Algal Biomass Conversion to Fuels via Combined Algae Processing (CAP): 2021 State of Technology and Future Research

Matthew Wiatrowski, Ryan Davis, and Jake Kruger

National Renewable Energy Laboratory

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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
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 the National Renewable Energy Laboratory [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 a recently incorporated 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 2021 updates to minimum fuel selling price (MFSP). This update maintains an important recent inclusion of polyurethane (PU) previously incorporated in the 2020 SOT as a value-added coproduct. It is well understood that reaching target MFSPs for algal biofuel production must involve substantial revenue from a high-value coproduct; the inclusion of PU in the SOT represents an important step in making this necessity a reality. Polyols are produced from algal lipids using a one-pot epoxidation and ring-opening reaction, which are then further reacted with an isocyanate cross-linker to produce a flexible polyurethane foam. In recent years, NREL has made significant advancements in the production of a non-isocyanate polyurethane (NIPU) foam, which has the benefit of avoiding toxic and environmentally harmful isocyanates; however, the market values and commercial scale-up ramifications of a full-scale NIPU facility have yet to be fully understood. Thus, a conventional (isocyanate-based) polyurethane process is again maintained here as an exemplary approach to inclusion of high-value PU coproducts in a CAP biorefinery, based on inputs furnished from Algenesis/UCSD.

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, reflecting experimental data from NREL CAP research and development activities. In spite of further experimental work undertaken in the CAP research program over the course of 2021, primarily a comprehensive study evaluating multiple pretreatment technology options spanning a range of algae species to identify optimal technologies/pretreatment conditions as may be best suited to a particular species, pretreatment efficacy was ultimately not shown to demonstrate further improvements beyond prior

performance benchmarks. Accordingly, details for pretreatment, as well as all other operations in the CAP process, were maintained consistently with those reflected in the prior 2020 SOT. This includes 83% pretreatment sugar yields, 96% lipid extraction recovery, and sugar fermentation yields of 0.41 or 0.33 g/g available sugars (based on fermentation to carboxylic acids or 2,3-butanediol [BDO] fuel precursor intermediates, respectively, subsequently catalytically upgraded to hydrocarbon fuels). Maintaining those same fractional conversions and other operational parameters coupled with the updated 2021 SOT MBSP value of $694/ton (based on ASU evaporation rates), the 2021 MFSP translates to $6.26/gallon gasoline equivalent (GGE) and $6.61/GGE for the acids and BDO fermentation pathways, respectively. Alternatively, the 2021 MBSP value associated with Florida Algae (FA) evaporation rates at $611/ton ash-free dry weight (AFDW) would reduce the MFSP to $5.04/GGE and $5.46/GGE for the acids and BDO cases, respectively.

Relative to the 2020 SOT case, this indicates a minimal increase of $0.10–$0.14/GGE (roughly 2%) for both the acids and BDO pathways, attributed to minimal increases in upstream algal biomass costs from slightly lower demonstrated cultivation productivities in the 2021 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 63.4 GGE/ton and 63.3 GGE/ton AFDW for the acids and BDO pathways, respectively, translating to 1,631 and 1,629 GGE/acre-year when including upstream cultivation productivity and seasonal biomass storage losses (based on wet seasonal storage reflective of HCSD biomass compositions), again quite comparable to previous 2020 SOT benchmarks. 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.

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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 "n^{th}-plant" production cost for this pre-commercial process.

Over recent years, NREL has published a number of reports for both the production of algal biomass and the conversion of algae to fuels via the "combined algae processing" (CAP) pathway [2-4], all of which focus on achieving a modeled MFSP of $2.50/gallon gasoline equivalent (GGE) from algal biomass. Combined analysis from the 2014 and 2016 reports [3, 4], which focus primarily on the production of algal fuels (fermenting sugars to ethanol and upgrading lipids to diesel-range blendstocks), finds an MFSP of $5.90/GGE (2014$) when considering out-year targets. Even considering substantial improvements around biomass cultivation costs (with MBSP goals near $500/ton, representing the largest contributor to overall fuel cost), this represents a roughly sevenfold increase over terrestrial biomass cost goals [5]. At even high fuel yield targets of 100 GGE/ton, as can be achieved from algal biomass conversion pathways, this translates to an MFSP of $5/GGE tied to feedstock cost alone. Thus, it has become increasingly clear that additional biorefinery revenue will be necessary in order to offset feedstock and conversion processing costs to reduce MFSPs. Accordingly, recent iterations of the CAP process have begun to consider the inclusion of value-added coproducts to ultimately meet Bioenergy Technologies Office (BETO) targets of $2.5/GGE by 2030 [6].

In light of this importance for non-fuel coproducts to be produced alongside fuels in order to drive down MFSPs in the future, various 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 the revenue required to offset feedstock costs due to relatively high selling prices and market volumes. Accordingly, a PU coproduct was incorporated for the first time into the 2020 state of technology (SOT), based on conventional synthesis chemistries via polyol intermediate reaction with isocyanates [7]. Although alternative and potentially lower-cost (and potentially more environmentally beneficial) approaches to algal PU production are also possible, for example based on NREL-developed non-isocyanate polyurethane (NIPU) chemistries using diamine cross-linkers [8], the research for such pathways is still considered to be in early stages with higher uncertainties regarding design, cost, and scale-up implications for techno-economic analysis (TEA) modeling purposes, as well as market values for such alternative PU products, and accordingly they are again not yet considered for formal SOT inclusion in the present update. Thus, the same isocyanate-based PU processing details were maintained in this SOT, reflecting inputs previously furnished via industry and academic collaborators Algenesis and the University of California, San Diego (UCSD) [9].

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 (Development of Integrated Screening, Cultivar Optimization, and Verification Research [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) 2021 SOT is shown in Figure 1. This configuration reflects a consistent process design as utilized in the latest 2020 SOT report, 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 [6, 7].

In summary, the process approach 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 [10]). 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 [11]. This represents an improvement over historical SOT data previously reflected at 74% combined yields from earlier work. Further experimental work was conducted during 2021 investigating a number of pretreatment technologies being considered across a range of strains/conditions (discussed in the next section), but ultimately none were demonstrated to improve overall yields/economics beyond the latest data discussed above from the 2020 SOT; thus, the 2020 SOT basis was ultimately maintained here.

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 basis 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. No further work was conducted during 2021 on either fermentation pathway (within the algae research platform); thus, all details for fermentation and subsequent catalytic upgrading were maintained consistently with prior recent SOTs and will not be repeated here [7, 12].

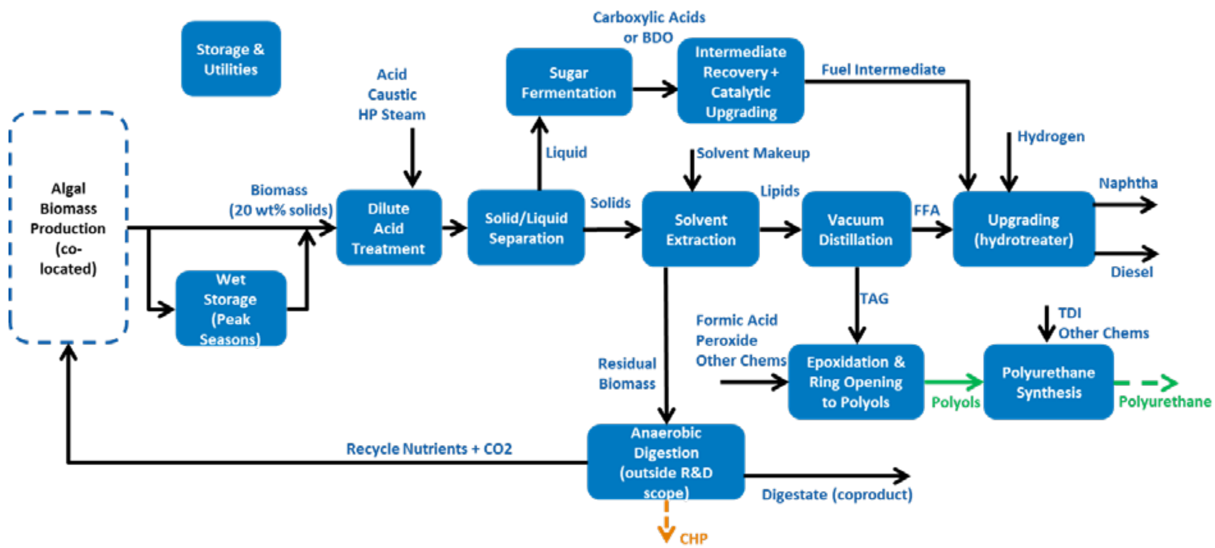

Figure 1. Schematic diagram of CAP configuration for the FY 2021 SOT

The solids product from upstream 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) cosolvent. 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 N/P nutrients back to cultivation. The remaining lipids undergo a three-step purification process to remove impurities, followed by a vacuum distillation step to yield triacylglycerides (TAGs) and free fatty acids. The free fatty acid 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. Again, no further improvements were demonstrated experimentally during 2021 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 1 and Table 2.

Table 1. Process Conditions and Conversions Observed from Experimental CAP Data, Utilized for FY 2021 SOT as Maintained from Prior SOTs [13-16]. Italicized lines represent modeling assumptions, outside experimental scope. Polyol/polyurethane details are presented in Table 2.

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 • Solid-liquid separation 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 flocculant loading (g/kg insoluble solids)	10		
Solid-liquid separation membrane capacity (kg insoluble solids/m^2-h)	30		
Sugar Fermentation	**Acids**	**BDO**	
Fermentation productivity (g/L-h)	0.3	56-hour batch	• Acids data based on NREL algae platform R&D in FY 2018; BDO data based on inputs from NREL researchers under FY 2018 Rewiring Algal Carbon Energetics for Renewables (RACER) project fermentation work on *Desmodesmus* C046
Sugar diversion to organism seed growth	*10%* [b]	*10%* [b]	
Glucose utilization to product	92% [c]	89% [c, d]	
Mannose utilization to product	92% [c]	89% [c, d]	
Glycerol utilization to product	92% [c]	0% [c, d]	
Butyric acid yield (g/g total available sugars)	0.39	N/A	
Acetic acid yield (g/g total available sugars)	0.10	N/A	
BDO yield (g/g total available sugars)	N/A	0.33	
Acetoin yield (g/g total available sugars)	N/A	0.09	
Catalytic upgrading carbon efficiency (HDO feed vs. recovered intermediate) [e]	83%	98%	
Lipid Extraction + Upgrading			
Extraction configuration	3-stage continuous stirred-tank reactor + 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		
Continuous stirred-tank reactor 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} weight hourly space velocity		
Hydrotreating renewable diesel blendstock yield (wt % of oil feed) [f]	62.1%		
Hydrotreating naphtha yield (wt % of oil feed) [f]	21.8% [g]		
Hydrotreating H_2 consumption (wt % of oil feed)	2.23% [h]		

[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 [3].

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

[d] Includes BDO and acetoin.

[e] Catalytic upgrading of fermentation intermediates to final hydrocarbon fuels is outside R&D scope; set consistently with *2017 Algae Harmonization Study* for acids case [6] and Biochemical Platform FY 2018 SOT data for BDO case. Value represents upgrading yields to the final fuel finishing (hydrotreating) reactor feed.

[f] Hydrotreating yields are based on adjusting original experimental data [14] to achieve 100% mass closure, based on lipid hydrotreating alone (not including coprocessed BDO/acids intermediate products).

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

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

The polyurethane production process, shown in Figure 2, consists of a one-pot epoxidation and ring-opening reaction to polyols, followed by polymerization with toluene diisocyanate to produce polyurethane foam. This "conventional" polyurethane process, most recently updated as outlined in the 2019 CAP update technical report [2], uses information furnished from industry databases and engineering subcontractors for the production of polyurethane from algae- or plant-based lipids. In the present SOT assessment, the polyol production portion of the process has been further updated to reflect inputs obtained from industry collaborators Algenesis and UCSD, under the umbrella of BETO-supported research in this space, documented in further detail in the 2020 SOT report [7] with key parameters summarized in Table 2.

Recent experimental work at NREL has begun investigating a more novel route to PU products that may offer several benefits over the traditional route described above, primarily avoidance of toxic and environmentally harmful isocyanate cross-linkers [17, 18]. The NIPU route maintains the initial epoxidation step, but rather than epoxide ring opening to polyols, the ring is reacted with CO_2, forming a carbonate group [8, 19]. These carbonate groups may react with diamine cross-linkers to form NIPU end products, potentially enabling a fully renewable PU process given that the diamines could be derived from the algal biomass. While this work has yielded promising results and more recently has shown the *potential* to further improve economics through the use of a lower-cost and more environmentally beneficial diamine to replace isocyanate [20], the NIPU process remains not yet ready for incorporation in the current CAP SOT update, primarily given uncertainties related to design and costs upon scale-up to commercial levels and resultant market values of the NIPU material. Thus, at present, the conventional isocyanate route is maintained here as an exemplary reflection of this coproduct opportunity in the CAP process, consistent with the details described in the 2020 SOT.

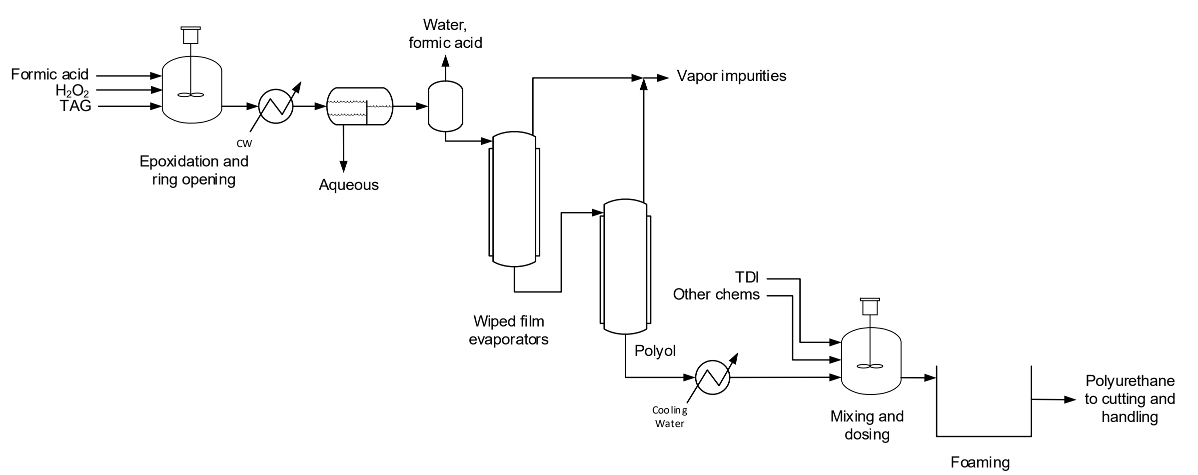

Figure 2. Process flow diagram of the conventional polyol/polyurethane production train for the FY 2020–2021 SOT

Table 2. Process Inputs for Polyurethane Production, Maintained from the 2020 SOT [7]

Parameter	Specification	Basis
Epoxidation and ring opening		
Temperature	75°C	[21]
Pressure	1 atm	[21]
Residence time	6 hours	[21]
H_2O_2	1.5x double bonds	50% stoichiometric excess
Formic acid	Equimolar with double bonds	[21]
Power	0.54 MWh/ton polyol	Input from Nexant [2]
Cooling water	220 w/w polyol	Input from Nexant [2]
Low-pressure steam	0.02 w/w polyol	Input from Nexant [2]
Nitrogen	0.02 w/w polyol	Input from Nexant [2]
Other chemicals	$46.70/ton polyol	Input from Nexant [2]
Polyurethane production		
Toluene diisocyanate	0.5 mole/mole hydroxyl group	Stoichiometric
Water	0.0281 w/w polyol	Input from Nexant [2]
Diethanolamine	0.0026 w/w polyol	Input from Nexant [2]
Surfactant	0.0049 w/w polyol	Input from Nexant [2]
Power	0.004 w/w polyol	Input from Nexant [2]

As summarized above, ultimately there were no substantive updates to the 2021 SOT relative to the prior 2020 SOT benchmark specific to any of the associated operations in the CAP conversion process, in part due to no further experimental work performed on some steps (fermentation, catalytic upgrading of fermentation intermediates, polyol/polyurethane coproduction), as well as further experimental work performed but ultimately not shown to demonstrate further improvements over current benchmark performance levels (pretreatment; discussed further below). Thus, the key update reflected in the present SOT is attributed to upstream modifications around FY 2021 algae cultivation yields, seasonal flows, and biomass costs (MBSP). All pertinent details for those parameters are summarized in the accompanying FY 2021 algal biomass SOT report; in summary, FY 2021 algae farm MBSPs were estimated at $694/ton or $611/ton AFDW for the Arizona State University (ASU) vs. Florida Algae (FA) evaporation scenarios, respectively (unlined ponds, increasing to $864/ton or $781/ton for fully lined ponds, respectively). This was tied to a minor 4% *reduction* in annual cultivation productivity (17.6 g/m^2/day, relative to the FY 2020 basis of 18.4 g/m^2/day) and associated minimally reduced throughputs through the CAP facility (though with these impacts somewhat offset by a lower seasonal variability in the FY 2021 cultivation data of 2.9:1).

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 are based on collaborations with partners at INL, who have been coordinating work on this subject over recent years [10]. In the FY 2021 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. This updated basis includes a notable improvement in overall degradation loss relative to earlier storage trials (13%, compared to a 23% loss previously), as well as an adjustment in the compositional changes and acid production in the stored biomass (personal communication, Brad Wahlen [INL], November 2020). The fresh and stored biomass compositions are summarized in Table 3, based on inputs from INL extrapolated to the same HCSD strain basis assumed here. The resulting raw seasonal and post-storage biomass flowrates are depicted in Figure 3. At the 2.9:1 seasonal variability from cultivation (an improvement relative to 3.8:1 in FY 2020, albeit incurred because of a substantial 25% reduction in summertime cultivation productivity), roughly 15% of total annual biomass production must be sent to seasonal storage, which—coupled with the 13% storage degradation losses—translates to a minor 1.9% overall loss of annual biomass feed to the CAP facility. This translates to a minimal improvement compared to the FY 2020 SOT at 2.6% given the reduced seasonal variability, somewhat offsetting the minimally higher MBSP penalty. The acid degradation products are ultimately relegated to AD, with the exception of a small amount of acetic acid, which gets converted in the acids pathway.

Table 3. Input Compositions to CAP Models Before and After Wet Storage Losses, Based on Raw HCSD Composition and Adjustments Applied to the HCSD Baseline to Reflect Degradation Losses as Measured by INL [10], (personal communication, Brad Wahlen [INL], November 2020)

	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
Free fatty acids	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

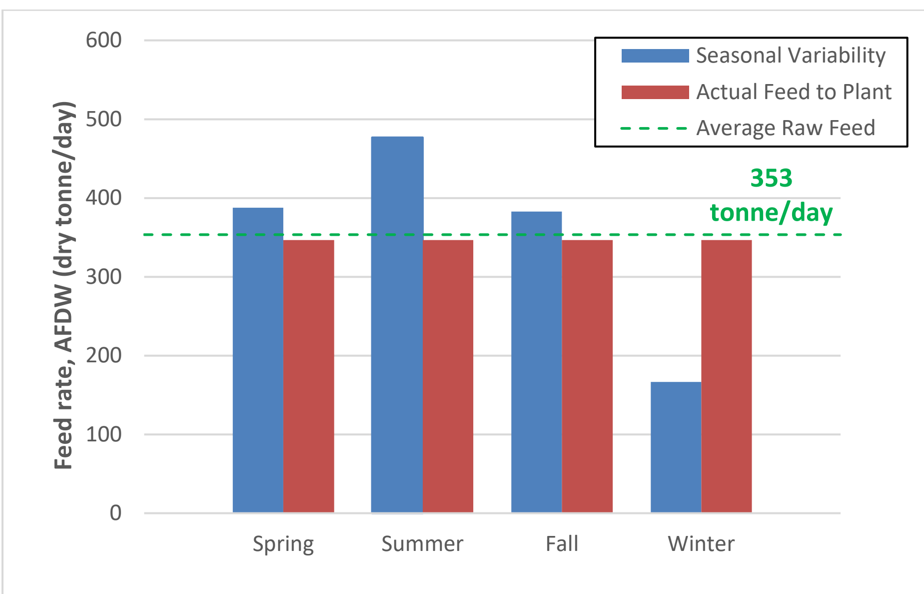

Figure 3. Seasonal and annual average feed rates to conversion facility (AFDW basis, FA evaporation scenario)

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

Discussion of Additional R&D Activities

In FY 2021, a key focus for NREL's CAP research efforts was around further evaluation of the pretreatment step, given that this operation represents the largest degree of room for further improvement between SOT benchmark performance levels and future 2030 targets, beyond the need for further cultivation improvements required upstream (as shown in Table 6). Specifically, NREL's CAPSLOC project conducted a comprehensive experimental investigation spanning five pretreatment technologies evaluated across numerous algal biomass samples, with a goal to identify the most suitable pretreatment operation as may be utilized for a particular algae species, as well as identifying optimal conditions to maximize downstream yields through lipid extraction and soluble liquor upgrading (e.g., fermentation to fuel intermediates or other products) within the CAP framework. The algae species evaluated spanned common strains investigated under recent SOT cultivation trials, as well as algae cultivated for wastewater treatment, extracted residues from industry, and other strains of commercial interest, largely based on nutrient-replete/high-protein compositions, but also including the standard high-carbohydrate *Scenedesmus* strain (*Scenedesmus acutus* 0401*)* assumed as the basis in this SOT and projected for final 2030 targets (summarized in Table 4). The pretreatment technologies evaluated are summarized in Table 5 and included dilute Brønsted acid (i.e., sulfuric acid as currently utilized in the SOT pathways), dilute Lewis acid (utilizing $FeCl_3$ as an alternative acid for pretreatment), Twitchell Brønsted acid (sulfuric acid pretreatment operated under lower-severity conditions for extended residence time), dilute alkali, and enzymatic hydrolysis. A sixth pretreatment option utilizing flash hydrolysis was also originally planned, but due to COVID-19 constraints could not be completed in the same time frame as the others.

Table 4. Algae Strains Considered under CAPSLOC Pretreatment Study and Associated Biomass Compositions [22]

Sample	*pH*	*Ash*	*Protein*	*Carbohydrate*	*Lipids*	*Total Carbon*	*Total Nitrogen*
Wastewater treatment collaborator	6.66	12.34	43.83	9.98	6.99	46.79	9.17
Tetraselmis sp.	7.52	19.50	35.75	6.78	7.28	42.26	7.48
Industry collaborator	6.72	25.62	32.22	6.88	8.49	40.89	6.74
Scenedesmus acutus 0401	5.40	2.24	11.33	46.77	24.64	52.45	2.37
Scenedesmus IITRIND2	5.28	8.28	43.88	5.98	8.83	46.15	9.18
Scenedesmus obliquus UTEX393	5.96	7.32	47.51	10.15	7.08	48.18	9.94
Monoraphidium minutum 26BAM	5.37	6.65	41.06	11.06	9.30	49.87	8.59
Picochlorum celerei	6.05	17.53	42.69	5.32	9.58	43.58	8.93

Ultimately, when averaged across the biomass samples, the dilute and Twitchell Brønsted acid cases were shown to achieve the best overall "combined pretreatment effectiveness" as a metric combining the efficacy of both total organic carbon yields to the liquor fraction (i.e., solubilization of carbohydrates, as well as protein, into the liquor phase for subsequent upgrading via fermentation or other means) and lipid extraction yields. The pretreatment efficacy was only slightly better than dilute NaOH pretreatment, but not substantially. Dilute Lewis acid and enzymatic pretreatments were also within the range that further development could make them competitive. Given the fact that all other pretreatment technologies evaluated did not generally demonstrate an equivalent or higher pretreatment efficacy to the base case approach (dilute Brønsted [sulfuric] acid at elevated severity) and considering that their implementation would not likely represent a capital/operating cost savings, none of the alternative pretreatment technologies were ultimately selected to replace the standard dilute sulfuric acid approach for purposes of updating the present SOT. The final pretreatment option that couldn't be investigated experimentally, namely flash hydrolysis, does however present an opportunity to reduce pretreatment costs [2], although generally appears to be better suited for protein solubilization and subsequent upgrading strategies than carbohydrate hydrolysis/solubilization. Within the data set furnished for the dilute Brønsted (sulfuric) acid case, as sugar yields were not ultimately shown to achieve any better results than those reflected in the prior 2020 SOT update, the prior basis was maintained here.

Table 5. Summary of Pretreatment Approaches Considered under CAPSLOC Study [22]

Pretreatment	Operating Conditions
Dilute Brønsted acid	Temperature = 135°C–175°C Residence time = 15 min Biomass:H_2SO_4 = 10:1–30:1
Dilute Lewis acid	Temperature = 135°C–175°C Residence time = 15 min Biomass:$FeCl_3$ = 10:1–30:1
Twitchell Brønsted acid	Temperature = 80°C–120°C Residence time = 8–16 h Biomass:H_2SO_4 = 10:1
Dilute alkali	Temperature = 135°C–175°C Residence time = 15 min Biomass:NaOH = 10:1–30:1
Enzymatic hydrolysis	Temperature = 30°C–50°C Residence time = 24 h Biomass:enzyme = 25:1–187.5:1
Flash hydrolysis [a]	Temperature = 180°C–240°C Residence time = 10 sec Pressure = 800–1,600 psig

[a] Flash hydrolysis option was ultimately not evaluated experimentally during FY 2021 time frame due to COVID-19 restrictions.

Results

TEA Results

The updates discussed above (adjusted biomass flowrates and MBSP costs from the upstream biomass production model) resulted in minor increases in overall MFSPs for the FY 2021 SOT. These results are summarized in Figure 4 for the present FY 2021 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 2020 results are also shown for comparison. The results of this analysis indicate an **FY 2021 SOT MFSP of $6.26/GGE (acids pathway) or $6.61/GGE (BDO pathway) for the ASU evaporation MBSP basis, or $5.04/GGE and $5.46/GGE (acids versus BDO) for the FA evaporation basis (all results in 2016$).** Compared to the FY 2020 SOT at $6.12–$6.50/GGE for ASU evaporation or $4.94–$5.33/GGE for FA evaporation (acids vs. BDO pathways, respectively), this represents an overall MFSP increase of approximately 2% for all cases ($0.10–$0.14/GGE). These moderate increases can generally be attributed to slightly higher MBSPs and lower biomass feed rates from the biomass cultivation facility, but overall do not represent significant deviations from the FY 2020 SOT benchmark.

As is 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 lipid content [26%], and high carbohydrate content [48%] while meeting productivity targets associated with nutrient-replete, high-protein biomass) [4, 23]. A sensitivity case was previously investigated as part of the 2020 SOT, considering the harvested compositions documented from the upstream cultivation trials at that time [7]. As both the MBSP and "as-harvested" compositions were quite comparable this year, another sensitivity case was not rerun for this 2021 SOT, as the MFSP impacts would be expected to also compare quite similarly with those documented previously. In summary, the 2020 harvested biomass contained considerably lower carbohydrate (9%) and fatty acid methyl ester lipid (9%) content, with corresponding increased protein content (45%), which combined with an increased MBSP ($707/ton) would result in an MFSP of $38.67/GGE (acids pathway) or $39.76/GGE (BDO pathway) for the FA evaporation basis within the current CAP configuration. However, it is again stressed that the process design investigated 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 SOT results would show considerable improvement for an alternative process design optimized for the high-protein biomass.

Between the two fermentation pathways, the acids pathway SOT continues to reflect a slightly lower MFSP than the BDO pathway, driven by comparable yields and operating costs but 4% lower total capital costs (primarily reflecting lower fermentation and upgrading costs, with aqueous BDO upgrading particularly costly at the low 7.3% BDO concentration levels observed 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 4. TEA results for 2020–2021 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 5 provides the same MFSP cost breakdowns for the SOT cases as shown in Figure 4, but formatted for simplicity reflecting only the FA evaporation cases, and also 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 6; 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) [12]. The feedstock cost associated with these parameters is virtually equivalent to the cost for the FY 2021 SOT; therefore, improvements between the FY 2021 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 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 the 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 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 resulted 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 coproduction bars included in Figure 5 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, is 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 [17, 18, 20].

As discussed in other recent work [2, 24], we reiterate that the future projection scenarios shown in Figure 5 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 [22], fermentation of high-protein and high-carbohydrate hydrolysates to other fuel and coproduct precursors [6, 25], and alternative valorization approaches for the residual solids [26, 27]. 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 focus.

Finally, Table 6 provides key technical and cost details associated with the various cases presented in Figure 5. This table shows that room for improvement continues to exist moving forward beyond the current SOT baseline, particularly with respect to cultivation productivity (42% 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 (17% and 7% improvement in the acids [targeting butyric acid exclusively] and BDO pathways, respectively). Lipid extraction and upgrading yields have essentially achieved final target levels, but further room for improvement exists (i.e., around catalyst robustness and resistance to deactivation). 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 [20].

Note that the "conversion" contribution to MFSP for all cases in Table 6 reflects the net sum of all conversion process costs ("positive" bars in Figure 5) combined with the coproduct processing costs and revenues ("negative" bars in Figure 5); 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 new CAP approach discussed previously or other variants that may support higher-protein algal biomass feedstocks.

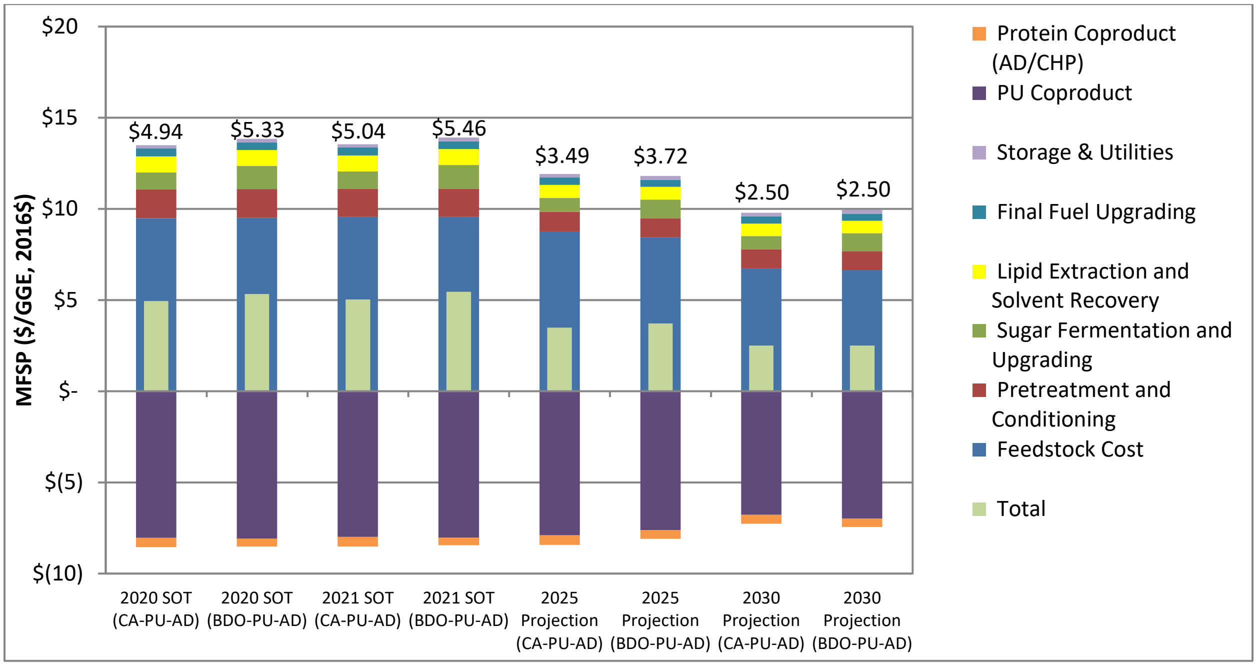

Figure 5. Summary of MFSP cost breakdowns for SOTs and future example projection scenarios (FA evaporation scenarios)

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 6. Technical Overview Table for Cost and Process Metrics Associated with FY 2020–2021 SOT Cases, Compared to Example 2030 Projection Scenarios. SOT Cases Only Reflect FA Evaporation Scenarios for Simplicity.

Metric	2020 SOT (Acids-PU) – FA Evap	2020 SOT (BDO-PU) – FA Evap	2021 SOT (Acids-PU) – FA Evap	2021 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]	$4.94 [$7.61]	$5.33 [$8.00]	$5.04 [$7.70]	$5.46 [$8.12]	$3.49	$3.72	$2.50	$2.50
Feedstock contribution ($/GGE, 2016$)[a]	$9.50 [$12.16]	$9.50 [$12.17]	$9.56 [$12.22]	$9.57 [$12.23]	$8.75	$8.44	$6.74	$6.65
Conversion contribution ($/GGE, 2016$)[a]	($4.54) [($4.54)]	($4.17) [($4.17)]	($4.52) [($4.52)]	($4.11) [($4.11)]	($5.25)	($4.72)	($4.24)	($4.15)
Yield (GGE/ton AFDW)	63.0	62.9	63.4	63.3	68.3	70.8	71.7	72.7
Renewable diesel blendstock yield (GGE/ton AFDW)	45.3	40.8	45.5	41.0	48.9	45.0	51.5	46.6
Naphtha yield (GGE/ton AFDW)	17.8	22.2	17.9	22.3	19.4	25.7	20.2	26.2
Finished fuel products yield (GGE/acre/yr)	1,685	1,682	1,631	1,629	2,494	2,587	2,619	2,658
C yield to fuels from biomass	31.1%	30.8%	31.1%	30.8%	32.8%	33.8%	34.5%	34.7%
C yield to coproducts from biomass (algal carbon only)	20.6%	20.6%	20.6%	20.6%	20.5%	20.5%	18.6%	19.4%
Feedstock								
Feedstock cost ($/ton AFDW)[a]	$603 [$772] [b]	$603 [$772] [b]	$611 [$781] [b]	$611 [$781] [b]	$602	$602	$488	$488
Year-average cultivation productivity (g/m^2/day AFDW)	18.4	18.4	17.6	17.6	20	20	25	25
Max seasonal variability (max:min productivity)	3.8:1	3.8:1	2.9:1	2.9:1	3.0:1	3.0:1	3.0:1	3.0:1
Harvested biomass lipid content (dry wt % as fatty acid methyl ester)	26% [b]	26% [b]	26% [b]	26% [b]	26%	26%	26%	26%
Harvested biomass concentration (g/L AFDW)	0.46	0.46	0.46	0.46	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	2020 SOT (Acids-PU) – FA Evap	2020 SOT (BDO-PU) – FA Evap	2021 SOT (Acids-PU) – FA Evap	2021 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)	0.3	1.3 (56-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]	73	N/A [d]	90	N/A [d]	90
Glucose to product [e]	92%	74%	92%	74%	95%	95%	95%	95%
Mannose to product [e]	92%	55%	92%	55%	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	0.34	0.48	0.34	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, 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 blendstock yield (wt % of total feed) [g]	64.4%	56.6%	64.4%	56.6%	64.5%	55.8%	64.3%	56.0%
Fuel finishing naphtha yield (wt % of total feed) [g]	25.3%	30.5%	25.3%	30.5%	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%/73%	100%/51%	100%/73%	100%/54%	100%/73%	100%/53%
AD biogas yield (L CH_4/g total solids)	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 *Desmodesmus*, *Scenedesmus*, *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 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 7 summarizes key sustainability indicators as may be taken directly from the Aspen Plus process. 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 are summarized in Appendix B.

Table 7. Sustainability Indicators for FY 2021 SOT CAP Models

		FY 2021 SOT Fermentation Pathway	
Parameter		**Acids**	**BDO**
Fuel yield by weight of biomass	GGE per dry ton biomass	63.4	63.3
Carbon efficiency to fuels	% of algal C used	31.1	30.8
Carbon efficiency to coproduct	% of algal C used	20.6	20.6
Electricity import/export	kWh/GGE	−5.42 (export)	−5.52 (export)
Natural gas import	MJ/GGE	100	166
Water consumption [a]	m^3/day	1,430	2,293
Water consumption [a]	gal/GGE	15.3	24.5

[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 2021 SOT minimum fuel selling price of $6.26/GGE (acids pathway) or $6.61/GGE (BDO pathway) for the ASU evaporation MBSP basis, or $5.04/GGE and $5.46/GGE (acids versus BDO) for the FA evaporation basis (all results in 2016$)** for the unlined pond base case. SOT fuel costs for the alternative fully lined pond scenario would increase to $8.92/GGE or $9.27/GGE for the acids and BDO cases, respectively, under baseline ASU evaporation rates.

Relative to the prior FY 2020 SOT, the impacts to the FY 2021 MFSP are minimal, at a roughly 2% increase in overall modeled MFSP for either fuel pathway. This is primarily a reflection of minimally lower (4%) cultivation productivity upstream (tied primarily to reduced summer productivity for *P. celeri* likely attributed to monsoon weather confounding factors) and resultant 1%–2% increase in MBSP, and associated lower throughputs impacting economies of scale. Despite comprehensive experimental work focused on evaluating numerous CAP pretreatment operations across a range of algal species, no further improvements were ultimately achieved in pretreatment or other CAP steps relative to prior performance benchmarks; thus, all CAP details remain unchanged from the FY 2020 basis. However, in turn, the FY 2020 SOT highlighted substantial MFSP improvements over prior years attributed to the inclusion of polyurethane as a value-added coproduct. 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 $0.35/GGE lower for acids than BDO), primarily due to better fermentation performance/yields toward acids, though this difference would likely shrink if BDO fermentation were to improve or conditions were further optimized for higher titers.

As discussed in prior SOT reports, beyond current benchmarks, to increase yields and reduce MFSP cost on the conversion side moving forward under this 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 the latest findings discussed here for the pretreatment technology scan across multiple algae species, pretreatment efficacy so far appears limited to a level somewhat below 2030 targets at 83% instead of the 90% target (also somewhat dependent on species/biomass source, as may necessitate optimized conversion approaches—albeit with lower variation observed amongst high-protein strains). Additionally, while lipid extraction and upgrading yields have been demonstrated near their final goals for this CAP approach, 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 coprocessing 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 level; however, further advancements in NIPU research may warrant inclusion in future SOTs. First, a better understanding of key processing design/cost considerations would be required, as well as product applications and price values for such a material. Based on separate TEA, 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 more 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.

Future experimental plans also intend to continue investigating alternative CAP 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 in the event that 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 $2.5/GGE 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):		**$5.04 /GGE**
Contributions:	Feedstock	$9.56 /GGE
	Conversion	-$4.52 /GGE
Total Fuel Production (RDB + Naphtha + Ethanol):		8.16 MMGGE/yr
RDB Production:		5.86 MMGGE/yr
Naphtha Production:		2.30 MMGGE/yr
Ethanol Production:		0.00 MMGGE/yr
Total Fuel Yield (RDB + Naphtha + Ethanol:		63.43 GGE / dry U.S. ton feedstock
Feedstock Cost:		$611 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	$23,400,000
A200: Carboxylic Acid Fermentation and Distillation	$14,200,000
A200: 2,3-BDO Fermentation and Upgrading	$0
A300: Lipid Extraction and Separation	$16,300,000
A400: Product Purification and Upgrading	$4,500,000
A500: Protein/Residual Processing	$4,600,000
A600: Combined Heat and Power	$6,600,000
A700: Utilities & Storage	$3,000,000
Total Installed Equipment Cost	$72,600,000
Added Direct + Indirect Costs	$204,100,000
(% of TCI)	73.76%
Total Capital Investment (TCI)	$276,700,000
Installed Equiptment Cost/Annual GGE	$8.90
Total Capital Investment/Annual GGE	$33.92
Loan Rate	8%
Term(years)	10
Capital Charge Factor (Computed)	0.090
Carbon Retention Efficiencies:	
Total Carbon Efficiency to Fuel and Products	59.2%
(Fuel C/Biomass C)	
RDB (RDB C/Biomass C)	22.4%
Naphtha (Naphtha C/Biomass C)	8.7%
Polyurethane (total C in PU/Biomass C)	28.1%
Polyurethane (algal C in PU/Biomass C)	20.6%

Fuel Yields	
RDB Production (U.S. ton/yr)	18,031
Naphtha Production (U.S. ton/yr)	7,077

Manufacturing Costs (cents/GGE)	
Feedstock	955.8
Pretreatment Chemicals	48.9
A200 chemicals	27.8
Lipid Extraction and Cleanup Chemicals	21.6
Hydrogen	15.2
Polyurethane Inputs	349.5
Supplemental Natural Gas	44.1
Remaining Raw Materials	2.0
Coproduct Credits	-1420.2
Other Credits (recycled nutrients, etc.)	-87.6
Exported Electricity	-31.0
Catalysts	3.7
Fixed Costs	136.5
Capital Depreciation	136.1
Average Income Tax	32.9
Average Return on Investment	268.7

Manufacturing Costs ($/yr)	
Feedstock	$78,000,000
Pretreatment Chemicals	$4,000,000
A200 chemicals	$2,300,000
Lipid Extraction and Cleanup Chemicals	$1,800,000
Hydrogen	$1,200,000
Polyurethane Inputs	$28,500,000
Supplemental Natural Gas	$3,600,000
Remaining Raw Materials	$200,000
Coproduct Credits	-$115,800,000
Other Credits (recycled nutrients, etc.)	-$7,100,000
Exported Electricity	-$2,500,000
Catalysts	$300,000
Fixed Costs	$11,100,000
Capital Depreciation	$11,100,000
Average Income Tax	$2,700,000
Average Return on Investment	$21,900,000

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):	**$5.46 /GGE**
Contributions:	Feedstock	$9.57 /GGE
	Conversion	-$4.11 /GGE
	Total Fuel Production (RDB + Naphtha + Ethanol):	8.15 MMGGE/yr
	RDB Production:	5.28 MMGGE/yr
	Naphtha Production:	2.87 MMGGE/yr
	Ethanol Production:	0.00 MMGGE/yr
	Total Fuel Yield (RDB + Naphtha + Ethanol:	63.35 GGE / dry U.S. ton feedstock
	Feedstock Cost:	$611 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	$23,400,000
A200: Carboxylic Acid Fermentation and Distillation	$0
A200: 2,3-BDO Fermentation and Upgrading	$19,500,000
A300: Lipid Extraction and Separation	$16,300,000
A400: Product Purification and Upgrading	$4,600,000
A500: Protein/Residual Processing	$3,900,000
A600: Combined Heat and Power	$7,900,000
A700: Utilities & Storage	$3,300,000
Total Installed Equipment Cost	$78,900,000
Added Direct + Indirect Costs	$209,900,000
(% of TCI)	72.68%
Total Capital Investment (TCI)	$288,800,000
Installed Equiptment Cost/Annual GGE	$9.69
Total Capital Investment/Annual GGE	$35.45
Loan Rate	8%
Term(years)	10
Capital Charge Factor (Computed)	0.089
Carbon Retention Efficiencies:	
Total Carbon Efficiency to Fuel and Products	59.0%
(Fuel C/Biomass C)	
RDB (RDB C/Biomass C)	20.1%
Naphtha (Naphtha C/Biomass C)	10.7%
Polyurethane (total C in PU/Biomass C)	28.1%
Polyurethane (algal C in PU/Biomass C)	20.6%

Fuel Yields	
RDB Production (U.S. ton/yr)	16,240
Naphtha Production (U.S. ton/yr)	8,753

Manufacturing Costs (cents/GGE)	
Feedstock	957.0
Pretreatment Chemicals	49.0
A200 chemicals	27.6
Lipid Extraction and Cleanup Chemicals	21.7
Hydrogen	13.7
Polyurethane Inputs	350.0
Supplemental Natural Gas	73.5
Remaining Raw Materials	3.2
Coproduct Credits	-1422.0
Other Credits (recycled nutrients, etc.)	-99.0
Exported Electricity	-31.6
Catalysts	5.5
Fixed Costs	139.7
Capital Depreciation	139.9
Average Income Tax	34.4
Average Return on Investment	283.4

Manufacturing Costs ($/yr)	
Feedstock	$78,000,000
Pretreatment Chemicals	$4,000,000
A200 chemicals	$2,200,000
Lipid Extraction and Cleanup Chemicals	$1,800,000
Hydrogen	$1,100,000
Polyurethane Inputs	$28,500,000
Supplemental Natural Gas	$6,000,000
Remaining Raw Materials	$300,000
Coproduct Credits	-$115,800,000
Other Credits (recycled nutrients, etc.)	-$8,100,000
Exported Electricity	-$2,600,000
Catalysts	$400,000
Fixed Costs	$11,400,000
Capital Depreciation	$11,400,000
Average Income Tax	$2,800,000
Average Return on Investment	$23,100,000

Appendix B. Life Cycle Inventory for 2021 CAP SOT Models

Acids Case: SOT input and output inventory data for the modeled CAP process. (Note: hourly rates are based on annual averages over all modeled seasons.)

Resource Consumption	kg/h
Feedstock (AFDW basis)	14,727
Pretreatment	
Sulfuric acid (93% pure)	1,301
Ammonia	421
Lipid Extraction and Cleanup	
Hexane requirement	77
Ethanol	31
Phosphoric acid (oil cleanup)	42
Silica (oil cleanup)	4
Clay (oil cleanup)	8
Carboxylic Acid Conversion	
Corn steep liquor	669
Diammonium phosphate	70
Hydrotalcite	1
Flocculant	59
Hexane	1
Ketonization catalyst (ZrO_2)	0.03
Condensation catalyst (niobic acid)	0.20
Final Fuel Upgrading (HDO/HI)	
Hydrogen	97
One-step HDO/HI catalyst (1% Pt/SAPO-11)	0.21
Polyurethane Production	
Formic acid	320
H_2O_2	507
Nitrogen	48
Toluene diisocyanate	880
Diethanolamine	9
Surfactant	16
Tin catalyst (stannous octoate)	6
DABCO (1,4-diazabicyclo[2.2.2]octane)	3
Other Resource Consumption	
Supplemental natural gas	1,850
Process water	59,606
Output Streams	
AD digestate cake (dry basis total flow)	3,398
AD digestate cake bioavailable N	17
AD effluent NH_3	210
AD effluent diammonium phosphate	102
Recycle water (excluding N/P nutrients)	95,794
Direct Air Emissions	
H_2O	31,652
CO_2 Recycle	
CO_2 (biogenic)	8,460
CO_2 (fossil)	5,595
Biomass Loss from Storage	
Algae biomass loss from wet storage	293

BDO Case: SOT input and output inventory data for the modeled CAP process. (Note: hourly rates shown based on annual averages over all modeled seasons.)

Resource Consumption	**kg/h**
Feedstock (AFDW basis)	14,727
Pretreatment	
Sulfuric acid (93% pure)	1,304
Ammonia	421
Lipid Extraction and Cleanup	
Hexane requirement	78
Ethanol	31
Phosphoric acid (oil cleanup)	42
Silica (oil cleanup)	4
Clay (oil cleanup)	8
2,3-BDO Conversion	
Corn steep liquor	99
Diammonium phosphate	12
Hydrogen	76
Flocculant	59
Dehydration catalyst	0.06
Oligomerization catalyst	0.11
Final Fuel Upgrading (HDO/HI)	
Hydrogen	87
One-step HDO/HI catalyst (1% Pt/SAPO-11)	0.23
Polyurethane Production	
Formic acid	320
H_2O_2	507
Catalysts and other chemicals	48
Nitrogen	880
Toluene diisocyanate	9
Diethanolamine	16
Surfactant	320
Tin catalyst (stannous octoate)	6
DABCO (1,4-diazabicyclo[2.2.2]octane)	3
Other Resource Consumption	
Supplemental natural gas	3,079
Process water	95,525
Output Streams	
AD digestate cake (dry basis total flow)	3,231
AD digestate cake bioavailable N	16
AD effluent NH_3	204
AD effluent diammonium phosphate	72
Recycle water (excluding N/P nutrients)	98,151
Direct Air Emissions	
H_2O	37,235
CO_2 Recycle	
CO_2 (biogenic)	8,338
CO_2 (fossil)	8,967
Biomass Loss from Storage	
Algae biomass loss from wet storage	293