Algal Biomass Production via Open Pond Algae Farm Cultivation: 2023 State of Technology and Future Research

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National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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15013 Denver West Parkway
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List of Acronyms

AFDW	ash-free dry weight
ANL	Argonne National Laboratory
ASU	Arizona State University
ATP^3	Algae Testbed Public-Private Partnership
AzCATI	Arizona Center for Algae Technology and Innovation
BETO	Bioenergy Technologies Office
CAP	combined algae processing
CO_2	carbon dioxide
DISCOVR	Development of Integrated Screening, Cultivar Optimization, and Verification Research
FA	Florida Algae (testbed site under ATP^3 consortium)
FAME	fatty acid methyl ester
FY	fiscal year
HCSD	high-carbohydrate *Scenedesmus*
MBSP	minimum biomass selling price
MFSP	minimum fuel selling price
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
SOT	state of technology
TEA	techno-economic analysis

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 historically focused 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 the Development of Integrated Screening, Cultivar Optimization, and Verification Research (DISCOVR) consortium efforts, driven by data furnished by Arizona State University (ASU) at the Arizona Center for Algae Technology and Innovation (AzCATI) testbed site. The CAP model is based on experimental efforts conducted primarily under NREL research and development projects.

This report focuses on front-end algal biomass production, documenting the pertinent algal biomass cultivation parameters that were input to the NREL open pond algae farm model. Through partnerships under DISCOVR, collaborators at ASU furnished details on cultivation performance metrics including biomass productivity and harvest densities for recent growth trials done at the AzCATI site. The resulting biomass productivity was calculated at 16.7 $g/m^2/day$ (ash-free dry weight [AFDW], annual average) for seasonal cultivation of *Picochlorum celeri* TG2 and *Monoraphidium minutum* 26B-AM biomass strains at the ASU site. *Picochlorum celeri* achieved the best productivity from April to September, with *Monoraphidium minutum* 26B-AM being used between October and March. *Tetraselmis striata* LANL1001, usually part of the strain rotation in previous cultivation SOTs, was supplanted by *Monoraphidium minutum* 26B-AM in this year's outdoor cultivation trials.

After incorporating the production data into a techno-economic analysis (TEA) model for algal biomass production based on a hypothetical commercial facility consisting of 5,000 acres of cultivation pond area (based on NREL's 2016 algae farm design case), the resulting **minimum biomass selling price (MBSP) for algae was estimated at $740/ton** (AFDW basis) in 2016 dollars, assuming "n^{th}-plant" economics for a mature facility utilizing low-cost unlined ponds, coupled with a targeted biomass composition consistent with NREL's high-carbohydrate *Scenedesmus* (HCSD) projections to ensure consistent nutrient costing versus downstream recycle credits from conversion operations. Alternatively, a scenario assuming the use of fully lined ponds would translate to an SOT biomass cost of $920/ton. Another alternative scenario was also considered based on evaporation rates and salt blowdown disposal requirements reflective of the Algae Testbed Public-Private Partnership (ATP^3) consortium's previous Florida Algae (FA) site (the basis for prior 2015–2016 SOT data before being decommissioned and unavailable for later SOTs). This scenario would reduce **MBSP to $654/ton** for the unlined pond case or $833/ton for the lined case, given significantly lower net evaporation rates (evaporation

minus precipitation) and thus salt accumulation levels in the ponds, a critical factor to consider for saline cultivation.

Relative to the Fiscal Year (FY) 2022 SOT at $681/ton or $602/ton for ASU and FA evaporation scenarios, respectively (unlined pond basis), this year's numbers represent a significant increase in MBSP of around 8.5%. This is primarily attributed to the drop in yearly average cultivation productivity observed at the AzCATI site (supported by the efforts under the DISCOVR consortium noted above) during FY 2023 cultivation campaigns. After the rebound in annual productivities observed in the FY 2022 SOT, this year's SOT saw a reduction in productivity for all seasons: 10% in fall, 13% in winter, 11% in spring, and 8% in summer. Experimental online time was shown to slightly decrease, with the number of cultivation production days behind the seasonal productivity data down to 350 days (357 in FY 2022), exceeding NREL's n^{th}-plant model basis fixed at 330 days per year of production uptime. After including downstream dewatering/blowdown and short-term storage losses, the overall modeled biomass production output to conversion was calculated at 24.3 tons/acre-yr for both the ASU and FA evaporation basis. Outdoor cultivation campaigns over recent SOT trials have made use of a fungicide to control contamination during key seasons. While the cost of fungicide utilized experimentally was not explicitly included in this n^{th}-plant analysis, prior sensitivity cases in past SOTs have shown the inclusion of fungicide cost to incur minimal impacts to MBSP below $10/ton; thus, this was not evaluated further this year.

Finally, this milestone reports on key process sustainability indicators for the biomass production stage, including annual biomass yields, facility power demand, and water consumption. 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 (ANL) collaborators. Expanding from the industry case study that was included in the 2022 SOT, in Appendix C of this report we provide an update reflecting improved performance data observed by an industry collaborator attributed to the use of a new strain achieving higher lipid productivity rates beyond what was demonstrated previously.

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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 (NPV) of zero for a 10% internal rate of return (IRR) 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 design reports for both the production of algal biomass and the conversion of algae to fuels via the "combined algae processing" (CAP) pathway [2, 3], both of which focused on out-year targets that, if achieved, would translate to a modeled MBSP of $494/ton for biomass (2014 $, ash-free dry weight [AFDW] basis) and MFSP of $5.90 per gallon gasoline equivalent for resulting fuels (after revising the original CAP design case to match up with the outputs from the newer algae farm design case, as documented in the 2016 Multi-Year Program Plan [4]). The latter MFSP projection was based on NREL's original CAP approach focused on fuels via well-understood conversion technologies [5], which is evolving toward a focus on hydrocarbon fuels and value-added coproducts to reduce the MFSP toward future targets. However, to achieve such fuel cost goals in the future, substantial improvements are required, particularly around biomass cultivation costs, representing the largest contributor to overall fuel cost, driven most strongly in turn by the achievable annual cultivation productivity. Accordingly, this has been the primary parameter of focus in prior algae farm State of Technology (SOT) updates since 2015, as well as more broadly in the Bioenergy Technologies Office (BETO) Algae Platform as the subject of numerous funding grants over that time frame.

Upon initiation of algal MBSP benchmarking with the Fiscal Year (FY) 2015 SOT, the demonstrated annual productivity was 8.5 $g/m^2/day$ based on the first year of data generated under a prior consortium titled the Algae Testbed Public-Private Partnership (ATP^3), translating to a modeled MBSP of $1,142/ton in 2016 $. Relative to final future targets of $488/ton at 25 $g/m^2/day$ (updated here to 2016 $ and 21% taxes, versus $494/ton in 2014 $ noted earlier), this implied a need to improve productivity roughly threefold in order to reduce MBSP by 60%. Initially, subsequent improvements made after the FY 2015 SOT were modest relative to the degree of improvement ultimately required, but this in part reflected the fact that the initial focus of ATP^3 was strictly to maintain uniformity across testbed sites in establishing transparent benchmarks more than to improve performance. More recently, efforts have shifted to specifically focus on improving cultivation productivity based on hypothesis-driven research to evaluate the most promising strains and cultivation conditions, translating to a more notable improvement in recent SOTs.

The biomass production SOT inputs for the present exercise were all sourced from the Arizona Center for Algae Technology and Innovation (AzCATI) testbed site operating outdoor ponds over seasonal periods spanning the course of a year. All cultivation trials selected for incorporation in this year's 2023 SOT benchmark leverage Arizona State University's (ASU's) expertise in performing the cultivation work under the support of the Development of Integrated Screening, Cultivar Optimization, and Verification Research (DISCOVR) consortium (discovr.labworks.org/). In keeping with prior SOTs, the cultivation practices and data generation were all based on consistent methods that have been well established by ASU across all season/strain cases. Beyond the crucial cultivation operation itself, other steps in the algae farm model are considered either outside the scope of battery limits (such as CO_2 and nutrient delivery logistics) or otherwise outside the scope of experimental work and therefore available data to which we have access (namely algal biomass dewatering, which was maintained fixed in the biomass production SOT model, consistent with the design case). The model will be improved in out-years with the incorporation of relevant data in these areas, replacing the assumptions currently in place.

We again reiterate that the present SOT analysis and the resultant MBSP 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 prices (MBSPs) have 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. We also acknowledge 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) 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 algal biomass modeling work conducted for this SOT milestone makes use of the prior Aspen modeling framework that was originally established for the 2016 algae farm design report [2, 3]. For the present SOT update, NREL's publicly available, Excel-based techno-economic analysis (TEA) modeling tool reflecting this same framework was exercised, after updating to the same process/financial parameters as employed for recent SOTs [6]. The process models remain separated between front-end cultivation and dewatering of algal biomass and back-end conversion of biomass via CAP. However, by utilizing the same biomass flow rates, concentrations, and costs (MBSPs)—as well as pertinent credits for nutrient and CO_2 recycles—consistently between the two sides of the process, the resulting MFSP is consistent with a single fully integrated production and conversion facility.

The process schematic for the algal biomass production process as the subject of this SOT discussion is depicted in Figure 1. In summary, the overarching process for the production facility consists of 5,000 acres of production ponds (10 acres each) with a total facility footprint of 7,615 acres, coupled to an inoculum propagation system consisting of a series of closed and open growth systems of increasingly larger size, as well as dewatering operations made up of in-ground gravity settlers, hollow fiber membranes, and centrifugation in sequence to ultimately concentrate the biomass from the harvested density up to 20 wt % solids AFDW. The production facility also includes costs for CO_2 (sourced from off-site flue gas carbon capture technology), fertilizer nutrients, delivery pipelines for makeup water from a nearby groundwater resource, and pipelines for on-site culture circulation and CO_2 delivery to ponds. With the ponds representing the critical and most costly step of the process, the n^{th}-plant commercial facility stipulates the use of 10-acre ponds, which are considerably larger than today's "large-scale" standards of 2–3-acre ponds, in order to maximize economy-of-scale benefits. There is an additional stipulation that the ponds are unlined (making use of native clay soils) except for small portions of the pond where a plastic liner is used to control erosion. While such a low-cost pond design may reasonably be viewed as representative of a future n^{th}-plant facility, a second alternative scenario also considers the use of fully lined ponds that are more typical in today's early demonstration facilities (or which otherwise may more likely be required in the case of saline cultures). The cost and circulation power demands for the 10-acre ponds are based on average values attributed to four separate pond design estimates that were furnished to NREL from external consultants in support of the 2016 design report.

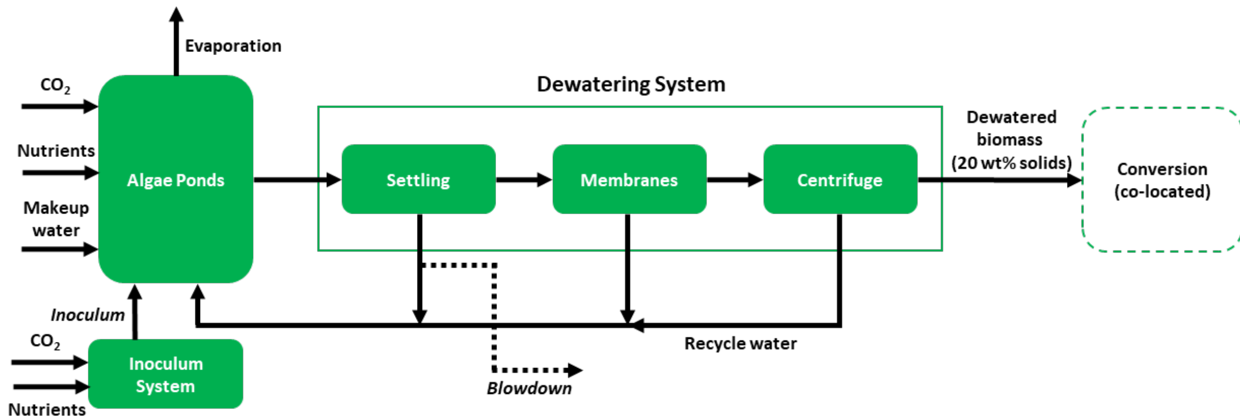

Figure 1. Schematic diagram summarizing key operations for algae biomass farm process model.

Experimental data outputs to SOT model are primarily focused on the main production pond step, with other operations either considered outside battery limits (CO_2, nutrient, and water logistics) or otherwise outside the scope of currently available data (dewatering), and thus set consistent with future design case targets.

As noted above, the inputs for the biomass production model were based on seasonal performance data generated under cultivation trials at the AzCATI testbed site over the past year (data from fall 2022 through summer 2023 feeding the FY 2023 SOT), with the key parameters utilized in the TEA model being productivity rates, biomass density at harvest, and average daily pond evaporation. Biomass composition estimates are also provided here. However, similar to previous SOT practices, the measured composition is based on biomass cultivated under nutrient-replete conditions, translating to high levels of protein and ash but relatively low levels of carbohydrates and lipids. More details on estimated and measured composition are provided below, but in summary, combined carbohydrate and lipid levels generally remain below 30% for the seasonal strains reflected in the FY 2023 SOT, which is impractical for NREL's CAP model in its historical configuration focused to date on these two constituents, while protein has traditionally been relegated to anaerobic digestion. Thus, also similar to prior SOTs, the base case FY 2023 SOT model assumes the composition of high-carbohydrate *Scenedesmus* (HCSD) for the cultivation process model, given that *Scenedesmus* was the basis used for CAP conversion experiments, and this composition is also consistent with the targeted 2030 goals as described in the algae farm design case [3]. The SOT baseline cultivation model therefore assumes seasonal productivities, harvest densities, and evaporation rates attributed to the provided cultivation measurements across two seasonally rotated strains (*Picochlorum celeri* and *Monoraphidium minutum*), overlaid with HCSD compositional assumptions for nutrient costing.

Details on cultivation protocols and methods, as well as productivity calculations used to inform this year's SOT, are consistent with prior SOTs [7, 8] and based on work performed by the same partners at ASU. The cultivation experiments are carried out in 4.2-m^2 open ponds with online monitoring of culture health. Operational conditions include semi-continuous operation over all seasons with harvesting and dilution of the cultures up to three times per week, from which the productivity is calculated as harvest yields based on AFDW. Additionally, while there was a substantial number of other experimental activities and strains evaluated under the support of DISCOVR, as well as other collaborations making use of ASU's testbed facilities, this milestone report is not intended to provide an exhaustive summary of all such activities. We defer to the associated reports for those respective efforts to provide a more thorough documentation of all activities, methods, hypotheses investigated, lessons learned on what worked and did not work, etc. Only those details as pertinent to the cases/datasets selected to form the basis for the SOT inputs are discussed here.

Fall cultivation trials considered three strains: *Picochlorum celeri* TG2, *Monoraphidium minutum* 26B-AM, and *Tetraselmis striata* LANL1001. The strain rotation with best productivities followed the same pattern as in FY 2022: *P. celeri* in September and 26B-AM in October and November. Despite a significant decline relative to FY 2022 for September, *P. celeri* reached a monthly productivity of 19.6 g/m^2/day, a decrease of 1.5% in comparison to the same month in FY 2022. On the other hand, 26B-AM showed more significant reductions in productivity relative to FY 2022 for October (8.7%) and November (25.2%), reaching 15.8 and 8.6 g/m^2/day, respectively. The formal SOT seasonal average for this season was 14.7 g/m^2/day, a decline of 9.7% compared to 16.2 g/m^2/day for FY 2022. The cause for the reductions in productivity is still unclear, particularly for *P. celeri*, as contaminations with aphelids (and potentially bacteria) could have been active at the time of 26B-AM cultivations. Additionally, measurements indicate overall warmer morning temperatures in September and October 2022 but cooler in November for both maximum and minimum water temperatures—something that could ultimately influence the observed productivities.

Winter trials followed, with 26B-AM being the overall top performer in FY 2023. For comparison purposes, *T. striata* was the main strain for the season in FY 2022. The 26B-AM strain showed productivities of 6.4, 7.2, and 9.9 g/m^2/day for December, January, and February, respectively, which correspond to reductions of 22.9%, 5.3%, and 11.6% relative to *T. striata* performance in the previous year. In FY 2023, *T. striata* showed an overall decline in productivities of more than 33% relative to FY 2022, being supplanted by 26B-AM. While the exact causes for the reduced performance of *T. striata* have yet to be determined, several possibilities exist in the form of an unusually cold winter, variability with respect to flocculation behavior, and differences in the overall microbial community.

Seasonal productivities for both *T. striata* and *P. celeri* during spring continued to decline in comparison with the same period in FY 2022. The strain rotation strategy considered in this season consisted of 26B-AM being considered in March and *P. celeri* in both April and May. The overall productivity for spring was estimated at 17.7 g/m^2/day, a reduction of 11.1% in comparison to the same season in FY 2022. All months saw a decline in productivity relative to the same period in the previous year: 10.3% in March, 7.8% in April, and 14.3% in May. Again, the reasons for this behavior remain unclear, although amoeba grazing was observed for *P. celeri* cultivations.

Finally, an overall decline of 8.2% in the average productivity was measured in summer. *P. celeri* showed the largest decline in June (19.6%) and only slight reductions in July and August (around 2% each) in comparison to the previous year. This season saw continuing pest activity in the form of active grazing by amoeba, suspected bacterial parasitoids, and by end of the summer, fungal parasitoids, which could have played a role in the lower productivities observed.

As a result from the combined seasonal performances, the overall annual average for FY 2023 was 16.7 g/m^2/day, a net decrease of 9.9% in comparison to the 18.6 g/m^2/day achieved in the previous FY (detailed in Table 1). Additional detailed modeling analysis may be warranted to investigate the contribution of both contaminations and abiotic parameters toward the decline in productivities seen in FY 2023 in comparison to FY 2022 numbers. Based on this year's overall performance, future outdoor cultivation trials will require a year-over-year increase in productivities of around 6% so BETO's goal of 25 g/m^2/day can be achieved by 2030.

Table 1. Monthly Cultivation Performance for FY 2023 SOT Trials.

Source: John McGowen, ASU

Season	Month	Productivity, g/m^2/day	AFDW at Harvest, g/L	Strain [a]	Days	Season Avg.
Fall	September	19.6	0.29	*P. celeri*	30	14.7
	October	15.8	0.32	26B-AM	22	
	November	8.6	0.25	26B-AM	27	
Winter	December	6.4	0.31	26B-AM	29	7.8
	January	7.2	0.31	26B-AM	34	
	February	9.9	0.27	26B-AM	28	
Spring	March	13.9	0.31	26B-AM	32	17.7
	April	18.8	0.30	*P. celeri*	26	
	May	20.3	0.30	*P. celeri*	30	
Summer	June	24.9	0.37	*P. celeri*	30	26.7
	July	27.7	0.36	*P. celeri*	30	
	August	27.5	0.31	*P. celeri*	32	

[a] Strain IDs = *Picochlorum celeri* and *Monoraphidium minutum* 26B-AM.

Table 2 presents a summary of the cultivation productivity, harvest density, and daily evaporation rates on a seasonal average basis attributed to the ASU data used in the 2023 SOT, in comparison to prior data used in the 2016–2022 SOTs (data for the 2015 SOT are omitted due to space constraints; the reader is referred to a previous cultivation SOT report for the full dataset related to this year [9]). As noted in prior SOT milestone reports, the first 2 years constituting the 2015–2016 SOTs were based on cultivation work done at ATP^3's Florida Algae (FA) testbed site, given improved productivities and climate conditions that had been observed at that site while it was operating. However, that site was subsequently decommissioned as the land it occupied was no longer available for ATP^3 use, which prompted a change to the ASU testbed site for all cultivation work supporting the 2017 SOT onward. This incurs an obvious but unavoidable disconnect in consistently comparing cultivation performance throughout the full span of the reported years, given different weather variables (e.g., solar irradiance, temperatures, seasonal swings) between the two testbed locations. Accordingly, the SOT continues the prior practice of evaluating costs for the AzCATI-demonstrated productivities overlaid with both ASU and FA seasonal evaporation rates.

Based on the selected cases for the FY 2023 SOT as shown in Table 2, the resulting year-average productivity is 16.7 g/m^2/day, which represents a 10% decline over the FY 2022 SOT basis of 18.5 g/m^2/day, with reductions in productivities across all seasons. This result is, however, accompanied by a very high usage of the experimental ponds—close to 100% of every month—equating to 350 days of productive cultivation uptime over the full course of FY 2023 (exceeding the fixed n^{th}-plant model assumption at 330 days/year). This latest performance level is on par with data previously reported elsewhere publicly [10–12], including the SOT for the previous FY [9], and is based on transparent data and calculation methods provided firsthand. A direct comparison against such other reported values is obfuscated by different locations, pond designs, harvesting protocols, and calculation methodologies for productivity.

Table 2. Cultivation Productivity (AFDW), Harvest Density (AFDW), and Daily Evaporation Rate for Selected 2023 Cultivation Trials at ASU Site, Compared Against Prior Cultivation Trials at ASU and FA Sites

	Productivity, g/m^2/day	Harvest Density, g/L	Evaporation Rate, cm/day	Algae Strain	Harvests per Week	Harvest Volume, Fraction of Pond	Daily Dilution Rate, Fraction of Pond
2016 SOT (Florida Algae/ATP^3)							
Fall 2015	7.0	0.20	0.01	*Desmo*	3x	0.50	0.21
Winter 2014	5.0	0.23	0.01	*Nanno*	1x	0.75	0.11
Spring 2015	11.1	0.28	0.14	*Nanno*	3x	0.25	0.11
Summer 2015	13.3	0.32	0.02	*Desmo*	3x	0.50	0.21
Average	**9.1**	**0.26**	**0.04**				
2017 SOT (ASU/ATP^3)							
Fall 2016	8.5	0.30	0.7	*Nanno*	N/A (batch, harvested every 1–3 weeks)		
Winter 2016	5.5	0.36	0.2	*Kirch*	N/A (batch, harvested every 2–3 weeks)		
Spring 2016	13.2 (ARID) [a]	0.74	0.9	*Scened*	5x	0.25	0.18
Summer 2015 [b]	14.1	0.32	1.2	*Desmo*	3x	0.50	0.21
Average	**10.3**	**0.43**	**0.7** [e]				
2018 SOT (ASU/ATP^3-DISCOVR-RACER) [c]							
Fall 2016 [d]	8.5	0.30	0.7	*Nanno*	N/A (batch, harvested every 1–3 weeks)		
Winter 2018	7.7	0.69	0.2	*Scened/Monor*	N/A (batch, harvested every 10–13 days)		
Spring 2018	15.2	0.70	0.9	*Monor*	1–3x	0.83	0.17
Summer 2018	15.4	0.35	1.2	*Desmo X2*	3x	0.55	0.20
Average	**11.7**	**0.51**	**0.7** [e]				
2019 SOT (ASU/DISCOVR)							
Fall 2018	11.4	0.41	0.7	*Desmo/Monor*	2.4x (avg)	0.50	0.17
Winter 2019	6.5	0.51	0.2	*Monor*	1.3x (avg)	0.65	0.12
Spring 2019	18.7	0.60	0.9	*Scened/Monor*	2.0x (avg)	0.63	0.18
Summer 2019	27.1	0.43	1.2	*Scened*	3.0x (avg)	0.75	0.32
Average	**15.9**	**0.49**	**0.7** [e]				
2020 SOT (ASU/DISCOVR)							
Fall 2019	15.0	0.35	0.7	*Scened/Monor*	2.3x (avg)	0.64	0.22
Winter 2020	8.3	0.55	0.2	*Monor*	1.2x (avg)	0.70	0.12
Spring 2020	18.5	0.43	0.9	*Scened/Monor*	2.4x (avg)	0.78	0.28
Summer 2020	31.6	0.50	1.2	*Pico*	3.0x (avg)	0.79	0.34
Average	**18.4**	**0.46**	**0.7** [e]				
2021 SOT (ASU/DISCOVR)							
Fall 2020	19.1	0.35	0.7	*Pico/Tetra*	2.3x (avg)	0.76	0.27
Winter 2021	8.3	0.33	0.2	*Tetra*	1.2x (avg)	0.76	0.13
Spring 2021	19.4	0.41	0.9	*Monor*	2.3x (avg)	0.69	0.24
Summer 2021	23.8	0.38	1.2	*Pico*	2.8x (avg)	0.79	0.32
Average	**17.6**	**0.37**	**0.7** [e]				
2022 SOT (ASU/DISCOVR)							
Fall 2021	16.2	0.34	0.7	*Pico/Monor*	2.3x (avg)	0.67	0.23
Winter 2022	9.0	0.29	0.2	*Tetra*	1.5x (avg)	0.62	0.14
Spring 2022	19.8	0.38	0.9	*Monor/Pico*	3.0x (avg)	0.62	0.27
Summer 2022	29.0	0.41	1.2	*Pico*	3.4x (avg)	0.71	0.35
Average	**18.5**	**0.35**	**0.7** [e]				
2023 SOT (ASU/DISCOVR)							
Fall 2022	14.7	0.29	0.7	*Pico/Monor*	2.5x (avg)	0.61	0.24
Winter 2023	7.8	0.30	0.2	*Monor*	1.2x (avg)	0.72	0.13
Spring 2023	17.7	0.30	0.9	*Monor/Pico*	2.9x (avg)	0.68	0.28
Summer 2023	26.7	0.35	1.2	*Pico*	4.0x (avg)	0.68	0.40
Average	**16.7**	**0.31**	**0.7** [e]				

[a] Algae Raceway Integrated Design.
[b] No new summer 2016 data available; summer 2015 data at ASU are maintained for 2017 SOT.
[c] RACER: Rewiring Algal Carbon Energetics for Renewables.
[d] No new fall 2017 data available; fall 2016 data at ASU are maintained for 2018 SOT.
[e] Evaporation rate set based on 2017 algae harmonization report for site nearby Phoenix, Arizona (30-year average).

Similar to prior SOT practices, the base case SOT biomass model conducted here maintains the values for seasonal cultivation productivity performance and pond densities as demonstrated at ASU but overlaid with the HCSD biomass compositional attributes for purposes of running the same HCSD composition through the CAP model as well, and to ensure consistent treatment between raw cultivation nutrient/CO_2 costs versus recycle credits from downstream conversion. The HCSD composition is also consistent with the basis utilized in the 2016 algae farm design case. As an alternate sensitivity case, although harvested compositions were not available for the 2023 trials, if the harvested compositions as presented and discussed in the FY 2022 SOT report (likely to remain consistent here) [9] were reflected through the SOT models, the resultant MBSPs would increase by approximately $94/ton relative to the HCSD basis, primarily by way of increased N/P nutrient demands (although noting that the majority of this increase would subsequently be offset by nutrient recycle credits taken in downstream conversion models). It may be technically and economically feasible to achieve the HCSD compositional basis by adjusting the cultivation approach to include a nutrient-depleted cultivation induction phase that rapidly shifts biomass composition [13]. This is the basis of an approach taken by Viridos using engineered algae strains and implemented at the multi-acre scale at the California Advanced Algae Facility (CAAF). Appendix C presents a case study reflecting updated data furnished by Viridos for high-lipid cultivation in simulated pond conditions.

Table 3. Elemental and Component Compositions for High-Carbohydrate Scenedesmus (HCSD) Biomass (Used for the SOT Base Case Model), Adjusted to 100% Mass Balance Closure, per NREL Algae Farm Design Case [3, 14]

Elemental (AFDW)	HCSD Basis Composition
C	54.0
H	8.2
O	35.5
N	1.8
S	0.2
P	0.22
Total	100.0%
Component (dry wt)	
Ash	2.4
Protein	13.2
FAME lipids	26.0 [a]
Glycerol	3.0 [a]
Non-fuel polar lipid impurities	1.0
Sterols	1.8 [b]
Fermentable carbohydrates	47.8 [c]
Other carbohydrates (galactose)	3.2
Cell mass	1.6
Total	100.0%

[a] Lipids originally characterized as triglycerides (1:1 FAME equivalent); adjusted here to free fatty acid plus glycerol (reflective of actual components in pretreated hydrolysate for *Scenedesmus* biomass).
[b] Sterols originally included in "polar lipid impurity" fraction in prior models. Value currently estimated for HCSD, based on a representative earlier-harvest biomass sample.
[c] "Fermentable carbohydrates" consists of 75.1% glucose and 24.9% mannose.

For modeling purposes, the SOT cultivation data for the parameters noted above were input into the "Area 100" section of the biomass production model (cultivation ponds). All other portions of the model were unchanged relative to details described in the design report [3], including makeup CO_2 and water delivery costs to the facility, as well as dewatering design and performance (maintaining the use of in-ground gravity settlers, followed by hollow fiber membranes, and then centrifugation to concentrate the biomass to 1%, 13%, and then 20% AFDW, respectively). In practice, the use of several strains in the FY 2023 SOT dataset may incur challenges in dewatering through primary settling, based on qualitative observations for their settling propensity during the cultivation campaigns. However, as dewatering remains outside the scope of SOT experimental focus, the basis dewatering approach was left unchanged here (though dewatering operations and/or prioritizing for strains with good settling ability have already been identified as key issues for future investigation).

The inoculum system capital and operating costs were maintained at the same fraction of production pond costs as the design case basis. Facility circulation pipelines were resized to reduce pipeline diameters associated with lower overall flows and circulation rates for the SOT models relative to the design case. Additionally, CO_2 utilization in the pond was maintained at an assumed 90% of the feed CO_2. The production ponds assumed in the model were based on 10-acre individual open raceway ponds, grouped into 50 "modules" within the overall 5,000-acre farm (based on cultivation area).

As noted above, initial SOTs in FY 2015–2016 utilized cultivation data from the FA testbed site before transitioning to the ASU site for the FY 2017–2023 SOTs, given advantages for the FA site being located in the region (Gulf Coast) that has historically been viewed as most optimal for siting commercial algae farms given high productivities and low water consumption [15, 16]. In addition to the disconnects this switch incurs with respect to locational variables that influence seasonal cultivation productivity, another artifact of the transition to the ASU site that also artificially influences biomass costs is the evaporation rates, which are significantly higher in Arizona than in Florida (where "evaporation rate" here is defined as net evaporation minus precipitation to replenish pond water levels). Namely, the net annual average pan evaporation estimated for the ASU site is 0.73 cm/day, versus 0.04 cm/day previously utilized for the FA site (both largely based on evaporation rates taken from local resource assessment models for each location, again based on net evaporation less precipitation). For saline cultivation, as is currently stipulated by BETO to be required for SOTs and design cases moving forward, higher evaporation rates translate to higher blowdown requirements from the system to maintain pond salt tolerance limits of the strain. This saline blowdown must be disposed of and cannot merely be discharged to local water bodies unless the site is located on the coast and can be discharged to the ocean. The current farm models assume the use of deep-well saltwater injection, similar to practices employed for hydraulic fracturing in petroleum extraction. At an assumed makeup salt content of 7.7 parts per thousand (ppt) for locally sourced saline groundwater and an operating expense of $1.80/$m^3$ blowdown water disposal, *the blowdown requirements for a farm located in Arizona add significant costs to the overall MBSPs relative to a farm located in Florida for saline cultivation scenarios.*

To mitigate this cost as much as possible, the practice is maintained similar to prior SOTs in first routing the blowdown to evaporation ponds to reduce the overall volume of water being disposed of (based on the same seasonal evaporation rates as the production ponds), costed at

$49,455/acre assuming fully lined but simple shallow pits. The ponds are sized to reduce overall water content by 75% (near solubility limits for the dissolved salts). Additionally, the organism salt tolerance was assumed fixed at 50 ppt, which is higher than typical saline strains but within limits recently observed for a hypersaline strain up to 78 ppt and consistent with the salinity levels employed for the *P. celeri* strain. A second scenario is also considered based on evaporation rates previously modeled for the FA site to control for the influence of this variable in the overall MBSP estimates in comparing to the FA basis in prior SOTs.

Results

TEA Results

Based on the key inputs from the cultivation activities noted above that were applied through NREL's biomass production model (i.e., utilizing the SOT productivity, harvest density, and pond evaporation data modeled by PNNL's Biomass Assessment Team for the seasonal strain production cases, coupled with the fixed HCSD compositional attributes as discussed above), the resulting MBSP costs are presented in Figure 2 (and further detailed in Table 4). For reference, Figure 2 also shows the estimated SOT costs for an alternative fully lined pond scenario, as well as the final target design case projections for the same HCSD biomass as established in the biomass design report [3] (although now reflecting the target year as 2030 for ultimately achieving 25-g/m^2/day annual productivity). All current, back-cast, and future costs reflected here are consistent with the latest financial parameters based on 2016 $ and 21% tax rates, as applied universally for all BETO platform models. **The resulting MBSP was estimated as $740/ton AFDW in 2016 $ for the "unlined pond" base case when reflecting ASU evaporation rates/blowdown demands, which would reduce to $654/ton if instead reflecting FA evaporation rates, as was the basis for the 2015–2016 SOTs**. This is compared to the 2030 design case target of $488/ton (again in 2016 $, maintained as the basis for the remainder of this discussion unless otherwise noted). SOT costs for the "fully lined" alternative scenario would increase up to 27% to $920/ton or $833/ton for the ASU and FA evaporation basis, respectively. As in prior SOTs, the cost of fluazinam usage during relevant months is not explicitly included in this n^{th}-plant analysis, but this has been found in the past to constitute a minimal impact on overall costs (adding less than $10/ton to the overall MBSP when investigated in prior SOT years during months in which it was used during outdoor cultivation trials).

As documented in prior SOTs, the algal biomass cost values are strongly influenced by productivity, estimated at an annual average of 16.7 g/m^2/day (AFDW) for the DISCOVR/ASU cultivation activities described above, representing a significant decrease of nearly 10% in annual average cultivation productivity relative to the FY 2022 SOT basis (18.5 g/m^2/day) [9]. After a small increase of around 5% in productivity between FY 2021 and 2022, this year's SOT saw productivities go back to numbers found between FY 2019 and FY 2020. This performance still represents a nearly twofold improvement relative to the initial 8.5-g/m^2/day benchmark in the original FY 2015 SOT. While this highlights substantial progress over the past 7 years, further improvements still are needed to achieve the final goal of 25 g/m^2/day by 2030, or 20 g/m^2/day by 2025 (as a plausible interim case on the path to 2030). Ongoing work under the DISCOVR consortium is aiming to set out-year goals around these parameters to keep progress on track over future years. Relative to historical progress made to date (productivity improvements of 7%, 13%, 14%, 36%, and 16% in 2016–2020 relative to each preceding year, followed by a 4% reduction in 2021, a 5% increase measured in 2022, and this year's reduction of nearly 10%), it is unlikely such substantial improvements will be sustainable on such a level moving forward indefinitely. Fortunately, a reasonable degree of improvement on the order of 6% year over year is all that must be demonstrated over the next 7 years to ultimately achieve the 2030 goal of 25 g/m^2/day.

Additionally, for the recent FY 2017–2023 SOTs based on local evaporation rates pertinent to ASU's site, salt management/disposal costs were also seen to incur substantial cost penalties relative to those details at a Gulf Coast site with less net evaporation, such as FA. As noted previously, given significantly higher "net" evaporation rates (inclusive of precipitation considerations) for the ASU site (Phoenix, Arizona) versus the FA site (Vero Beach, Florida), this requires substantially more removal of blowdown, as shown in Figure 1, to maintain salt levels within strain tolerance. In turn, the blowdown must be disposed of, assuming costs commensurate with deep-well saline injection. The costs for the injection/disposal step are maintained at $\$1.80/m^3$ (2016 \$) [17–21], consistent with the FY 2017 SOT discussion. In addition, as described previously, two other mitigation measures were also maintained: (1) evaporation ponds on the blowdown waste stream to reduce overall volumes by 75%, and (2) increasing salt tolerance limits up to 50 ppt (utilized for both FA and ASU evaporation cases). Given that salt disposal incurs a large and artificial penalty on MBSP, to control for this variable and provide a more consistent comparison against the FY 2015–2016 SOTs, the alternative FY 2023 SOT scenario based on FA evaporation rates is important to consider given that overall, this basis reduces MBSP costs by $86/ton relative to the ASU evaporation basis. Thus, this reiterates a challenge in managing salt that arid climates face with high evaporation/low precipitation, relative to lower-evaporation locations (such as the U.S. Gulf Coast), if focused on saline cultivation. This also highlights opportunities for water recovery and recycling strategies in water-stressed areas. Given that the primary resources and expertise in algal cultivation to support the SOTs reside at ASU, we will continue to report on SOT MBSPs attributed to both Arizona and Florida evaporation rates, assuming similar performance could be achieved at the latter location.

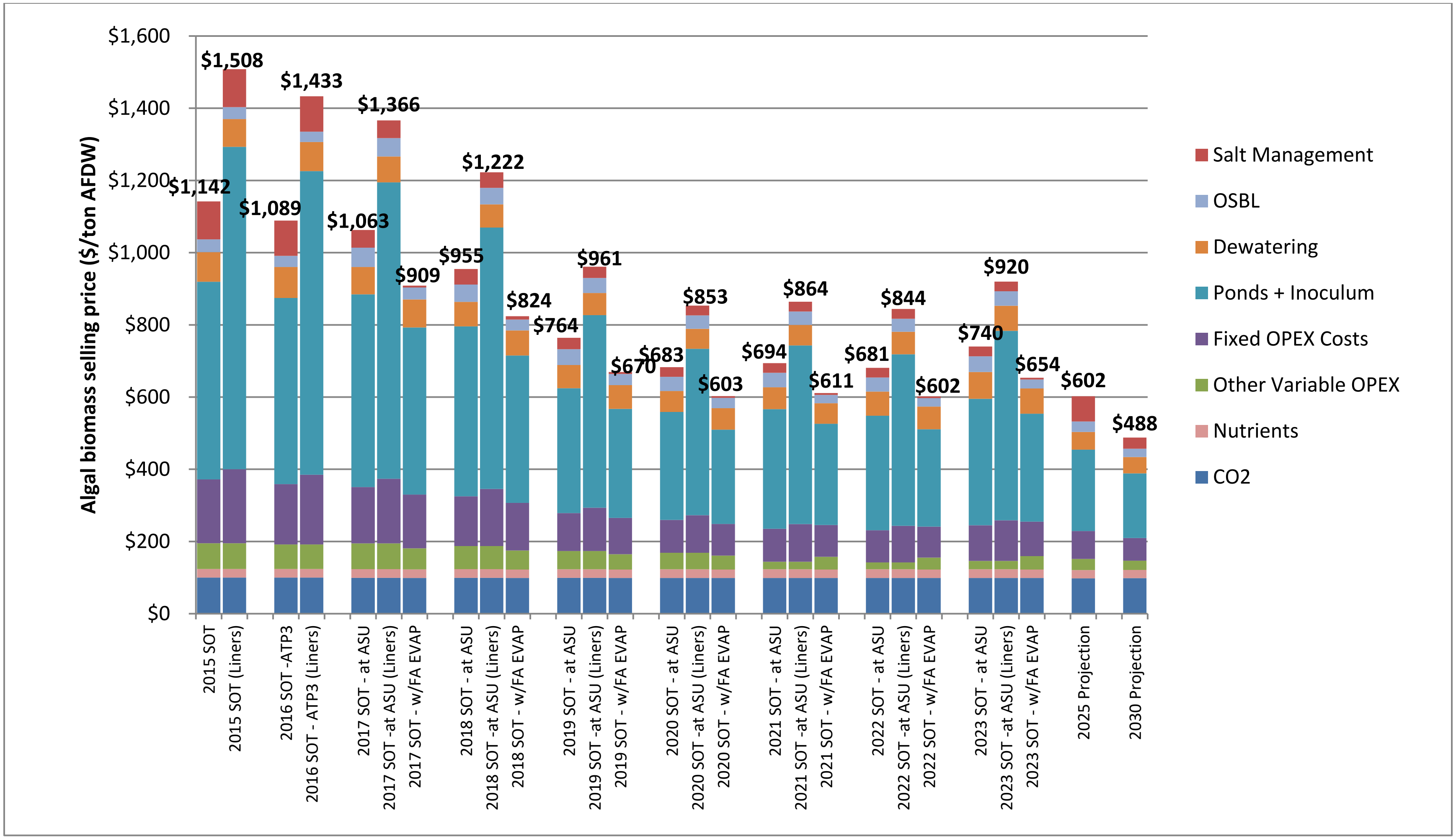

Figure 2. Biomass production MBSP results and cost breakdowns by major contributions for the 2023 SOT, compared against 2015–2022 SOTs and 2025/2030 projections for reference [3] (2016 $, all based on HCSD composition).

First two 2017–2023 SOT bars are based on ASU cultivation performance with ASU local evaporation rates; third bar is based on ASU cultivation performance with Florida Algae (FA) evaporation rates. OPEX: operating expenses; OSBL: outside battery limits.

Table 4. Technical Overview Table for Cost and Process Metrics Associated With Current and Back-Cast Algal Biomass SOT Cases, Compared Alongside Future 2025–2030 Projections – FA Evaporation Basis (Costs in 2016 $). Includes alternate 2016 point furnished by a BETO grant recipient (ABY1) performer.

Processing Area Cost Contributions & Key Technical Parameters	Metric	2016 SOT – ATP[3] [a]	2016 – ABY1 [a]	2017 SOT (FA Evap) [a,b]	2018 SOT (FA Evap) [a,c]	2019 SOT (FA Evap) [a,d]	2020 SOT (FA Evap) [a,e]	2021 SOT (FA Evap) [a,f]	2022 SOT (FA Evap) [a,g]	2023 SOT (FA Evap) [a,h]	2025 Projection	2030 Projection
Biomass selling price (with liners)	$/ton AFDW	$1,089 ($1,433)	$960 ($1,250)	$909 ($1,211)	$824 ($1,090)	$670 ($866)	$603 ($772)	$611 ($781)	$602 ($765)	$652 ($831)	$602	$488
Production cost (with liners)	$/ton AFDW	$947 ($1,291)	$824 ($1,115)	$775 ($1,078)	$704 ($970)	$556 ($752)	$500 ($669)	$516 ($686)	$501 ($673)	$542 ($721)	$509	$400
Harvest/dewatering cost	$/ton AFDW	$110	$107	$97	$87	$82	$75	$72	$79	$88	$62	$63
Other cost (facility circulation, storage)	$/ton AFDW	$32	$28	$36	$33	$32	$28	$22	$22	$24	$32	$25
Net biomass production yield [i]	Ton AFDW/ acre-year	13.2	15.6	15.0	17.0	23.1	26.7	25.5	26.8	24.3	29.9	37.2
Cultivation productivity (annual average)	$g/m^2/day$	9.1	10.7	10.3	11.7	15.9	18.4	17.6	18.5	16.7	20	25
Max. seasonal production variability	Max:min productivity	2.6:1	3.6:1	2.6:1	2.0:1	4.2:1	3.8:1	2.9:1	3.2:1	3.4:1	3:1	3:1
Biomass harvest concentration	g/L AFDW	0.26	~0.5	0.43	0.51	0.49	0.46	0.37	0.35	0.31	0.5	0.5
Total farm power demand	kWh/ton AFDW	831	739	717	647	529	486	523	513	583	395	334

[a] Base case assumes *n*[th]-plant facility utilizing low-cost unlined ponds; alternative SOT scenarios consider fully lined ponds with resulting costs shown in parentheses.
[b] FY 2017 values shown are for FA evaporation basis for consistency with prior FY 2015–2016 SOTs and future projection cases. ASU evaporation basis values are as follows: biomass selling price = $1,063/ton ($1,366/ton lined); production cost = $896/ton ($1,199/ton lined); harvest/dewatering cost = $93/ton; other cost = $74/ton.
[c] FY 2018 values shown are for FA evaporation basis for consistency with prior FY 2015–2016 SOTs and future projection cases. ASU evaporation basis values are as follows: biomass selling price = $955/ton ($1,222/ton lined); production cost = $806/ton ($1,073/ton lined); harvest/dewatering cost = $84/ton; other cost = $65/ton.
[d] FY 2019 values shown are for FA evaporation basis for consistency with prior FY 2015–2016 SOTs and future projection cases. ASU evaporation basis values are as follows: biomass selling price = $764/ton ($961/ton lined); production cost = $629/ton ($827/ton lined); harvest/dewatering cost = $79/ton; other cost = $55/ton.
[e] FY 2020 values shown are for FA evaporation basis for consistency with prior FY 2015–2016 SOTs and future projection cases. ASU evaporation basis values are as follows: biomass selling price = $683/ton ($853/ton lined); production cost = $563/ton ($733/ton lined); harvest/dewatering cost = $71/ton; other cost = $49/ton.
[f] FY 2021 values shown are for FA evaporation basis for consistency with prior FY 2015–2016 SOTs and future projection cases. ASU evaporation basis values are as follows: biomass selling price = $694/ton ($864/ton lined); production cost = $569/ton ($739/ton lined); harvest/dewatering cost = $75/ton; other cost = $50/ton.
[g] FY 2022 values shown are for FA evaporation basis for consistency with prior FY 2015–2016 SOTs and future projection cases. ASU evaporation basis values are as follows: biomass selling price = $681/ton ($844/ton lined); production cost = $551/ton ($724/ton lined); harvest/dewatering cost = $82/ton; other cost = $48/ton.
[h] FY 2023 values shown are for FA evaporation basis for consistency with prior FY 2015–2016 SOTs and future projection cases. ASU evaporation basis values are as follows: biomass selling price = $740/ton ($920/ton lined); production cost = $596/ton ($776/ton lined); harvest/dewatering cost = $91/ton; other cost = $53/ton.
[i] Net yield to downstream conversion, after blowdown/short-term storage losses.

Sustainability Metric Indicators

In addition to the TEA results noted above, we also report here on associated sustainability "indicators" attributed to the algae farm SOT model. In keeping with recent BETO guidance for all formal life cycle assessment sustainability metrics to be handled by Argonne National Laboratory (ANL) 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 ANL). Instead, Table 5 summarizes key sustainability indicators as may be taken directly from the process models. Namely, for the biomass production SOT this includes areal biomass yields, carbon efficiency from delivered CO_2, facility power demand, and water consumption. On the latter parameter, net makeup water demands are listed, but because this SOT and all future projections are to be based on saline cultivation per recent BETO guidance, this does not count against formal consumptive water use, which is based strictly on freshwater consumption (zero in the case of the algal biomass production models). The process input/output inventories furnished to ANL for subsequent supply chain sustainability analysis are summarized in Appendix B.

Table 5. Sustainability Indicators for FY 2023 SOT Biomass Model

		FY 2023 SOT Evaporation Basis	
Parameter	**Metric**	**ASU Evap**	**FA Evap**
Net biomass yield to conversion	ton/acre-yr AFDW [a]	24.3	24.3
Carbon efficiency to biomass	% of delivered CO_2 [b]	90%	90%
Electricity import	kWh/ton AFDW	708	583
Natural gas import	MJ/ton AFDW	N/A	N/A
Water consumption (SALINE ONLY)	gal/ton AFDW [c]	135,407	8,731
Water consumption (SALINE ONLY)	m^3/day [c]	188,273	12,170

[a] Net areal biomass yield after accounting for blowdown/short-term storage losses (output to conversion).
[b] No SOT data available to date; fixed constant in SOT models at 90%, consistent with targets from algae farm design case.
[c] Values are for saline makeup water only; does not count against formal BETO metrics based on freshwater consumption.

Concluding Remarks

Based on incorporating experimentally observed performance metrics for algal cultivation as achieved under DISCOVR efforts into NREL's latest algal biomass production model (while leaving all other process and costing assumptions for non-cultivation operations unchanged relative to the 2016 biomass design case), **the estimated base case SOT minimum biomass selling price is $740/ton AFDW in 2016 $ for ASU site evaporation/blowdown rates, or $654/ton for coastal evaporation/blowdown rates in FY 2023.** This represents the best available seasonal cultivation data attributed to ASU production of *Picochlorum* and *Monoraphidium* strains rotated seasonally (overlayed with NREL's HCSD biomass composition), assuming an n^{th}-plant model utilizing low-cost unlined ponds. Alternatively, a scenario employing fully lined ponds would translate to a considerably higher SOT biomass cost of $920/ton and $833/ton for the ASU and FA evaporation cases, respectively. The SOT MBSP value is tied primarily to ASU-demonstrated productivity rates, calculated at a yearly average of 16.7 g/m^2/day AFDW for the AzCATI site—after significant declines in productivity throughout all seasons relative to FY 2022 performance. This represents a decrease of nearly 10% in productivity from the FY 2022 SOT basis of 18.5 g/m^2/day, leading to an increase of 8.6% in SOT biomass cost. Such results are intermediate to the numbers found between FY 2019 and FY 2020 runs. While the cost of fluazinam fungicide utilized experimentally was not explicitly included in this n^{th}-plant analysis, previous sensitivity analyses documented in prior SOT reports have demonstrated this to incur minimal MBSP impacts—less than $10/ton—and thus this was not further evaluated here.

Given the significant logistical and cost challenges attributed to salt management and disposal in the case of saline cultivation, which are intensified in arid regions with high evaporation (as indicated by the MBSP differences between ASU and FA evaporation), from strictly a practical cost minimization standpoint, this points to either (1) utilizing freshwater cultivation in those areas (which is also a challenge given limited freshwater resources in those same areas), or (2) siting commercial facilities in low-evaporation regions (e.g., U.S. Gulf Coast area). In light of the artificial cost impact incurred around evaporation/salt blowdown disposal, which is otherwise irrelevant of scientific advancements, a more consistent basis for comparison to prior SOTs may be the ASU data overlaid with FA evaporation rates ($654/ton MBSP, a significant increase in comparison to the $602/ton benchmark in the FY 2022 SOT on this basis). In fact, because FA annual average productivity had originally been seen to be similar or marginally better than at ASU for both the FY 2015 and FY 2016 SOT datasets under ATP[3], the MBSP may plausibly be expected to be lower than the $654/ton value if a Gulf Coast site were still available.

As part of future SOT efforts, cultivation trials will need to credibly demonstrate substantial improvements in both productivity and compositional quality, in moving toward 2030 design case targets. On the first topic, as discussed in this report, it became clear that some strains might be on the top end of their performance, and even susceptible to contamination/pest pressures, which could hinder further gains in productivity moving forward. On the latter metric, in order to improve compositional quality, particularly toward higher-carbohydrate or lipid (and lower-protein) biomass, separate trials with alternative strains have been and are being carried out to improve their compositional profile for bioenergy applications from carbohydrates and lipids e.g. in the CAP conversion pathway (efforts not presented in this report). Additionally, other gaps that could be better addressed in future SOT iterations include tracking (and ultimately improving on) CO_2 utilization efficiency, TEA implications of cultivation dynamics around batch versus semi-continuous harvesting, cost trade-offs between contamination mitigation measures versus crash frequency or growth rate penalties, and experimental demonstrations for dewatering efficacy, or at least propensity for a strain to settle. Likewise, a more detailed TEA approach to quantifying economic implications for seasonal strain rotation to weigh penalties versus benefits relative to the use of a single strain year-round would be useful moving forward. Such details are being considered in greater granularity in support of a pre-n^{th}-plant "operational baseline" metric under the TEA subtask of the DISCOVR consortium, with further work planned in subsequent years of the project.

Consistent with prior SOT conclusions, we reiterate that improving cultivation performance (yield/composition) and controlling cultivation costs will be key to achieving economically viable algal biofuels for any conversion pathway option. On the cost control side, this would call for eventually demonstrating the viable use of large-scale unlined growth ponds on the order of 10 acres [3], or potentially pursuing low-cost photobioreactor/pond hybrid systems, as previously published in literature [10]. Additionally, wastewater treatment with algae systems may provide alternative cost benefits including reduced nutrient costs and water treatment credits [22]. This point has been recently reinforced through discussions with wastewater treatment technology providers in industry, who are looking to scale up algae-based wastewater treatment in the near term, as well as through internal NREL TEA modeling to quantify economic incentives for algal water treatment scenarios, albeit at more limited national scalability for commodity biomass/biofuel production potential [23, 24].

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Appendix A. TEA Summary Sheet for Base Case Biomass Cultivation SOT Benchmark Model (FA and ASU Evaporation MBSP Scenarios, 2016 Dollars)

Algal Biomass Production Process Engineering Analysis

2023 SOT with FA Evaporation Rates
All Values in 2016$

MBSP (Minimum Biomass Selling Price):	**$654 /US Dry Ton (AFDW)**
Contributions: CO2 and Nutrients	**$119 /US Dry Ton**
Cultivation	**$408 /US Dry Ton**
Other Production	**$127 /US Dry Ton**
Total Biomass Production (AFDW Basis)	0.12 MM US Ton/yr
Total Biomass Yield (AFDW Basis)	24.3 US Ton/acre/yr
	54.5 Metric tonne/ha/yr
Internal Rate of Return (After-Tax)	10%
Equity Percent of Total Investment	40%

Capital Costs	
Production ponds	$162,882,284
Inoculum Ponds	$16,568,371
CO2 Delivery	$4,881,511
Makeup Water Delivery + On-Site Circulation	$6,741,026
Dewatering	$41,911,360
Storage	$3,460,394
Total Installed Equipment Cost	$236,444,945
Added Direct + Indirect Costs	$151,555,055
(% of TCI)	39%
Total Capital Investment (TCI)	$388,000,000
Installed Equipment Cost/Annual US dry ton biomass	$1,946
Total Capital Investment/Annual US dry ton biomass	$3,193
Loan Rate	8.0%
Term (years)	10
Capital Charge Factor (Computed)	0.124

Cost Breakdowns ($/US Ton AFDW Biomass product)	
CO2	$96
Ammonia	$16
Diammonium Phosphate	$6
Power	$38
Chilled Water Utility	$7
Fixed Costs	$95
Capital Depreciation	$95
Average Income Tax	$31
Average Return on Investment	$268

Cost Breakdowns ($/yr)	
CO2	$12,100,000
Ammonia	$2,100,000
Diammonium Phosphate	$800,000
Power	$4,800,000
Chilled Water Utility	$900,000
Fixed Costs	$12,000,000
Capital Depreciation	$11,600,000
Average Income Tax	$3,800,000
Average Return on Investment	$32,600,000

Algal Biomass Production Process Engineering Analysis

2023 SOT with ASU Evaporation Rates
All Values in 2016$

MBSP (Minimum Biomass Selling Price):	**$740**	**/US Dry Ton (AFDW)**
Contributions: CO2 and Nutrients	**$119**	**/US Dry Ton**
Cultivation	**$461**	**/US Dry Ton**
Other Production	**$159**	**/US Dry Ton**
Total Biomass Production (AFDW Basis)	0.12	MM US Ton/yr
Total Biomass Yield (AFDW Basis)	24.2	US Ton/acre/yr
	54.3	Metric tonne/ha/yr
Internal Rate of Return (After-Tax)	10%	
Equity Percent of Total Investment	40%	

Capital Costs	
Production ponds	$181,370,691
Inoculum Ponds	$18,449,010
CO2 Delivery	$4,881,511
Makeup Water Delivery + On-Site Circulation	$9,697,897
Dewatering	$42,343,056
Storage	$10,146,506
Total Installed Equipment Cost	$266,888,671
Added Direct + Indirect Costs	$162,111,329
(% of TCI)	38%
Total Capital Investment (TCI)	$429,000,000
Installed Equipment Cost/Annual US dry ton biomass	$2,202
Total Capital Investment/Annual US dry ton biomass	$3,539
Loan Rate	8.0%
Term (years)	10
Capital Charge Factor (Computed)	0.132

Cost Breakdowns ($/US Ton AFDW Biomass product)	
CO2	$96
Ammonia	$17
Diammonium Phosphate	$6
Power	$46
Chilled Water Utility	$7
Fixed Costs	$99
Capital Depreciation	$106
Average Income Tax	$34
Average Return on Investment	$328

Cost Breakdowns ($/yr)	
CO2	$12,100,000
Ammonia	$2,100,000
Diammonium Phosphate	$800,000
Power	$5,900,000
Chilled Water Utility	$900,000
Fixed Costs	$12,400,000
Capital Depreciation	$12,900,000
Average Income Tax	$4,100,000
Average Return on Investment	$39,800,000

Appendix B. Life Cycle Inventory for 2023 SOT Algae Farm Model

Table B-1. SOT Front-End Input and Output Data for the Modeled Algae Production Facility (10-Acre Average Base Case).

Note: Daily rates are based on annual averages over all modeled seasons based on a 24-hour day.

Products, kg/h	**Annual Average Rates FA Evap**	**Annual Average Rates ASU Evap**
Algal biomass (AFDW) [a]	14,481	14,445
Algal biomass (total including ash) [a]	14,837	14,800
Resource Consumption, kg/h		
CO_2 (counted as biogenic)	32,152	32,152
Ammonia	292	292
Diammonium phosphate (DAP)	140	140
Total process water input *(SALINE)* [b]	494,233	7,652,354
Electricity demand, kW	8,946	10,831
Output Streams, kg/h		
Water in biomass product stream	58,510	58,363
Water lost to blowdown	43,842	1,203,588
Algae lost in blowdown	1	38
Air Emissions, kg/h		
Water lost to evaporation	379,393	6,323,219
CO_2 outgassing from ponds (counted as biogenic)	3,101	3,101
O_2 to atmosphere	24,024	24,024

[a] Total after 1% algae loss for storage.
[b] Total water input, including the amount contained in the biomass product stream sent to conversion (in many cases, a large fraction of this water is ultimately recycled back to ponds from downstream conversion steps); all makeup water is saline.

Appendix C. Industry Case Study

Similar to the FY 2022 SOT update, a separate industry case study was again also considered reflecting an alternative scenario for algal biomass cultivation and conversion. This scenario is based on updated data furnished to NREL by Viridos, a commercial company pursuing algal biofuel production through engineered strains targeting high-lipid *and* high-productivity cultivation (i.e. maximizing "lipid productivity" as a combination of these factors). As described in the 2022 SOT report [9], the Viridos approach seeks to maximize lipid productivity through a two-stage pond system employing sequential "growth" and "induction" phases utilizing engineered strains that minimize reductions in overall biomass productivity when shifting to lipid accumulation. With 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), this case study provides an additional 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. However, we stress that this case study is *not* intended to represent actual Viridos company economics or Viridos business plans for subsequent biomass conversion, as such information is proprietary and was not made available to NREL.

For the 2022 SOT case study, Viridos provided NREL with cultivation data from outdoor pond trials conducted in summer 2022. For the updated 2023 case study, outdoor cultivation data were not available, and instead Viridos supplied data from a set of controlled pond simulators able to control environmental inputs. This is a scaled-down system with programmable light and temperature profiles designed to align with outdoor conditions at the Viridos site. While this introduces the potential for uncertainty in drawing direct comparisons with the 2022 data, Viridos supplied correlation curves across three benchmark strains (including the 2022 strain) that exhibited average lipid productivity alignment within 5% versus outdoor cultivations, helping to mitigate such concerns (see Figure C-1). In turn, pond simulations with a new engineered strain in 2023 were demonstrated to achieve a maximum lipid productivity roughly 30% higher (11.1 $g/m^2/day$, average of six replicates) than the simulated control case with the 2022 strain (8.5 $g/m^2/day$, average of 32 replicates). The 2023 simulated productivity, composition, and harvest density data are summarized in Table C-1, alongside the prior 2022 outdoor cultivation data. The compositional and harvest density data reflect the state of the biomass at harvest following the final induction pond stage, while the biomass productivity data are inclusive of both the growth and induction steps (i.e. the amount of biomass produced over the total cumulative pond area and number of days spent in both pond steps). All cases were maintained at 35-ppt salinity, with blowdown removal calculated assuming the same Florida seasonal evaporation rates as the SOT base case to allow consistent comparisons with the FA baseline and the 2022 Viridos case study that assumed the same basis. For TEA modeling purposes, the growth and induction ponds were assumed to be sized and operated identically, maintaining the same 10-acre paddlewheel raceway pond design/cost and total 5,000-acre pond area footprint for the farm as utilized in the standard NREL SOT models, while also maintaining the same dewatering assumptions as in the SOT cases.

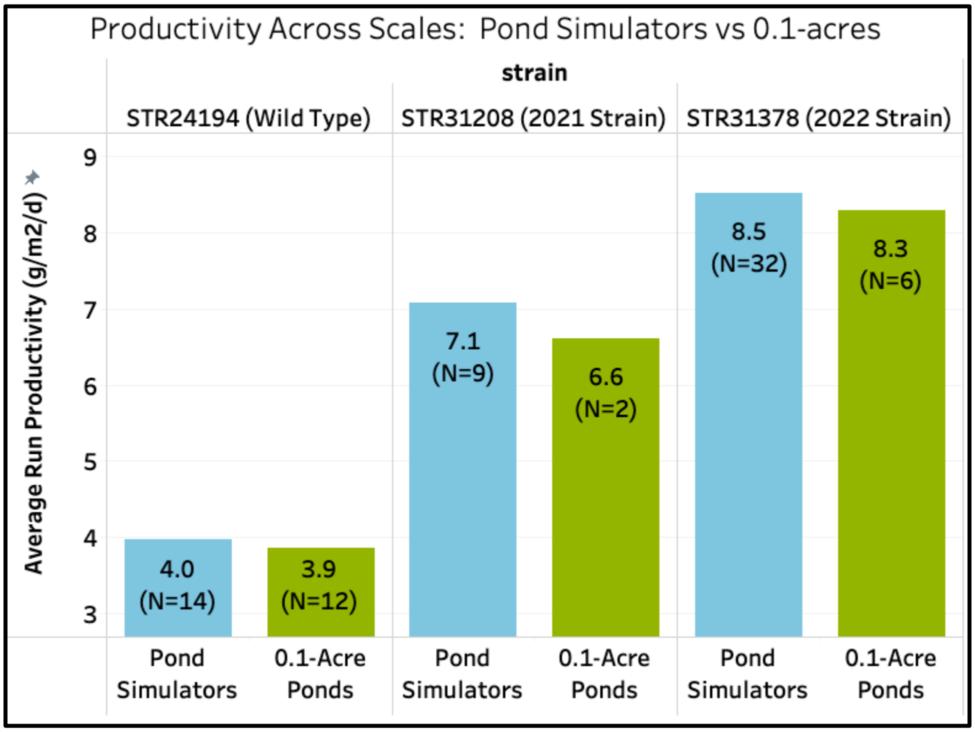

Figure C-1. Viridos-supplied correlations for lipid productivity between pond simulations and actual outdoor data spanning three benchmark strains (2022 reference strain = STR31378)

Table C-1. Viridos-Supplied Cultivation Data for 2023 Simulated Pond Trials, Compared Alongside 2022 Outdoor Cultivation Data Furnished Previously [9]

	2022 (Average, Strain STR31378, Outdoor)	2023 (Average, Strain STR33492, Simulated)
Elemental Composition (AFDW)		
C	50.3%	63.5%
H	8.9%	12.1%
O	36.3% [a]	19.9% [a]
N	2.2%	2.1%
S	2.3%	2.3%
P	0.2%	0.2% [b]
Component Composition (dry wt)		
Ash	26.7%	23.8%
Protein	8.0%	7.5%
FAME lipids	27.1%	47.4%
Non-FAME/polar lipids	-	-
Total carbohydrates	8.3%	9.1%
Cell mass/"other"	30.0%	12.2%
Total	100.0%	100.0%
Whole-biomass productivity (g/m^2/day AFDW)	22.4	20.2
Biomass density at harvest (g/L AFDW)	0.9	1.1
Lipid-only productivity at harvest (g/m^2/day FAME lipids) [c]	8.3	12.6
Max. lipid-only productivity – Viridos reported (g/m^2/day FAME lipids, max. day 5+) [d]	8.8	11.1

[a] Estimated by difference.
[b] Not measured, assumed equal to 2022 data [9].
[c] Snapshot of lipid productivity on the final day of induction (product of biomass productivity and FAME lipid content).
[d] Lipid productivity metric is based on lipid accumulation across growth and induction, as well as the cultivation footprint (days and areas) for both phases. It is standard reporting practice at Viridos to quantify a run's performance by taking the maximum value of the full process lipid productivity metrics on Day 5 or later of induction, because the team is intentionally growing past peak lipid productivity for research purposes.

As shown in Table C-1, the resulting whole-biomass productivity averaged over the simulated runs is 20.2 g/m^2/day (AFDW). When taken alone, this represents a slight decrease relative to the 2022 Viridos data from outdoor ponds at 22.4 g/m^2/day. However, when coupled with a significant 75% improvement in lipid content (from 27% on a dry weight basis in 2022 to 47% in 2023 with the new strain), the lipid productivity was shown to increase by roughly 50% based on the lipid content at harvest (12.6 versus 8.3 g/m^2/day), and by 26% based on the Viridos metric for "max. run" lipid productivity at a single point in the run after Day 5 (11.1 versus 8.8 g/m^2/day). From this basis, two scenarios were again considered, consistent with the approach taken in 2022: one sets this productivity only during the summer season and then extrapolates other seasonal productivities using the same shape of the curve (relative seasonal ratios) as the SOT basis, while a second scenario fixes this same 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]). The latter scenario reflects Viridos guidance on what they feel is attainable in other locations, potentially outside the United States, where such climatic conditions may be more optimal year-round as could sustain this productivity value on an annual basis. The resulting seasonal and annual productivities, as well as corresponding MBSPs, are presented in Table C-2 for either scenario in comparison to the SOT basis.

While the FY 2023 SOT basis reflected an MBSP of $654/ton AFDW for Florida seasonal evaporation rates, the new 2023 Viridos "seasonal productivity" case is estimated to yield an MBSP of $801/ton AFDW at the same conditions, reflective of a lower annual average biomass productivity (12.7 vs. 16.7 g/m^2/day AFDW for Viridos and the SOT basis, respectively), in turn dictated by a lower summer productivity followed by consistent relative ratios for the remaining seasons. However, similar to the discussion in the FY 2022 SOT, much of that increase in MBSP would be negated if using the compositions as harvested from the DISCOVR trials, as shown in Table 3 of that report [9], which would incur an increase of around $94/ton AFDW as opposed to the asserted HCSD compositional profile reflected for the SOT, as cultivations would require more nutrients with the higher nitrogen and phosphorus content. With the MBSP of that scenario at around $748/ton AFDW, the Viridos case with seasonal variation in biomass productivity would reflect a more comparable MBSP. The alternative case for the Viridos cultivation approach reflecting a fixed annual productivity on par with summer performance achieves a considerably lower MBSP of $554/ton AFDW, reducing by nearly $250/ton AFDW in comparison to the "seasonal productivity" basis in view of a higher annual average productivity estimated at 20.2 g/m^2/day AFDW. Downstream implications for the processing of algal biomass through NREL's CAP conversion framework are discussed next and illustrate that MBSP alone (i.e., in absence of product value) is insufficient to determine the true value of the output of an algae farm.

Table C-2. Seasonal/Annual Productivities and MBSPs Comparing the FY 2023 SOT Basis and Viridos Cases With Seasonally Varied and Fixed Annual Productivities

		FY 2023 SOT Basis	Viridos	
			Seasonal Variation	Fixed Productivity
Seasonal productivities (g/m^2/day AFDW)				
	Fall	14.7	11.1	20.2
	Winter	7.8	5.9	20.2
	Spring	17.7	13.4	20.2
	Summer	26.7	20.2	20.2
Annual average productivity (g/m^2/day AFDW)		16.7	12.7	20.2
Lipid-only productivity at harvest (g/m^2/day FAME lipids)		5.0	7.9	12.6
Minimum biomass selling price ($/ton AFDW)		$654	$801	$554

To assess the economic implications of converting the biomass to fuels and products, the CAP conversion model framework was leveraged consistent with that described in previous SOT reports [5]. The CAP approach fractionates the biomass into its biochemical constituents (carbohydrates, lipids, and proteins) to valorize each fraction individually. In the SOT CAP configuration used here, shown in Figure C-2, biomass is first subjected to a dilute acid pretreatment step to solubilize carbohydrates and enable lipid extraction. Carbohydrates are converted to fuels via fermentation to carboxylic acids and catalytic upgrading, while lipids are extracted and separated into triacylglycerides (TAG) and free fatty acids (FFA). As is consistent with the SOT framework, lipids were assumed to be present as 50% TAG and 50% FFA. The

FFA fraction is converted to fuels via hydrotreating, while the TAG portion is used for polyurethane production via epoxidation, ring opening, and reaction with a diisocyanate crosslinker, yielding 1.6 g polyurethane per g of lipid diverted to polyurethane production. The polyurethane foam coproduct, sold at a fixed price of $2.04/lb, enables significantly improved economics compared to a biorefinery producing only fuels from lipids. The remaining biomass is subjected to anaerobic digestion to recover nutrients and provide a supplemental heat source for the biorefinery. 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.

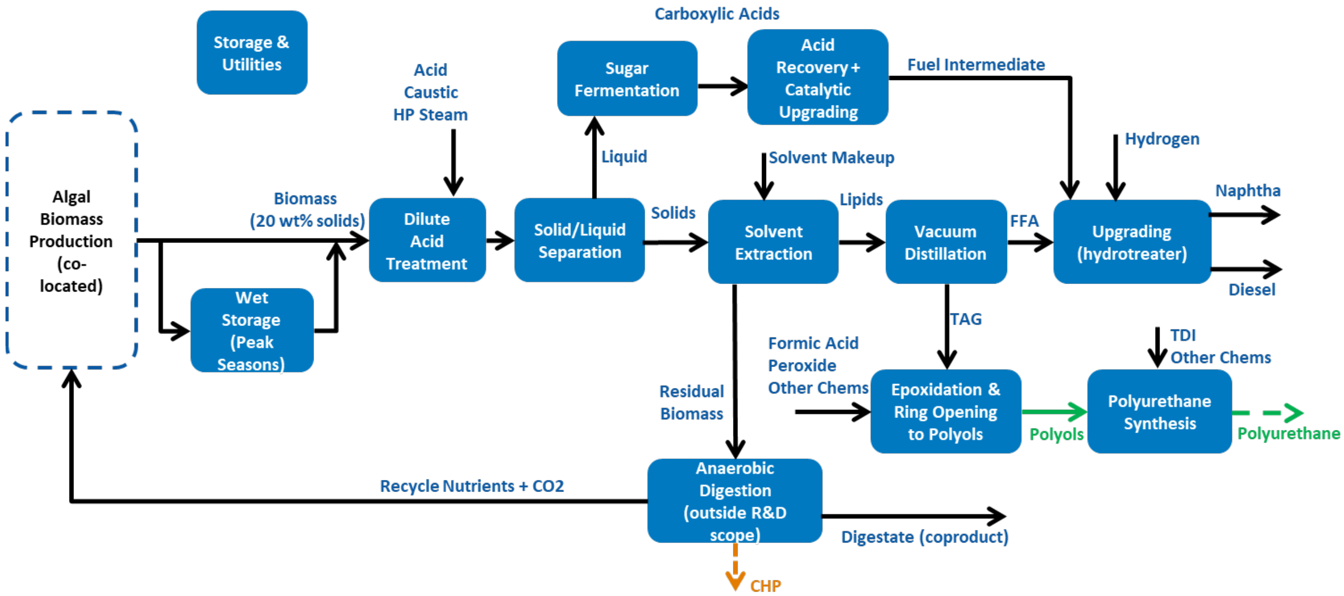

Figure C-2. Process flow diagram of the CAP configuration for the acids pathway SOT framework

The updated cultivation data from Viridos had a considerable impact on conversion process economics compared to the 2022 basis, as shown in Table C-3. The MFSP of the seasonal variation case was $0.20 per gallon gasoline equivalent (GGE), indicating that the modeled algae facility could achieve a 10% IRR even at near-zero fuel prices. The MFSP for the fixed productivity case was even more favorable, indicating a value of *negative* $4.38/GGE, meaning that a 10% IRR could be achieved even if the facility had to pay for fuel offtake, *when including polyurethane coproduction under the SOT framework assumptions*. These favorable results are strongly driven by higher fuel yields and revenues from the polyurethane coproduct, both of which are a result of the higher lipid content and associated lipid productivity enabled by the 2023 strain. For reference, the 2022 Viridos cases demonstrated a lipid productivity of 5.3 g/m^2/day (seasonally variable productivity) or 8.3 g/m^2/day (fixed productivity). Despite a slightly reduced biomass productivity, the increased lipid productivity based on simulated cultivations would result in significantly improved economics if in fact these results can be achieved in an outdoor environment, to the extent that a lower reliance on polyurethane coproducts could be accommodated while still maintaining favorable MFSPs. Lowering the reliance on a polyurethane coproduct is equally noteworthy, as this approaches the potential for algal oil to become a standalone product as a viable feedstock option for Sustainable Aviation Fuel (SAF).

Table C-3. MFSP and Fuel Production Metrics for the Viridos 2022 Outdoor and 2023 Simulated Pond Cases [5].

Results are relevant to the SOT conversion acids case, including a polyurethane coproduct from lipids and fermentation of carbohydrates to fuels via carboxylic acids.

	Viridos 2022		Viridos 2023	
	Seasonal Variation	Fixed Productivity	Seasonal Variation	Fixed Productivity
MFSP ($/GGE)	$7.69	$1.35	$0.20	−$4.38
Fuel yield (GGE/ton AFDW)	49.9	51.1	80.1	82.1
Fuel production (MM GGE/year)	5.4	8.6	7.8	12.7