversion of corn stover. Improvements are applied to the glucose fraction of the biomass only, while parameters regarding the conversion of the mannose fraction (not a significant component in corn stover) are maintained consistently with prior CAP SOTs. Additional parameters are also updated to reflect the most current understanding of each pathway, including an increase in the catalyst loading requirement in the ketonization step of the acids pathway and a decrease in the fermentation productivity in the BDO pathway. Additionally, the biomass feedstock costs (minimum biomass selling price [MBSP]), yields, and seasonal variability from the upstream cultivation SOT model were also incorporated into downstream Aspen Plus CAP models.

Details for all other operations in the CAP process were maintained consistent with those reflected in the prior 2021 SOT. This includes 83% pretreatment sugar yields, 96% lipid extraction recovery, and conversion of a portion of algal triglycerides to a polyurethane coproduct. Maintaining those operational parameters coupled with the updated 2022 SOT parameters, including an updated MBSP value of $681/ton (based on ASU evaporation rates), the 2022 MFSP translates to $5.99/gallon gasoline equivalent (GGE) and $6.28/GGE for the acids and BDO fermentation pathways, respectively. Alternatively, the 2022 MBSP value associated with Florida Algae (FA) evaporation rates at $602/ton ash-free dry weight (AFDW) would reduce the MFSP to $4.78/GGE and $5.08/GGE for the acids and BDO cases,

respectively. Relative to the 2021 SOT cases, this indicates a decrease of $0.26–$0.38/GGE (4-7%) attributed to improved fermentation performance and higher demonstrated cultivation productivities in the 2022 farm production SOT. In all cases, the addition of full pond liners in the upstream biomass farm models would increase SOT fuel costs by approximately $2.5/GGE relative to the above values based on minimally lined ponds. As in prior SOTs, these results are all based on an assumed biomass composition consistent with NREL's high-carbohydrate *Scenedesmus* (HCSD) composition targets.

The resulting total fuel yields were modeled as 64.4 GGE/ton and 65.7 GGE/ton AFDW for the acids and BDO pathways, respectively, translating to 1,798 and 1,835 GGE/acre-year. These fuel yields represent a minor increase of 1.5%–3.8% in fuel yield per ton of biomass and a more significant increase of 10.2%–12.5% on a fuel yield per acre basis (inclusive of upstream cultivation productivity performance). As in prior SOT reports, fuels are fractionated into naphtha and diesel yields; however, we also consider an alternative fractionation strategy for maximizing the production of sustainable aviation fuel (SAF). In this alternative approach, approximately two-thirds or more of the total fuel production in each pathway would fall in a boiling range suitable for blending with SAF, with SAF defined here as hydrocarbons ranging from C_8–C_{16}. Between the two pathways, the acids case has experimentally been shown to produce a high fraction of isomerized C_{14} alkanes, which are associated with more ideal fuel properties for SAF, whereas the BDO case produces a high degree of straight-chain C_8 alkanes, which would likely require additional catalysis advancements for further isomerization to meet SAF fuel property requirements.

Finally, this milestone reports on key process sustainability indicators for the CAP conversion stage, including mass and carbon yields to fuels and coproducts, freshwater consumption, and facility power balances/natural gas demands. In keeping with recent BETO guidance, formal life cycle assessment sustainability metrics such as greenhouse gas emissions or fossil energy consumption are not calculated here, but will be deferred to Argonne National Laboratory. Beyond the standard SOT models, in Appendix C of this report we also present an industry case study evaluating the conversion of algae biomass from several scenarios reflective of outdoor cultivation data furnished by an industry collaborator. This case study provides a supplementary datapoint on work being performed elsewhere achieving comparable cultivation productivity with more favorable compositional quality, producing biomass enriched in lipids as may be more optimal for conversion upgrading to fuels and products.

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Introduction

The National Renewable Energy Laboratory (NREL) develops and maintains techno-economic models that simulate the technical and economic aspects of conceptual biorefinery conversion pathways to biofuels and bioproducts, focused on both terrestrial and algal biomass processing routes. For a particular set of process parameters, material and energy balance and flow rate information is generated using simulation software such as Aspen Plus [1], for a given facility size or biomass throughput rate. These data are used to size and cost process equipment and compute raw material and other operating costs. Using a discounted cash flow rate of return analysis, the minimum fuel selling price (MFSP) or minimum biomass selling price (MBSP) required to obtain a net present value of zero for a 10% internal rate of return is determined. The result is a techno-economic model that reasonably estimates an "*nth*-plant" production cost for this pre-commercial process.

Prior studies have demonstrated that the production of fuels from algal biomass will require additional revenue to supplement the high cost of algae production in order to achieve economic viability [2]; or, alternatively, utilizing a lower-cost source of biomass such as that from wastewater treatment, harmful algal blooms, or other waste algal resources [3]. Combined analysis from earlier NREL design reports [4, 5], which focused primarily on the production of algal fuels (fermenting sugars to ethanol and upgrading lipids to diesel-range blendstocks), highlighted an MFSP potential of $5.90/GGE (2014$) when considering out-year targets. This included projections for biomass cultivation costs reductions with MBSP goals near $500/ton (representing the largest contributor to overall fuel cost), though still representing a roughly sevenfold increase over terrestrial biomass cost goals [6]. At even high fuel yield possibilities of 100 GGE/ton, as can be achieved from algal biomass conversion pathways, this translates to a minimum MFSP of $5/GGE tied to feedstock cost alone. Thus, it has become increasingly clear that additional biorefinery revenue will be necessary to offset algal feedstock and conversion processing costs to reduce MFSPs.

In light of this importance for increasing revenue beyond that achievable from fuels alone, various higher-value coproducts have been considered for inclusion in the CAP pathway, including succinic acid, surfactants, plastics, and polyols/polyurethanes. Polyurethane (PU) foam, producible from the unsaturated fatty acids found in algae, was identified as a leading candidate to supplement biorefinery revenues due to relatively high selling prices and market volumes. Accordingly, a PU coproduct was incorporated for the first time into the 2020 SOT, based on conventional synthesis chemistries via polyol intermediate reaction with isocyanates [7]. This approach has been maintained here; however, research and development for an alternative approach to instead produce non-isocyanate polyurethanes (NIPUs) has continued to progress in recent years [8] – the NIPU approach allows for a more "green chemistry" route to PU synthesis by replacing isocyanates (which are both toxic and environmentally deleterious by synthesis from phosgene, although the resultant isocyanate PU product itself is not toxic) with diamine and CO_2 co-reactants. However, due to uncertainties regarding design, cost, and scale-up implications for TEA modeling purposes, as well as market values for such NIPU products, the NIPU pathway is again not yet considered for formal SOT inclusion in the present update. While future design cases will aim to incorporate this NIPU concept to improve the economics and sustainability of the process based on currently-ongoing efforts to reduce TEA uncertainties, the standard isocyanate-based PU processing approach was maintained in this SOT, reflecting inputs previously furnished via industry and academic collaborators Algenesis and the University of California, San Diego (UCSD) [9]. For the present SOT assessment, this value-added PU coproduct is considered alongside other processing steps in two exemplary CAP configurations producing fuels, alongside combined heat and power as well as nutrient recycling back to cultivation, to inform SOT benchmarks for MFSP extrapolated to n^{th}-plant commercial scale.

We emphasize that the present SOT analysis and the resultant MBSP and MFSP values carry some uncertainty related to the assumptions and estimates made for capital and raw material costs. Without a detailed understanding of the underlying basis, the absolute computed selling price has limited relevance. By demonstrating the cost impact of various process parameters individually or in concert, the model helps guide research by indicating where the largest opportunities for cost reduction exist. It is also acknowledged that "state of technology" is arguably a misnomer because no commercial algal biofuel facility exists today (e.g., growing algal biomass for purposes of producing fuels at commercial scale), and because the SOT performance results documented here are based solely on NREL and partner (DISCOVR consortium, Idaho National Laboratory [INL], and UCSD) data and do not necessarily represent a broader picture of all performers within and beyond BETO's portfolio.

Discussion of Relevant Inputs Used in the SOT

The base case CAP configuration as maintained in NREL's fiscal year (FY) 2022 SOT is shown in Figure 1. This configuration reflects a consistent process design as utilized in the latest 2020 and 2021 SOT reports, including isolation of a portion of algal lipids for production of polyurethane (via conventional isocyanate reaction with polyols) as a high-value coproduct and key enabling factor to achieving $2.5/GGE MFSP goals by 2030 [7, 10, 11]. The configuration is also optimized for a fixed biomass compositional target with low protein and elevated carbohydrates/lipids as assumed in the above-cited prior historical SOTs and 2030 projections. Over recent years, NREL research has focused on strategies for the conversion of high-protein algae biomass to fuels and products. Proteinaceous biomass represents a more challenging feedstock to work with from a conversion standpoint; however, biomass productivities are maximized under nutrient-replete conditions which are concomitant with high-protein compositions. As biomass cultivation efforts have focused on optimizing productivity, strategies have been sought to facilitate the production of fuels and products from the resulting biomass. Numerous approaches have been considered, including (1) mild oxidative treatment (MOT) of proteins and carbohydrates to produce carboxylic acid intermediates which may be catalytically or biologically upgraded to fuels and products; (2) direct fermentation of proteins; and (3) sale of residual protein as a bioplastic co-feed, food/feed product, or graphite precursor. These strategies have shown varying degrees of promise for proteinaceous biomass; however, they are less applicable in the case of a high-carbohydrate biomass such as the basis modeled here, which is maintained consistently with previous SOT reports. This higher quality (lower-protein) composition benefits from a more straightforward approach with carbohydrate fermentation and lipid extraction and upgrading. However, future analysis efforts will continue investigating optimal conversion strategies to accommodate compositions for high-protein biomass (as may support higher achievable cultivation productivities) in parallel to biomass enriched in lipids and carbohydrates.

In summary, the CAP process approach reflected in this assessment utilizes diversion of peak seasonal biomass capacity from upstream cultivation in excess of the annual average feed rate to a wet anaerobic storage process, and pulling from storage during low production seasons below the average (with wet storage performance data furnished by partners at INL [12]). The material is delivered from cultivation after dewatering to 20 wt% solids ash-free dry weight (AFDW). Following storage as applicable, the biomass is routed to dilute acid pretreatment, traditionally used to hydrolyze carbohydrates to monomeric sugars and enable effective downstream lipid extraction. In the present SOT, more recent acid pretreatment yields were maintained as documented in the 2020 SOT, reflecting biomass samples (*Scenedesmus acutus* LRB-AP-0401) derived from INL's storage study achieving 83% overall combined sugar yields (81% glucose/92% mannose for fresh algae and 84% glucose/70% mannose for stored algae) when processed through NREL's ZipperClave pretreatment reactor at standard conditions [13].

The pretreated hydrolysate slurry is processed through solid/liquid separation using a vacuum filter press, with the solids routed to extraction and the liquor routed to sugar fermentation. The SOT schematic reflects two fuel fermentation pathways based on similar focus areas under the Biochemical Conversion Platform, namely fermentation to carboxylic acid or 2,3-butanediol (BDO) intermediates, in either case subsequently upgrading the given intermediate to final hydrocarbon fuel products through a series of catalytic steps. In prior SOT reports, fermentation parameters have been based solely on experimental results from algal hydrolysate. However, recent algae conversion research has focused more on alternative fermentation and protein valorization pathways, though further progress on these same fermentation and upgrading pathways has been made under the Biochemical Conversion Platform. This report leverages that progress as can reasonably be applied to algal hydrolysate to quantify associated economic implications.

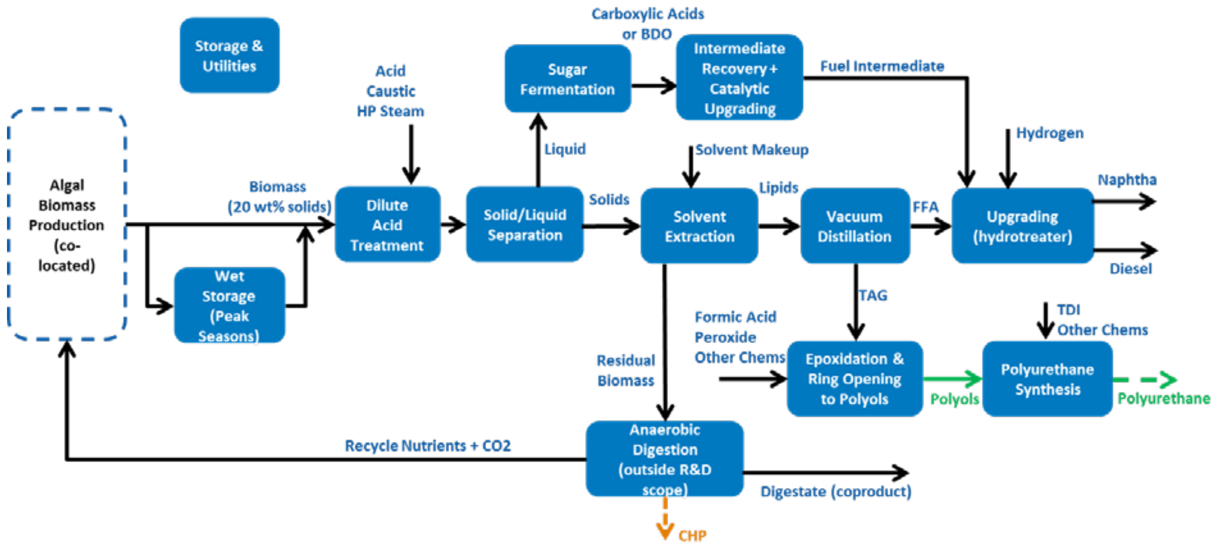

Figure 1. Schematic diagram of CAP configuration for the FY 2022 SOT

A summary of the changes to the 2022 SOT is shown in Table 1. Given the differences between lignocellulosic and algal carbohydrates, only advancements in glucose utilization and conversion were implemented. In contrast to lignocellulosic biomass (e.g., corn stover, which is the primary feedstock of interest under the Biochemical Platform), algal biomass also contains a significant fraction of mannose; in the modeled strain, mannose makes up approximately 26% of all fermentable sugars, with the remainder attributed to glucose, while mannose is a negligible component in typical corn stover hydrolysate. Therefore, the advancements demonstrated on corn stover hydrolysate were applied to the algal glucose substrate only, while parameters related to the conversion of the mannose fraction were maintained to be consistent with prior CAP SOT reports. Parameters applicable to both sugars (e.g., productivity) were adjusted proportionally based on the relative fractions of glucose and mannose. In the acids case, these changes included a slightly higher glucose utilization (95% vs. a previously demonstrated 92%), a significantly increased productivity (0.54 g/L-h vs. a previously demonstrated 0.30 g/L-h) and a notably improved selectivity to the more optimal acid component for downstream processing (98% selectivity to butyric acid vs. a previously demonstrated 82% relative to shorter-chain acids, based on advancements in strain selection and engineering). In the BDO case, the glucose utilization was more significantly increased (99% vs. a previously demonstrated 89%); however, this benefit was accompanied by a longer fermentation batch time (96 h vs. a previously demonstrated 56 h). Finally, an additional change was made in the acids pathway to decrease the Weight Hourly Space Velocity (WHSV) of the downstream ketonization catalyst (ZrO_2), from 6 h^{-1} to 0.4 h^{-1}, effectively increasing the catalyst loading per unit feed. This parameter, also updated in the FY 2022 Biochemical SOT [14], was changed following catalyst deactivation experiments which showed a higher rate of catalyst deactivation/coking than previous understanding.

Table 1. Summary of Updates Applied in the 2022 SOT

Biomass Cultivation	**FY 2021**	**FY 2022**
MBSP (minimally lined, FA evap, $/ton AFDW))	$611	$602
Acids Pathway		
Glucose utilization to product	92%	95%
Glucose product yield breakdown		
Butyric acid	82%	98%
Acetic acid	15%	2%
Formic acid	4%	0%
Mannose utilization to product	92%	92%
Mannose product yield breakdown		
Butyric acid	82%	82%
Acetic acid	15%	15%
Formic acid	4%	4%
Productivity (g/(L-h))	0.30	0.54
Ketonization WHSV (h^{-1})	6	0.4
BDO Pathway		
Glucose utilization to product	89%	99%
Mannose utilization to product	89%	89%
Fermentation batch time	56	96

The remainder of the process is maintained consistently with prior SOT updates. Following dilute acid pretreatment, the solids product from solid/liquid separation is routed to lipid extraction across a series of three mixing/phase separation steps in series, each utilizing a nonpolar (hexane or light naphtha) solvent with a polar (ethanol) co-solvent. Both the extract and raffinate phases are routed to distillation columns for recovery and recycle of the respective solvents. The raffinate product, enriched in protein after ethanol solvent recovery, is routed to anaerobic digestion (AD) to produce biogas for heat and power benefits as well as enabling recycle of nutrients back to cultivation. The remaining lipids undergo a three-step purification process to remove impurities, followed by a vacuum distillation step to fractionate triacylglycerides (TAGs) and free fatty acids (FFAs). The FFA portion is routed to hydrotreating for production of hydrocarbon fuels (consisting of a combined hydrodeoxygenation/hydroisomerization [HDO/HI] step), while the TAG portion is used to produce polyurethane. No further improvements were demonstrated experimentally during 2022 for the extraction, lipid upgrading, or polyol/polyurethane coproduct operations beyond those documented in prior SOT reports, and thus the details will not be repeated here, but key parameters for all steps are summarized in Table 2 and Table 3.

Table 2. Process Conditions and Conversions Observed from Experimental CAP Data, Utilized for FY 2022 SOT as Maintained from Prior SOTs [11, 15–18]. Italicized lines represent modeling assumptions, outside experimental scope. Polyol/polyurethane details are presented in Table 3.

Pretreatment	**Value**		**Experimental Notes**
Solids loading (wt%)	20% [a]		- Pretreatment data reflect FY 2020 NREL experimental work done under CPR project based on INL seasonal storage material - SLS vacuum membrane based on FY 2017 data
Acid loading (wt% vs. feed liquor)	2%		
Fermentable sugar release	83%		
Carbs to degradation products	1.5%		
Hydrolysate solid-liquid separation	Yes (vacuum belt filter with flocculant)		
Sugar loss in solid-liquid separation	5%		
Lipid loss in solid-liquid separation	0.5%		
Solid-liquid separation flocculent loading (g/kg insoluble solids)	10		
SLS membrane capacity (kg insoluble solids/m^2-h)	30		
Sugar Fermentation	**Acids**	**BDO**	
Fermentation productivity (g/L-h)	0.54	96-hour batch	- Parameters for acids (productivity, glucose utilization, butyric and acetic yields) and BDO (batch time, glucose utilization to product) updated based on demonstrated progress for corn stover fermentation [19]
Sugar diversion to organism seed growth	*10% [b]*	*10% [b]*	
Glucose utilization to product	95% [c]	99% [c]	
Mannose utilization to product	92% [c]	89% [c]	
Glycerol utilization to product	92% [c]	0% [c]	
Butyric acid yield (g/g total available sugars)	0.44	N/A	
Acetic acid yield (g/g total available sugars)	0.04	N/A	
BDO + acetoin yield (g/g total available sugars)	N/A	0.46	
Catalytic upgrading carbon efficiency (HDO feed vs. recovered intermediate) [d]	83%	98%	
Lipid Extraction + Upgrading			
Extraction configuration	3-stage CSTR + centrifugation with 2 solvents		- Extraction yields based on high-carbohydrate *Scenedesmus* (HCSD) biomass, FY 2018 data with light naphtha solvent - Hydrotreating (HDO+HI) yields based on HCSD-extracted lipids, maintaining FY 2017 data for one-step HDO + HI upgrading
Solvent loading (nonpolar: EtOH: dry biomass, wt)	2.7:1.1:1 g/g/g		
CSTR extraction residence time (min)	15		
Convertible lipid extraction yield per step	74%, 65.4%, 55.6%		
Total convertible lipid extraction yield	96.0%		
Non-sterol lipid impurity partition to extract	<11.5%		
Hydrotreating conditions	707°F, 435 psig, ~5,900 scf/bbl H_2 feed ratio		
Catalyst details	1% Pt/SAPO-11, 1 h^{-1} WHSV		
Hydrotreating renewable diesel blend-stock yield (wt% of oil feed) [e]	62.1%		
Hydrotreating naphtha yield (wt% of oil feed) [e]	21.8% [f]		
Hydrotreating H_2 consumption (wt% of oil feed)	2.23% [g]		

[a] Experimental work based on 18%–25% solids, adjusted here to 20% solids for consistency with previously published modeling framework; pretreatment performance is expected to remain unchanged at this value (unpublished data).

[b] Values were not determined here as part of the scope of experimental work; set consistent with previously documented models [5].

[c] Does not include sugar diversions to biomass seed growth assumed in the model.

[d] Catalytic upgrading of fermentation intermediates to final hydrocarbon fuels is outside R&D scope; set consistently with Biochemical Platform FY 2022 SOT data[14]. Value represents upgrading yields to the final fuel finishing (hydrotreating) reactor feed.

[e] Hydrotreating yields are based on adjusting original experimental data [16] to achieve 100% mass closure, based on lipid hydrotreating alone (not including co-processed BDO/acids intermediate products).

[f] Includes light gas correction, estimated separately via mass and element closure to 100%; based on lipids alone.

[g] H_2 consumption set in model to close elemental H balance; experimental H_2 consumption measured was lower; based on lipids alone.

Table 3. Process Inputs for Polyurethane Production, Maintained from the 2020 and 2021 SOTs [7, 11]

Parameter	Specification	Basis
Epoxidation and ring opening		
Temperature	75°C	[20]
Pressure	1 atm	[20]
Residence time	6 hours	[20]
H_2O_2	1.5x double bonds	50% stoichiometric excess
Formic acid	Equimolar with double bonds	[20]
Power	0.54 MWh/ton polyol	Input from Nexant [21]
Cooling water	220 w/w polyol	Input from Nexant [21]
Low-pressure steam	0.02 w/w polyol	Input from Nexant [21]
Nitrogen	0.02 w/w polyol	Input from Nexant [21]
Other chemicals	$46.70/ton polyol	Input from Nexant [21]
Polyurethane production		
TDI [a]	0.5 mole/mole hydroxyl group	Stoichiometric
Water	0.0281 w/w polyol	Input from Nexant [21]
DEOA [b]	0.0026 w/w polyol	Input from Nexant [21]
Surfactant	0.0049 w/w polyol	Input from Nexant [21]
Power	0.004 w/w polyol	Input from Nexant [21]

[a] Toluene diisocyanate
[b] Diethanolamine

In addition to updating the fermentation and catalytic upgrading parameters, other changes to the FY 2022 SOT can be attributed to upstream improvements around algae cultivation yields, seasonal flows, and biomass costs (MBSP). All pertinent details for those parameters are summarized in the accompanying FY 2022 algal biomass SOT report [22]; in summary, FY 2022 algae farm MBSPs were estimated at $681/ton or $602/ton AFDW for the Arizona State University (ASU) vs. Florida Algae (FA) evaporation scenarios, respectively (unlined ponds, increasing to $844/ton or $765/ton for fully lined ponds, respectively). This was tied to a 5% increase in annual cultivation productivity (18.5 $g/m^2/day$, relative to the FY 2021 basis of 17.6 $g/m^2/day$) and associated throughput increases through the CAP processing facility (though with these impacts somewhat offset by a higher seasonal variability in the FY2022 cultivation data of 3.2:1).

Consistent with prior SOTs, variability in biomass delivery rates from upstream seasonal cultivation is mitigated by diverting excess peak biomass capacity to a wet anaerobic storage process, to be blended with biomass from cultivation during low production seasons, targeting a fixed throughput rate through the CAP facility all year. The wet storage concept and associated data is based on collaborations with partners at INL, who have been coordinating work on this subject over recent years [12]. In the FY 2022 SOT, the details around the storage degradation losses and compositional shifts are maintained from the latest updates included in the prior FY 2020 SOT [7] based on data from INL, including a 13% degradation loss and the production of various carboxylic acids during storage. The fresh and stored biomass compositions and acid production rates are summarized in Table 4, based on inputs from INL and extrapolated to the same HCSD strain basis assumed here. The resulting raw seasonal and post-storage biomass flowrates are depicted in Figure 2. At the 3.2:1 seasonal variability from cultivation (a slight increase relative to 2.9:1 in FY 2021), roughly 17% of total annual biomass production must be sent to seasonal storage, which—coupled with the 13% storage degradation losses—translates to a minor 2.2% overall loss of annual biomass feed to the CAP facility.

Table 4. Input Compositions to CAP Models Before and After Wet Storage Losses, Based on Raw HCSD Composition as Well as Adjustments Applied to the HCSD Baseline to Reflect Degradation Losses as Measured by INL [12] and Included in Prior SOT Reports [7, 11]

	Raw Algae	Wet Storage Algae
Solids content (wt%)	20	20
Algae composition (wt%)		
Fermentable carbohydrates	47.8	45.5
Protein	13.2	13.2
TAG	14.5	15.0
FFA	13.0	13.4
Glycerol	1.5	1.5
Ash	2.4	2.4
Non-fermentable carbohydrates	3.2	3.0
Sterol	1.8	2.4
Non-fuel polar lipid impurities	1.0	1.4
Cell mass	1.6	2.2
Sum	100.0	100.0
Whole algal biomass intact after storage (kg)	1.0	0.868
Acid produced per kg of whole algae (after storage)		
Succinic acid, kg		0.037
Lactic acid, kg		0.052
Acetic acid, kg		0.003
Propionic acid, kg		0.006

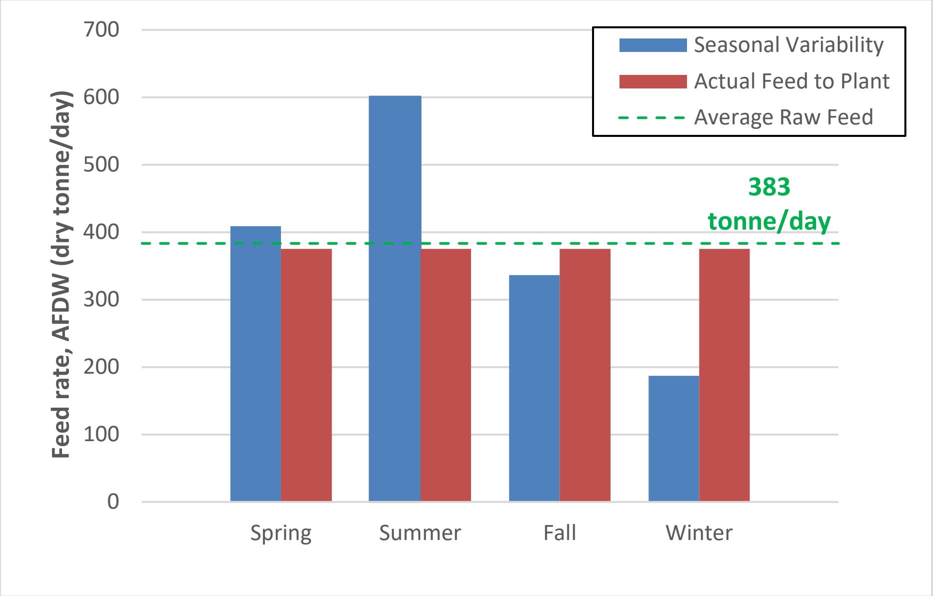

Figure 2. Seasonal and annual average feed rates to conversion facility (AFDW basis, FA evaporation scenario).

SOT basis assumes seasonal storage scenario represented by red bars (lower than annual average of blue bars due to seasonal storage losses)

Results

TEA Results

The updates discussed above (updated fermentation and catalytic upgrading parameters, along with adjusted biomass flowrates and MBSP costs from the upstream biomass production model) resulted in moderate decreases in overall MFSPs for the FY 2022 SOT. These results are summarized below in Figure 3 for the present FY 2022 SOT across both the acids and BDO fermentation pathways, and for both the ASU and FA evaporation rate assumptions under upstream biomass cultivation; analogous FY 2021 results are also shown for comparison. The results of this analysis indicate an **FY 2022 SOT MFSP of $5.99/GGE (acids pathway) or $6.28/GGE (BDO pathway) for the ASU evaporation MBSP basis, or $4.78/GGE and $5.08/GGE (acids versus BDO) for the FA evaporation basis (all results in 2016$).** Compared to the FY 2021 SOT at $6.26–$6.61/GGE for ASU evaporation or $5.04–$5.46/GGE for FA evaporation (acids vs. BDO pathways, respectively), this represents an overall MFSP decrease of 4%-7% for all cases ($0.26–$0.38/GGE). These moderate decreases can generally be attributed to increased fuel yields from carbohydrate conversions in the fermentation pathways and slightly lower MBSPs and higher biomass feed rates from the biomass cultivation facility. Fuel yields for both pathways were comparable, with values of 64.4 and 65.7 for the acids and BDO cases, respectively. In contrast to prior SOTs, the BDO case now reflects slightly higher fuel yields than the acid case, due to a proportionately higher increase in glucose utilization compared to the acids case. Fuels are fractionated into diesel- and naphtha- range blendstocks, as is consistent with prior SOTs. However, an alternative assessment was also performed to evaluate the maximum SAF potential for each pathway, defining SAF as hydrocarbons produced in the C_8-C_{16} range (as may at least be suitable for blending purposes within this boiling range) and alternating the fractionation strategy to produce SAF as a separate product beyond naphtha and diesel. Both pathway showed the potential to produce SAF as approximately two-thirds or more of the total fuel output, with no change in MFSP or overall fuel yields. The hydrocarbons produced in the acids pathway (i.e., from fermentation of algal sugars to acids and subsequent upgrading) are branched alkanes, which are better suited for SAF due to improved freeze point and related fuel properties compared to straight-chain alkanes [23-25]. In contrast, the BDO case produces primarily straight-chain alkanes at the lower end of the suitable boiling range (primarily C_8 hydrocarbons) which would be further constrained by blending limits or otherwise need to undergo further isomerization (either by improvements in current catalysts or by further reaction) to reach property specifications more suitable for jet fuel [23-25].

As noted above and consistent with prior SOTs, these values (for both MBSPs and MFSPs) are all based on the assertion of a fixed algal biomass composition consistent with NREL's HCSD future target projections (i.e., asserting an early stage of nutrient depletion with reduced protein content [13%], mid-level fatty acid methyl ester [FAME] lipid content [26%], and high carbohydrate content [48%] while meeting productivity targets associated with nutrient-replete, high-protein biomass) [4, 11]. To demonstrate the impact that a high-protein composition would have on process economics, a sensitivity case is also included which considers harvested compositions more consistent with the upstream cultivation trials. Since 2022 compositional data is not yet available at the time of this report, the composition is estimated based on previously characterized compositions of pertinent strains during their respective fractions of the year. In summary, the as-harvested biomass was estimated to contain considerably lower carbohydrate (7%) and FAME lipid (9%) content, with corresponding increased protein content (39%), which combined with an increased MBSP ($695/ton) for elevated nutrient demands would result in an MFSP of $41.55/GGE (acids pathway) or $42.27/GGE (BDO pathway) for the FA evaporation basis within the current CAP configuration. However, it is again stressed that the process design utilized here is not optimized for a high-protein biomass, with protein relegated to the production of biogas via AD. Thus, this high-protein composition is not a practical match for the current CAP configurations reflected here, and accordingly would not be run through these configurations in a realistic setting. These MFSP figures would show considerable improvement for an alternative process design optimized for such high-protein biomass (for example, an approach which valorizes residual solids as higher-value animal feed or bioplastic coproducts).

Between the two fermentation pathways, the acids pathway SOT continues to reflect a slightly lower MFSP than the BDO pathway, driven by comparable yields but 5% lower total capital costs and 2% lower operating costs (primarily reflecting lower fermentation and upgrading costs, with aqueous BDO upgrading particularly costly at the low 7.3% BDO concentration levels reflected in the present SOT). Given further improvements in BDO fermentation yields and use of more concentrated sugars (i.e., increased pretreatment sugar yields or higher sugar concentrations targeted through evaporation), the MFSP difference between the two fermentation pathways could reduce further.

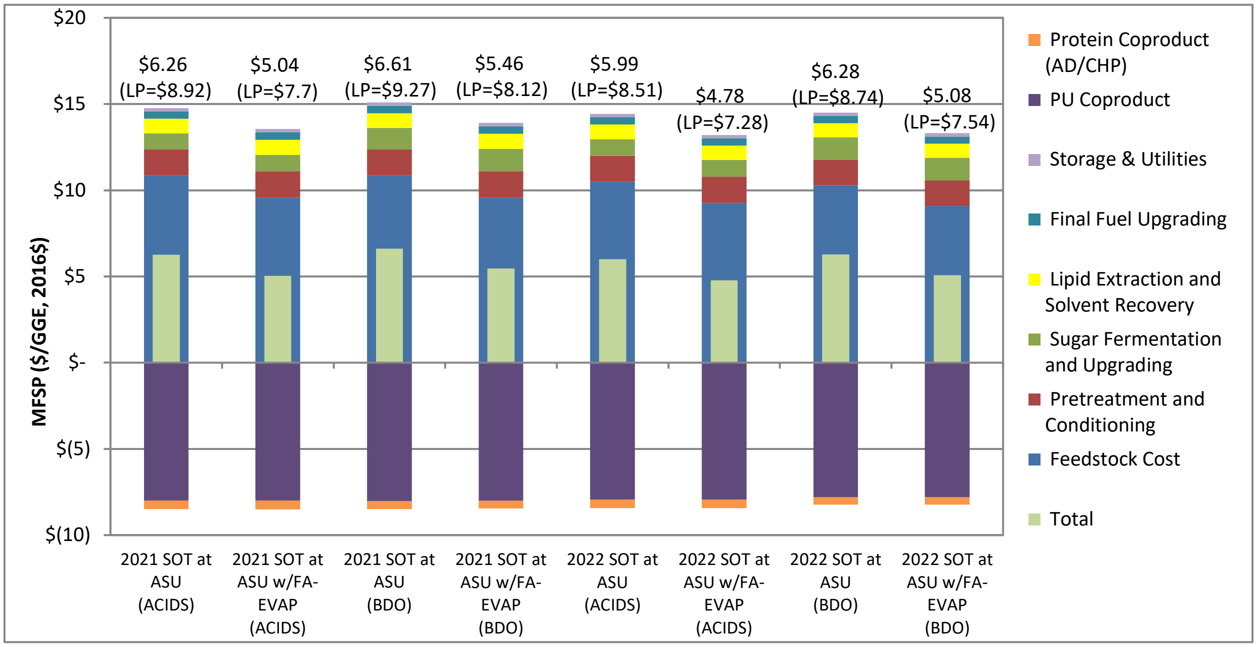

Figure 3. TEA results for 2021–2022 SOTs across both fermentation pathways (acids vs. BDO) and cultivation evaporation scenarios (ASU vs. FA evaporation MBSP).

Alternative MFSPs assuming fully lined ponds are shown in parentheses (LP = lined ponds)

Figure 4 provides the same MFSP cost breakdowns for the SOT cases as shown in Figure 3, but formatted for simplicity reflecting only the FA evaporation cases, and including example future projection scenarios for 2025 and 2030 reflecting additional process improvements for algae cultivation and conversion. The future scenarios assume continued improvement in CAP process parameters if this CAP process configuration were to be further pursued (instead of or alongside alternative CAP approaches also under consideration), and further improvements in biomass cultivation performance (discussed in the accompanying algal biomass SOT report). Specific process parameters used for each case are shown in Table 5; target improvements considered include advancements in cultivation, pretreatment, and sugar fermentation.

For simplicity, the process parameter targets associated with conversion are kept consistent between the 2025 and 2030 cases; in contrast, cultivation targets are adjusted to show incremental progress. While strictly intended to serve as *examples*, the 2025 case reflects an interim biomass yield of 29.4 ton/acre-yr (20 g/m^2/day at 330 days/year) [26]. The feedstock cost associated with these parameters is virtually equivalent to the cost for the FY 2022 SOT; therefore, improvements between the FY 2022 SOT and the 2025 target cases would largely imply moving toward achievement of the targeted biomass compositions during cultivation, coupled with targeted improvements in CAP conversion process parameters. These improvements would result in MFSPs of $3.49/GGE and $3.72/GGE for the acids and BDO cases, respectively. The final 2030 example cases demonstrate a viable path to ultimately achieve historical BETO MFSP targets of $2.5/GGE or lower, based solely on algal biomass, while capitalizing on the multi-fuel/product biorefinery concept of interest to BETO and avoiding small-market “niche” coproducts. That case assumes the same CAP processing targets as 2025 but with further reduced biomass costs tied to further improved cultivation performance. In these cases, analysis showed that diverting all TAGs to PU would result in MFSPs below the target value of $2.50/GGE ($1.84/GGE and $2.13/GGE for the acids and BDO cases, respectively). Accordingly, a portion of the TAG (9% for the acids case and 5% for the BDO case) was sent to fuels to demonstrate what would be required for future cases to meet targets of $2.50/GGE.

As discussed above, we again note here that the PU co-production bars included in Figure 4 are intended to demonstrate proof-of-concept *examples* for the ability to valorize a portion of algal lipids for high-value PU production, based to date on a better-understood TEA modeling framework reflective of isocyanate-based foam PU processing (and associated market values). Given that such technology is reasonably well understood, being pursued commercially, and makes use of toxic isocyanates, NREL experimental work is not currently investigating such PU product routes. Instead, recent NREL work has focused on a more novel carbonation/diamine cross-linking route to yield NIPU with the potential to enable fully renewable chemistries. Good initial progress has been made under that route, and we defer to the associated experimental project reports for a full accounting of that work and resultant data [27-29].

As discussed in other recent work [21, 30], we reiterate that the future projection scenarios shown in Figure 4 are by no means the only possible combinations of coproducts that support achieving less than $2.5/GGE algal fuel goals, but are initial examples that demonstrate proof of concept based on recent activities to select these products for further TEA consideration. It also should be noted that CAP R&D is simultaneously investigating other alternate processing routes, including additional pretreatment approaches [31], fermentation of high-protein and high-carbohydrate hydrolysates to other fuel and coproduct precursors [2, 10], as well as alternative valorization approaches for the residual solids [32, 33]. While the analysis of these options is less exhaustive than that of PU, they may still serve as alternate routes to achieving MFSP targets, especially for more challenging, high-protein feedstocks, which we intend to begin incorporating into future TEA studies.

Finally, Table 5 provides key technical and cost details associated with the various cases presented in Figure 4. This table shows that room for improvement continues to exist moving forward beyond the current SOT baseline, particularly with respect to cultivation productivity (35% improvement), but also for key cost drivers in CAP conversion based on the current configuration, including pretreatment sugar yields (8% improvement) and sugar fermentation/upgrading yields (4% improvement in both the acids [targeting butyric acid exclusively] and BDO pathways). Lipid extraction and upgrading yields are based on experimental data and have essentially achieved final target levels, but further room for improvement exists (i.e., around catalyst robustness and resistance to deactivation in the presence of heteroatoms in the extractable oils). Polyurethane conversion is based on complete conversion in epoxidation and ring opening, with foam production inputs consistent with mature technology, so it is also unlikely to contribute to further SOT improvements; however, advancements in the production of NIPUs could support a fully sustainable coproduct strategy, potentially at similar or decreased costs [29]. Polyurethane production costs/revenues may also vary depending on the final functionality of the product (e.g., flexible foam, rigid foam, or coatings/adhesives/sealants/elastomers).

Note that the "conversion" contribution to MFSP for all cases in Table 5 reflects the net sum of all conversion process costs ("positive" bars in Figure 4) combined with the coproduct processing costs and revenues ("negative" bars in Figure 4); thus, the conversion MFSP values on the order of negative $4/GGE or more for the future projection cases indicate that all non-feedstock conversion costs are outweighed by larger coproduct revenues, as required to compensate for high biomass costs inherent to microalgae farming. Finally, moving forward, other alternative CAP configurations may be further investigated as well, including the alternative CAP approaches discussed previously or other variants that may support higher-protein algal biomass feedstocks.

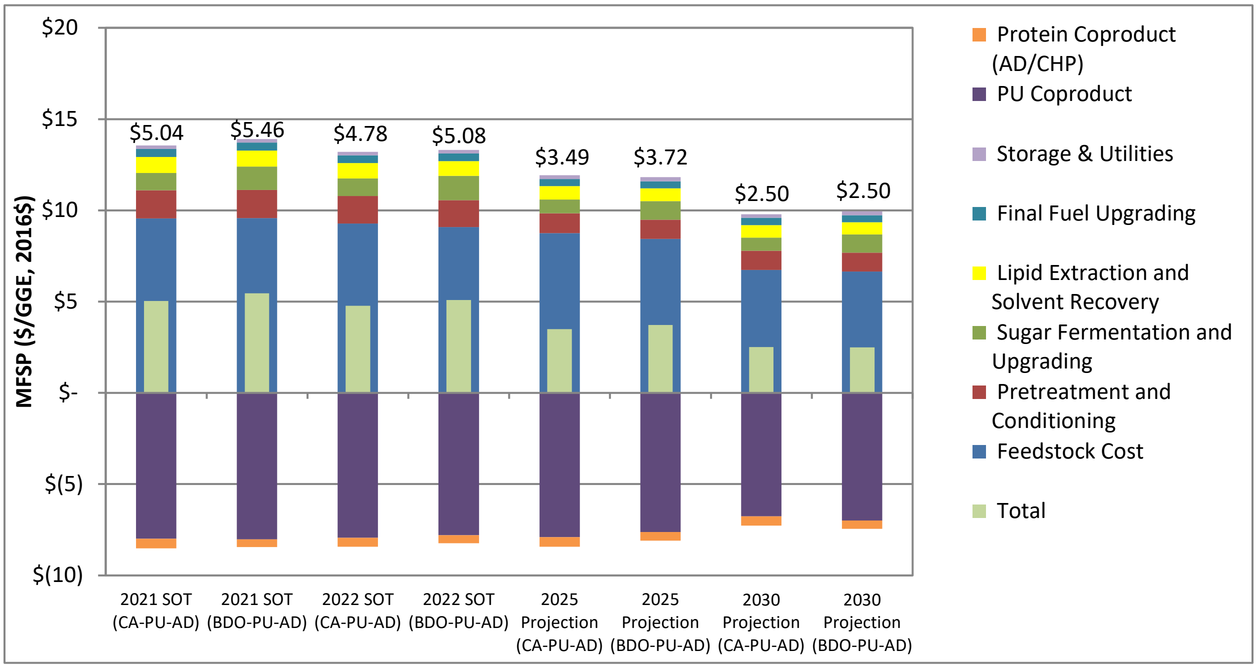

Figure 4. Summary of MFSP cost breakdowns for SOTs and future example projection scenarios (FA evaporation scenarios).

CA = sugar fermentation/upgrading to fuels via carboxylic acid intermediates; BDO = sugar fermentation/upgrading to fuels via 2,3-BDO intermediates; PU = polyurethanes derived from triglyceride fraction of lipids; all cases currently assume AD of protein residues, reflecting CAP configuration as depicted in Figure 1; 2030 cases are intentionally set to $2.50/GGE by varying the ratio of lipids sent to fuel vs. PU

Table 5. Technical Overview Table for Cost and Process Metrics Associated with FY 2021–2022 SOT Cases, Compared to Example 2030 Projection Scenarios. SOT Cases Only Reflect FA Evaporation Scenarios for Simplicity. Red text indicates a net negative contribution to the MFSP due to the inclusion of coproduct revenues which exceed conversion and coproduct processing costs.

Metric	2021 SOT (Acids-PU) – FA Evap	2021 SOT (BDO-PU) – FA Evap	2022 SOT (Acids-PU) – FA Evap	2022 SOT (BDO-PU) – FA Evap	2025 Projection (Acids-PU)	2025 Projection (BDO-PU)	2030 Projection (Acids-PU)	2030 Projection (BDO-PU)
MFSP ($/GGE, 2016$)[a]	$5.04 [$7.70]	$5.46 [$8.12]	$4.78 [$7.28]	$5.08 [$7.54]	$3.49	$3.72	$2.50	$2.50
Feedstock Contribution ($/GGE, 2016$)[a]	$9.56 [$12.22]	$9.57 [$12.23]	$9.27 [$11.78]	$9.09 [$11.55]	$8.75	$8.44	$6.74	$6.65
Conversion Contribution ($/GGE, 2016$)[a]	($4.52) [($4.52)]	($4.11) [($4.11)]	($4.50) [($4.50)]	($4.01) [($4.01)]	($5.25)	($4.72)	($4.24)	($4.15)
Yield (GGE/ton AFDW)	63.4	63.3	64.4	65.7	68.3	70.8	71.7	72.7
Renewable Diesel Blend-Stock Yield (GGE/ton AFDW)	45.5	41.0	46.2	42.2	48.9	45.0	51.5	46.6
Naphtha Yield (GGE/ton AFDW)	17.9	22.3	18.2	23.5	19.4	25.7	20.2	26.2
Finished Fuel Products Yield (GGE/acre/yr)	1,631	1,629	1,798	1,835	2,494	2,587	2,619	2,658
C Yield to Fuels from Biomass	31.1%	30.8%	31.7%	32.1%	32.8%	33.8%	34.5%	34.7%
C Yield to Coproducts from Biomass (algal carbon only)	20.6%	20.6%	20.6%	20.6%	20.5%	20.5%	18.6%	19.4%
Feedstock								
Feedstock Cost ($/ton AFDW)[a]	$611 [$781] [b]	$611 [$781] [b]	$602 [$765] [b]	$602 [$765] [b]	$602	$602	$488	$488
Year-Average Cultivation Productivity (g/m^2/day AFDW)	17.6	17.6	18.5	18.5	20	20	25	25
Max Seasonal Variability (max:min productivity)	2.9:1	2.9:1	3.2:1	3.2:1	3.0:1	3.0:1	3.0:1	3.0:1
Harvested Biomass Lipid Content (dry wt% as FAME)	26% [b]	26% [b]	26% [b]	26% [b]	26%	26%	26%	26%
Harvested Biomass Concentration (g/L AFDW)	0.37	0.37	0.35	0.35	0.5	0.5	0.5	0.5
Pretreatment + Conditioning								
Solids Loading (wt%)	20% [c]	20% [c]	20% [c]	20% [c]	20%	20%	20%	20%
Acid Loading (wt% versus feed water rate)	2%	2%	2%	2%	1%	1%	1%	1%
Fermentable Sugar Release (“glucose yield”)	83%	83%	83%	83%	90%	90%	90%	90%
Glucan to Degradation Products	1.5%	1.5%	1.5%	1.5%	0.3%	0.3%	0.3%	0.3%
Hydrolysate Solid-Liquid Separation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Metric	**2021 SOT (Acids-PU) – FA Evap**	**2021 SOT (BDO-PU) – FA Evap**	**2022 SOT (Acids-PU) – FA Evap**	**2022 SOT (BDO-PU) – FA Evap**	**2025 Projection (Acids-PU)**	**2025 Projection (BDO-PU)**	**2030 Projection (Acids-PU)**	**2030 Projection (BDO-PU)**
Sugar Fermentation + Catalytic Upgrading								
Fermentation Productivity (g/L-h)	0.3	1.3 (56-h batch time)	0.54	0.81 (96-h batch time)	2.0	2.0 (36-h batch time)	2.0	2.0 (36-h batch time)
Product titer (g/L)	N/A [d]	73	N/A [d]	78	N/A [d]	90	N/A [d]	90
Glucose to Product [e]	92%	89%	95%	99%	95%	95%	95%	95%
Mannose to Product [e]	92%	89%	92%	89%	95%	95%	95%	95%
Glycerol to Product [e]	92%	0%	92%	0%	95%	95%	95%	95%
Overall Fermentation Yield to Product (g/g total sugars) [e]	0.48	0.43	0.48	0.46	0.50	0.48	0.50	0.48
Catalytic Upgrading Carbon Yield to HDO Feed [f]	83%	98%	83%	98%	83%	98%	83%	98%
Lipid Processing								
Solvent Loading (nonpolar:EtOH:dry biomass ratio, wt)	2.7:1.1:1	2.7:1.1:1	2.7:1.1:1	2.7:1.1:1	2.7:1.1:1	2.7:1.1:1	2.7:1.1:1	2.7:1.1:1
Total Convertible Lipid Extraction Yield	96%	96%	96%	96%	96%	96%	96%	96%
Lipid Impurity Partition to Extract	<11.5%	<11.5%	<11.5%	<11.5%	<11.5%	<11.5%	<11.5%	<11.5%
Fuel Finishing Renewable Diesel Blend-Stock Yield (wt% of total feed) [g]	64.4%	56.6%	64.5%	56.3%	64.5%	55.8%	64.3%	56.0%
Fuel Finishing Naphtha Yield (wt% of total feed) [g]	25.3%	30.5%	25.4%	31.0%	25.6%	31.6%	25.3%	31.2%
Fuel Finishing H_2 Consumption (wt% of total feed) [g]	2.6%	2.2%	2.6%	2.2%	2.6%	2.2%	2.6%	2.2%
Polyol/Polyurethane Production								
Polyurethane yield from TAG (w/w TAG) [h]	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60
% TAG Diversion to Polyurethane Coproduct (%)	100%	100%	100%	100%	100%	100%	91%	95%
Overall Polyurethane Yield from Algae (wt% AFDW)	22.4%	22.4%	22.4%	22.4%	22.4%	22.4%	20.8%	21.6%
Protein/Stillage Processing								
N/P Recycle to Ponds (% of biomass feed to CAP)	100%/73%	100%/51%	100%/72%	100%/53%	100%/73%	100%/54%	100%/73%	100%/53%
AD Biogas Yield (L CH_4/g TS)	0.23	0.22	0.23	0.22	0.26	0.25	0.26	0.25

[a] First values represent unlined pond base case; values in brackets represent fully lined pond scenario

[b] SOT based on ASU production of *Monoraphidium*, *Tetraselmis*, and/or *Picochlorum* (as applicable) overlaid with target HCSD composition

[c] Experimental work conducted at pretreatment solids content varying around 20%, expected to perform the same as 20%

[d] Acids fermentation case based on continuous *in situ* acid removal across pertractive membrane

[e] "Product" refers to acetic/butyric acids for the acids case and 2,3-BDO and acetoin for the BDO case

[f] Represents overall catalytic upgrading yield of fermentation intermediates (after recovery) through feed to final fuel finishing (hydrotreating) step

[g] Final "fuel finishing" step is a combined hydrotreater to upgrade lipids plus the final intermediate from the sugar conversion train

[h] Only includes TAG utilized for PU production.

Sustainability Metric Indicators

In addition to the TEA results noted above, here we also report on associated sustainability "indicators" attributed to the algae CAP SOT model. In keeping with recent BETO guidance for all formal life cycle assessment sustainability metrics to be handled by Argonne National Laboratory to ensure no inconsistencies in such metrics versus NREL-calculated values (i.e., using the Greenhouse gases, Regulated Emissions, and Energy use in Technologies [GREET] model versus SimaPro), we avoid reporting on life cycle assessment parameters such as greenhouse gas emissions or fossil energy consumption in this report (but are currently working to provide the input/output inventories to partners at Argonne National Laboratory). Instead, Table 6 summarizes key sustainability indicators as may be taken directly from the process model. Namely, for the CAP conversion SOT, this includes mass and carbon yield to fuels, carbon yield to coproducts, facility power and natural gas demands, and freshwater demands for the conversion process. While most of the parameters are fairly comparable between the two pathways, the BDO pathway requires more heat and thus a higher natural gas import, which is co-fired in the AD biogas turbine, but which in turn also leads to more power generation through the turbine that translates to a larger net power export versus the acids pathway. The process input/output inventories furnished to Argonne National Laboratory for subsequent life cycle assessment supply chain sustainability analysis (SCSA) are summarized in Appendix B.

Table 6. Sustainability Indicators for the FY 2022 SOT CAP Models

		FY 2022 SOT Fermentation Pathway	
Parameter		**Acids**	**BDO**
Fuel Yield by Weight of Biomass	GGE per dry ton biomass	64.4	65.7
Carbon Efficiency to Fuels	% of algal C used	31.7	32.1
Carbon Efficiency to Coproduct	% of algal C used	20.6	20.6
Electricity Import/Export	kWh/GGE	−4.44 (export)	−5.05 (export)
Natural Gas Import	MJ/GGE	97	156
Water Consumption [a]	m^3/day	1,575	2,495
Water Consumption [a]	gal/GGE	15.3	23.7

[a] Reflects freshwater makeup for the CAP process, independent of water recycle to cultivation facility

Concluding Remarks

The updates incorporated into the SOT benchmark models translate to an **estimated FY 2022 SOT minimum fuel selling price of $5.99/GGE (acids pathway) or $6.28/GGE (BDO pathway) for the ASU evaporation MBSP basis, or $4.78/GGE and $5.08/GGE (acids versus BDO) for the FA evaporation basis (all results in 2016$)** for the unlined pond base case. SOT fuel costs for the alternative fully lined pond scenario would increase to $8.51/GGE or $8.74/GGE for the acids and BDO cases, respectively, under baseline ASU evaporation rates.

Relative to the prior FY 2021 SOT, the outputs from the FY 2022 MFSP are moderately improved, at a roughly 4%-7% decrease in overall modeled MFSP for either fuel pathway. This is primarily a reflection of improved fermentation and upgrading parameters (tied to a $0.12-$0.24/GGE decrease in MFSP for the acids and BDO cases, respectively) and improved cultivation productivity upstream (tied to a $0.14/GGE decrease in MFSP for both cases). Between the two sugar fermentation pathways for intermediate fuel precursor production, the acids pathway continues to indicate slightly lower MFSPs in the present SOT (roughly $0.3/GGE lower for acids than BDO), primarily due to slightly higher capital and operating costs associated with the processing and upgrading of aqueous BDO.

As discussed in prior SOT reports, to increase yields and reduce MFSP cost on the conversion side of the CAP configuration reflected here, further room exists to optimize pretreatment conditions and improve fermentable sugar yields (i.e., carbohydrate hydrolysis to monomeric sugars and fermentation yield to butyric acid or BDO). Though in light of recent findings discussed in the FY 2021 SOT for the pretreatment technology scan across multiple algae species [11], pretreatment efficacy so far appears limited to a level somewhat below 2030 targets at 83% instead of the 90% target (also somewhat species/biomass-source dependent, as may necessitate optimized conversion approaches – albeit with lower variation that has been observed amongst high-protein strains). Similarly, lipid extraction and upgrading yields have been demonstrated near their final goals for the HCSD strain modeled here but are also dependent on species and biomass composition. Further opportunities exist to demonstrate these levels of lipid yields across different strains and compositions. Additionally, further room for improvement exists around improving catalyst stability and activity for HDO plus HI functionalities in the presence of algal lipid impurities, and on better understanding ramifications on hydrotreater design for co-processing both lipids and the final intermediate compounds from sugar train upgrading through the same fuel finishing reactor.

Polyurethane production costs are unlikely to change significantly due to the relatively mature technology for conventional polyurethane production; however, recent advancements in NIPU research likely warrant inclusion in future TEA updates. First, a better understanding of key processing design/cost considerations is required, as well as product applications and price values for such a material. Based on separate TEA analysis, it is possible that NIPU could be produced at a lower cost than conventional PU given lower costs for diamine than isocyanate cross-linker agents, with preferable implications on safety, environmental, and sustainability aspects. Such benefits may even justify a higher selling price for NIPUs, which would further close the gap between SOT cost estimations and future targets. Costs may also change depending on the consideration of alternative PU/NIPU products, such as rigid foams or coatings/adhesives/sealants/elastomers.

Despite comprehensive experimental work focused on evaluating numerous alternative approaches to fermentation, protein valorization, and NIPU co-production, no further improvements were made within the SOT process design framework that would lead to further MFSP reductions beyond those documented here. However, advancements in these alternative approaches will be imperative for demonstrating economically viable fuel production from proteinaceous algal biomass. Future experimental plans will continue investigating alternative CAP processing schemes for different algal biomass compositions, including more optimal uses of algal protein. Experimental work so far in this area has demonstrated reasonable yields for solubilizing both proteins and carbohydrates, but has shown challenges associated with conversion of solids. Moving forward, a number of options will continue to be pursued to better understand and optimize such processing steps, and additionally to consider modifications to the process to accommodate and better valorize high-protein biomass. Those efforts would provide important “risk mitigation” strategies for the CAP pathway if the targeted HCSD-type compositions could not be achieved as projected and instead cultivation trials continued to produce higher-protein/lower-lipid biomass for the foreseeable future. In all cases involving high-protein biomass, inclusion of one or more value-added coproducts with sufficiently large market volumes, as feasible to derive from high-protein content biomass, will continue to be a central element for achieving BETO goals of economically feasible algal biofuels while supporting commodity-scale deployment of such algal biorefinery concepts.

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Appendix A. TEA Summary Sheet for Base Case CAP SOT Benchmark Model

Acids Case (FA Evaporation MBSP Scenario, 2016$)

Combined Algal Processing to Fuels and Bioproducts Process Engineering Analysis

Cost Year Basis: 2016 $

MFSP (Gasoline Equivalent Basis): $4.78 /GGE

Contributions: Feedstock $9.27 /GGE
Conversion -$4.50 /GGE

Total Fuel Production (RDB + Naphtha + Ethanol): 8.99 MMGGE/yr

RDB Production: 6.45 MMGGE/yr
Naphtha Production: 2.54 MMGGE/yr
Ethanol Production: 0.00 MMGGE/yr
Total Fuel Yield (RDB + Naphtha + Ethanol: 64.41 GGE / dry U.S. ton feedstock
Feedstock Cost: $602 dry U.S. Ton algal biomass (ash free)
Internal Rate of Return: 10%
Equity Percent of total Investment: 40%

Capital Costs	
A100: Pretreatment and Conditioning	$25,200,000
A200: Carboxylic Acid Fermentation and Distillation	$15,900,000
A200: 2,3-BDO Fermentation and Upgrading	$0
A300: Lipid Extraction and Separation	$17,100,000
A400: Product Purification and Upgrading	$4,700,000
A500: Protein/Residual Processing	$4,800,000
A600: Combined Heat and Power	$6,600,000
A700: Utilities & Storage	$3,400,000
Total Installed Equipment Cost	$77,700,000
Added Direct + Indirect Costs	$216,300,000
(% of TCI)	73.57%
Total Capital Investment (TCI)	$294,000,000
Installed Equiptment Cost/Annual GGE	$8.64
Total Capital Investment/Annual GGE	$32.70
Loan Rate	8%
Term(years)	10
Capital Charge Factor (Computed)	0.081
Carbon Retention Efficiencies:	
Total Carbon Efficiency to Fuel and Products	59.8%
(Fuel C/Biomass C)	
RDB (RDB C/Biomass C)	22.8%
Naphtha (Naphtha C/Biomass C)	8.9%
Polyurethane (total C in PU/Biomass C)	28.2%
Polyurethane (algal C in PU/Biomass C)	20.6%

Fuel Yields	
RDB Production (U.S. ton/yr)	19,857
Naphtha Production (U.S. ton/yr)	7,820

Manufacturing Costs (cents/GGE)	
Feedstock	927.3
Pretreatment Chemicals	48.3
A200 chemicals	27.2
Lipid Extraction and Cleanup Chemicals	21.3
Hydrogen	15.2
Polyurethane Inputs	343.4
Supplemental Natural Gas	42.8
Remaining Raw Materials	2.0
Coproduct Credits	-1395.1
Other Credits (recycled nutrients, etc.)	-85.6
Exported Electricity	-25.4
Catalysts	6.3
Fixed Costs	127.7
Capital Depreciation	103.4
Average Income Tax	31.7
Average Return on Investment	287.2

Manufacturing Costs ($/yr)	
Feedstock	$83,400,000
Pretreatment Chemicals	$4,300,000
A200 chemicals	$2,400,000
Lipid Extraction and Cleanup Chemicals	$1,900,000
Hydrogen	$1,400,000
Polyurethane Inputs	$30,900,000
Supplemental Natural Gas	$3,800,000
Remaining Raw Materials	$200,000
Coproduct Credits	-$125,400,000
Other Credits (recycled nutrients, etc.)	-$7,700,000
Exported Electricity	-$2,300,000
Catalysts	$600,000
Fixed Costs	$11,500,000
Capital Depreciation	$9,300,000
Average Income Tax	$2,900,000
Average Return on Investment	$25,800,000

BDO Case (FA Evaporation MBSP Scenario, 2016$)

Combined Algal Processing to Fuels and Bioproducts Process Engineering Analysis

	Cost Year Basis:	2016 $
	MFSP (Gasoline Equivalent Basis):	**$5.08 /GGE**
Contributions:	Feedstock	$9.09 /GGE
	Conversion	-$4.01 /GGE

Total Fuel Production (RDB + Naphtha + Ethanol):	9.17 MMGGE/yr
RDB Production:	5.90 MMGGE/yr
Naphtha Production:	3.28 MMGGE/yr
Ethanol Production:	0.00 MMGGE/yr
Total Fuel Yield (RDB + Naphtha + Ethanol:	65.71 GGE / dry U.S. ton feedstock
Feedstock Cost:	$602 dry U.S. Ton algal biomass (ash free)
Internal Rate of Return:	10%
Equity Percent of total Investment:	40%

Capital Costs	
A100: Pretreatment and Conditioning	$25,200,000
A200: Carboxylic Acid Fermentation and Distillation	$0
A200: 2,3-BDO Fermentation and Upgrading	$23,300,000
A300: Lipid Extraction and Separation	$17,100,000
A400: Product Purification and Upgrading	$5,000,000
A500: Protein/Residual Processing	$4,100,000
A600: Combined Heat and Power	$8,400,000
A700: Utilities & Storage	$3,500,000
Total Installed Equipment Cost	$86,600,000
Added Direct + Indirect Costs	$224,400,000
(% of TCI)	72.15%
Total Capital Investment (TCI)	$311,000,000
Installed Equiptment Cost/Annual GGE	$9.44
Total Capital Investment/Annual GGE	$33.90
Loan Rate	8%
Term(years)	10
Capital Charge Factor (Computed)	0.079
Carbon Retention Efficiencies:	
Total Carbon Efficiency to Fuel and Products	60.2%
(Fuel C/Biomass C)	
RDB (RDB C/Biomass C)	20.8%
Naphtha (Naphtha C/Biomass C)	11.3%
Polyurethane (total C in PU/Biomass C)	28.2%
Polyurethane (algal C in PU/Biomass C)	20.6%

Fuel Yields	
RDB Production (U.S. ton/yr)	18,151
Naphtha Production (U.S. ton/yr)	9,992

Manufacturing Costs (cents/GGE)	
Feedstock	908.8
Pretreatment Chemicals	47.4
A200 chemicals	27.5
Lipid Extraction and Cleanup Chemicals	20.8
Hydrogen	13.6
Polyurethane Inputs	336.5
Supplemental Natural Gas	68.8
Remaining Raw Materials	3.1
Coproduct Credits	-1367.4
Other Credits (recycled nutrients, etc.)	-94.4
Exported Electricity	-28.9
Catalysts	5.6
Fixed Costs	128.9
Capital Depreciation	106.8
Average Income Tax	32.9
Average Return on Investment	298.1

Manufacturing Costs ($/yr)	
Feedstock	$83,400,000
Pretreatment Chemicals	$4,300,000
A200 chemicals	$2,500,000
Lipid Extraction and Cleanup Chemicals	$1,900,000
Hydrogen	$1,200,000
Polyurethane Inputs	$30,900,000
Supplemental Natural Gas	$6,300,000
Remaining Raw Materials	$300,000
Coproduct Credits	-$125,400,000
Other Credits (recycled nutrients, etc.)	-$8,700,000
Exported Electricity	-$2,600,000
Catalysts	$500,000
Fixed Costs	$11,800,000
Capital Depreciation	$9,800,000
Average Income Tax	$3,000,000
Average Return on Investment	$27,300,000

Appendix B. Life Cycle Inventory for 2022 CAP SOT Models

Acids Case: SOT input and output inventory data for the modeled CAP process. Resource consumption is allocated by product when possible. (Note: hourly rates are based on annual averages over all modeled seasons.)

Allocation	Products	kg/h	MMkcal/h
Fuel	Diesel	2274	23.82
Fuel	Naphtha	896	9.38
PU	Polyurethane	3593	
Fuel+PU	Power exported to grid, kW	5045	

Allocation	Resource Consumption	kg/h
Fuel+PU	Feedstock (AFDW basis)	15987
	Pretreatment	
Fuel+PU	Sulfuric acid (93% pure)	1420
Fuel+PU	Ammonia	459
	Lipid Extraction and Cleanup	
Fuel+PU	Hexane	84
Fuel+PU	Ethanol	34
Fuel+PU	Phosphoric acid (oil cleanup)	46
Fuel+PU	Silica (oil cleanup)	5
Fuel+PU	Clay (oil cleanup)	9
	Carboxylic Acid Conversion	
Fuel	Corn steep liquor	721
Fuel	Diammonium phosphate	75
Fuel	Hydrotalcite	1
Fuel	Flocculant	64
Fuel	Hexane	1
Fuel	Ketonization catalyst (ZrO_2)	0
Fuel	Condensation catalyst (niobic acid)	0
	Final Fuel Upgrading (HDO/HI)	
Fuel	Hydrogen	107
Fuel	One-step HDO/HI catalyst (1% Pt/SAPO-11)	0.23
	Polyurethane Production	
PU	Formic acid	347
PU	H_2O_2	549
PU	Nitrogen	52
PU	Toluene diisocyanate	953
PU	Diethanolamine	9
PU	Surfactant	17
PU	Tin catalyst (stannous octoate)	6

PU	DABCO (1,4-diazabicyclo[2.2. 2]octane)	3
	Other Resource Consumption	
	Supplemental natural gas (total)	1977
Fuel+PU	Supplemental natural gas (fuel+PU)	944
Fuel	Supplemental natural gas (fuel)	120
PU	Supplemental natural gas (PU)	914
	Process water (total)	65643
Fuel+PU	Process water (fuel+PU)	47769
Fuel	Process water (fuel)	100
PU	Process water (PU)	17774
Allocation	**Output Streams**	**kg/h**
Fuel+PU	AD digestate cake (dry basis total flow)	3479
Fuel+PU	AD digestate cake bioavailable N	19
Fuel+PU	AD effluent NH_3	233
Fuel+PU	AD effluent diammonium phosphate	110
Fuel+PU	Recycle water (excluding N/P nutrients)	104969
	Direct Air Emissions	
Fuel+PU	H_2O	35306
	CO_2 Recycle	
Fuel+PU	CO_2 (biogenic)	9090
Fuel+PU	CO_2 (fossil)	5986
Allocation	**Biomass Loss from Storage**	**kg/h**
	Algae biomass loss from wet storage	357

BDO Case: SOT input and output inventory data for the modeled CAP process. Resource consumption is allocated by product when possible. (Note: hourly rates shown based on annual averages over all modeled seasons.)

Allocation	Products	kg/h	MMkcal/h
Fuel	Diesel	2079	21.77
Fuel	Naphtha	1144	12.10
PU	Polyurethane	3593	
Fuel+PU	Power exported to grid, kW	5846	

Allocation	Resource Consumption	kg/h
Fuel+PU	Feedstock (AFDW basis)	15987
	Pretreatment	
Fuel+PU	Sulfuric acid (93% pure)	1420
Fuel+PU	Ammonia	459
	Lipid Extraction and Cleanup	
Fuel+PU	Hexane	84
Fuel+PU	Ethanol	34
Fuel+PU	Phosphoric acid (oil cleanup)	46
Fuel+PU	Silica (oil cleanup)	5
Fuel+PU	Clay (oil cleanup)	9
	2,3-BDO Conversion	
Fuel	Corn steep liquor	107
Fuel	Diammonium phosphate	13
Fuel	Hydrogen	89
Fuel	Flocculant	64
Fuel	Dehydration catalyst	0.07
Fuel	Oligomerization catalyst	0.13
	Final Fuel Upgrading (HDO/HI)	
Fuel	Hydrogen	97
Fuel	One-step HDO/HI catalyst (1% Pt/SAPO-11)	0.25
	Polyurethane Production	
PU	Formic acid	347
PU	H_2O_2	549
PU	Nitrogen	52
PU	Toluene diisocyanate	953
PU	Diethanolamine	9
PU	Surfactant	17
PU	Tin catalyst (stannous octoate)	6
PU	DABCO (1,4-diazabicyclo[2.2. 2]octane)	3
	Other Resource Consumption	
	Supplemental natural gas (total)	3245
Fuel+PU	Supplemental natural gas (fuel+PU)	1280
Fuel	Supplemental natural gas (fuel)	756

PU	Supplemental natural gas (PU)	1210
	Process water (total)	103954
Fuel+PU	Process water (fuel+PU)	54374
Fuel	Process water (fuel)	31814
PU	Process water (PU)	17766
Allocation	**Output Streams**	**kg/h**
Fuel+PU	AD digestate cake (dry basis total flow)	3341
Fuel+PU	AD digestate cake bioavailable N	18
Fuel+PU	AD effluent NH_3	228
Fuel+PU	AD effluent diammonium phosphate	81
Fuel+PU	Recycle water (excluding N/P nutrients)	107210
	Direct Air Emissions	
Fuel+PU	H_2O	40822
	CO_2 Recycle	
Fuel+PU	CO_2 (biogenic)	8981
Fuel+PU	CO_2 (fossil)	9467
Allocation	**Biomass Loss from Storage**	**kg/h**
	Algae biomass loss from wet storage	357

Appendix C. Industry Case Study

To supplement the SOT discussion presented in this report, a separate industry case study was also assessed as described herein, reflecting an alternative scenario for algal biomass cultivation and conversion. This scenario is based on data furnished to NREL by Viridos, a commercial company pursuing algal biofuel production utilizing genetically engineered strains targeting high-lipid *and* high-productivity cultivation (i.e., maximizing "lipid productivity" as a combination of these factors). The Viridos approach seeks to overcome the traditionally conflicting tradeoffs between nutrient-replete cultivation promoting high biomass growth rates (reducing biomass production costs but at the expense of compositional quality) versus nutrient-deplete cultivation promoting lipid enrichment (high-lipid compositional quality but at the expense of lower growth rates and higher biomass production costs). Viridos has operationalized their approach by combining a two-stage pond system employing sequential "growth" and "induction" phases with the use of engineered strains which do not suffer the same degree of penalty on overall biomass productivity when shifting to lipid accumulation as other strains do.

In contrast, the DISCOVR cultivation trials that inform the SOT inputs focused primarily on maximizing biomass productivity rates under nutrient-replete, high-protein/low-lipid conditions (upon which an asserted target composition is assumed as discussed in the accompanying SOT report). As such, this industry case study provides a real-world reference point to highlight economic implications via NREL's TEA model framework for cultivation performance capable of achieving favorable lipid productivity rates today based on Viridos data. This case study, however, is *not* intended to represent actual Viridos company economics, nor Viridos business plans for subsequent biomass conversion, as such information is proprietary and was not made available to NREL.

Details on the biomass cultivation portion of the industry case study can be found in Appendix C of the accompanying FY 2022 algae cultivation SOT report [22]. Two Viridos cultivation scenarios were considered, each based on average data from three separate runs spanning June through September 2022. The first scenario assumes the experimentally demonstrated productivity is only met during the summer season and extrapolates other seasonal productivities using the same seasonal ratios as the SOT basis, while the other fixes the summer productivity as an annual value achievable all year. The former scenario was included to provide a more direct comparison against the SOT basis (i.e., assuming the algae farm is sited in a similar location with similar seasonal solar irradiance and temperature variations to estimate what the remaining seasonal productivities might be [though stressing the remaining seasons are *not* based on Viridos-supplied data]), while the latter scenario reflects Viridos guidance on what they feel is attainable in other locations, potentially outside the U.S., where such climatic conditions may be more optimal year-round as could sustain this productivity value on an annual basis. The average biomass compositional data for these runs are shown in Table S1 along with the average productivity and calculated MBSP as presented in Appendix C of the FY 2022 algae cultivation SOT report [22]; relevant data for the SOT case is also included, again reiterating that the SOT basis reflects the asserted HCSD composition, recognizing the SOT MBSP would increase by $94/ton (to $696/ton) if instead using the composition as-harvested from the DISCOVR cultivation trials.

Table S1. Biomass compositional data and algae cultivation results for the industry case study. Additional details can be found in Appendix C of the FY 2022 algae cultivation SOT report [22]. All cases assume biomass cultivation in minimally lined ponds with FA-based evaporation rates. Inputs and results for the FY22 SOT case, based on the target HCSD composition, are also shown for comparison.

		FY22 SOT (Target HCSD composition, seasonal variation)	Viridos (Seasonal variation)	Viridos (Fixed productivity)
Component Composition (dry wt)				
	Ash	2.4%	26.7%	
	Protein	13.2%	8.0%	
	FAME lipids	29.0%	27.1%	
	Non-FAME/polar lipids	2.8%	-	
	Total carbohydrates	51.0%	8.3%	
	Cell mass/"other"	1.6%	30.0%	
Lipid only productivity at harvest (g/m^2/day FAME lipids) [a]		5.50	5.28	8.27
Annual average productivity (g/m^2/day AFDW)		18.5	14.3	22.4
Minimum biomass selling price ($/ton AFDW)		602	709	495

[a] Snapshot of lipid productivity on the final day of induction (AFDW biomass productivity x AFDW lipid content at harvest). See Table S1 in Appendix C of the FY 2022 algae cultivation SOT report [22] for further details and corresponding values for “max lipid productivity” achieved following 5 or more days of induction, as reported by Viridos.

To assess the economic implications of downstream processing of the Viridos biomass, outputs from the algae cultivation models were used in combination with the CAP conversion framework. The conversion process design was identical to that used for the SOT case (Figure 1) including dilute acid pretreatment, fermentation and upgrading of carbohydrates to fuels (for simplicity only reflecting the acids intermediate pathway), extraction and upgrading of lipids to fuels and a polyurethane coproduct, and anaerobic digestion of the remaining biomass. A seasonal storage step was also maintained for the seasonal variation case; however, it was not required for the fixed productivity case because biomass rates were asserted to be fixed year-round. Also consistent with the SOT case, lipids were assumed to be present as 50% TAG (upgraded to polyurethanes) and 50% FFA (upgraded to fuels).

Results for the industry case study are shown in Table S2. An MFSP of $7.69/GGE was estimated for the Viridos seasonal variation case, which could further improve substantially to an MFSP of $1.35/GGE for the Viridos fixed productivity scenario. For context, these can be compared to an MFSP of $4.78/GGE for the FY 2022 acids SOT case, which pairs demonstrated seasonal DISCOVR productivity data with a target HCSD composition elevated in both carbohydrates and lipids as discussed in the preceding report. The somewhat lower MFSP for the SOT case is driven by a correspondingly higher fuel yield enabled by the elevated HCSD carbohydrate fraction, at otherwise comparable lipid levels. Alternatively, if the as-harvested composition of the SOT biomass is used based on lower carbohydrate/lipid and higher protein content under the nutrient-replete conditions used in the DISCOVR cultivation trials (see Table 3 of the accompanying FY 2022 algae cultivation SOT report [22]), an MFSP of $41.55/GGE would be observed (recognizing that is not a practical composition to be paired with this CAP conversion approach, as discussed in the main body of this report). It should be noted that the optimal process design may vary depending on composition (for example, including a fermentation step may not make sense for compositions low in carbohydrates such as the Viridos composition or the as-harvested SOT composition); however, the above values reflect maintaining the same conversion process in all cases for consistency. These results highlight key advancements made in industry towards demonstrating comparable biomass productivities relative to the SOT while simultaneously achieving more favorable biomass compositions optimized for fuel production from lipids (i.e., approaching HCSD compositional targets particularly with respect to enriched lipid levels). This helps serve as an example to validate the SOT compositional assumptions as being within reason, given compositional shifting has not been a focus of the DISCOVR work otherwise serving as the basis for cultivation SOT data. Moreover, although the MFSP results for the Viridos seasonal variability scenario are somewhat higher than the SOT basis (assuming the target HCSD composition), they still reflect a favorable outcome approaching economic viability in the more near-term, given that they also do not include any policy credits currently available (while also representing a vast improvement over MFSP results when considering the DISCOVR as-harvested biomass compositions). Additionally, the fixed productivity results for the Viridos scenario imply a potential path for cost-competitive biofuels and polyurethane products at present, even without inclusion of policy credits, if such a “lipid productivity” could in fact be achieved year-round in a suitable location as envisioned by Viridos.

Table S2. TEA results for the industry case study. All cases include conversion of carbohydrates to fuels via the acids pathway and biomass cultivation in minimally lined ponds with FA-based evaporation rates. Results for the FY22 acids SOT case, based on a target HCSD composition, are also shown for comparison.

	FY22 SOT (Target HCSD composition, seasonal variation)	**Viridos (Seasonal variation)**	**Viridos (Fixed productivity)**
MFSP ($/GGE)	$4.78	$7.69	$1.35
Feedstock Contribution	$9.27	$14.09	$9.61
Conversion Contribution	-$4.50	-$6.40	-$8.27
Yield (GGE/ton AFDW)	64.4	49.9	51.1