Algal Biomass Production via Open Pond Algae Farm Cultivation: 2021 State of Technology and Future Research

Bruno Klein and Ryan Davis

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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National Renewable Energy Laboratory
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*
LCA	life cycle assessment
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 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 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 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 rates were calculated as 17.6 g/m^2/day (ash-free dry weight [AFDW], annual average) for seasonal cultivation of *Picochlorum celeri*, *Tetraselmis striata*, and *Monoraphidium minutum* 26B-AM biomass strains, grown in September–October (fall) and June–August (summer), November–February (fall through winter), and March–May (spring), respectively, at the ASU site.

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 $694/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 $864/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 $611/ton** for the unlined pond case or $781/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) 2020 SOT at $683/ton or $603/ton for ASU and FA evaporation scenarios, respectively (unlined pond basis), the FY 2021 SOT represents a slight increase in MBSP of 1%–2%. This is primarily attributed to a slight 4% reduction in annual cultivation productivity achieved at the AzCATI site (supported by the efforts under the DISCOVR consortium noted above) observed during FY 2021 cultivation campaigns. Although small, this was the first SOT year a slight penalty in MBSP was incurred, tied primarily to a 25% reduction in summer productivity achieved with the *P. celeri* strain (partially offset by 5% and 27% gains in spring and fall season productivities, respectively), believed to largely be attributed to monsoon weather conditions in the summer outside of experimental control. However, the underlying experimental online time was shown to be further increased, with the number of cultivation production days behind the seasonal productivity data growing from 353 (FY 2020) to 360 (FY 2021), 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 25.5 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 collaborators.

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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, which is evolving toward a focus on hydrocarbon fuels and value-added coproducts to reduce the MFSP toward future targets. However, in order 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 by roughly threefold in order to reduce MBSP by 60%. Initially, subsequent improvements made after the FY 2015 SOT point 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 2021 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 (https://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 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 since 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) 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 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 [5]. 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 (MBSP)—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 in size) 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, with 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.

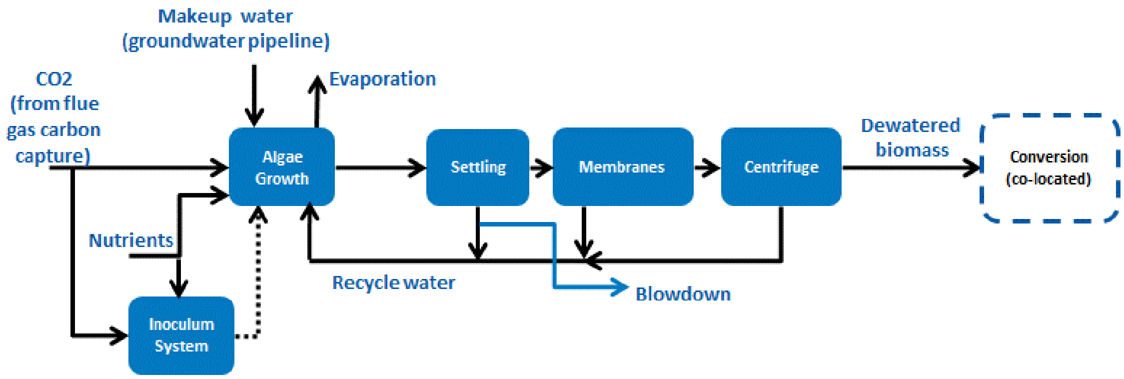

Figure 1. Schematic diagram summarizing key operations for algae biomass farm process model.

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, 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 2020 through summer 2021 feeding the FY 2021 SOT), with the key parameters utilized in the TEA model being productivity rates, biomass density at harvest, and average daily pond evaporation. Additionally, biomass composition estimates are 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 2021 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 2021 SOT model assumes the composition of high-carbohydrate *Scenedesmus* (HCSD) for both the cultivation and CAP conversion process models, 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 three seasonally rotated strains (*Pichochlorum*,* Tetraselmis*, and* Monoraphidium*), overlaid with HCSD compositional assumptions for nutrient costing. The SOT CAP conversion model assumes this same HCSD composition and resulting seasonal flows from the farm model, with yields across each conversion step set based on experimental data also generally utilizing* Scenedesmus. NREL has recently begun to investigate new CAP configuration options that may allow more feedstock flexibility, including the capability to more effectively utilize higher-protein algae strains [6], but further work and optimization is ongoing.

Details on cultivation protocols and methods, as well as productivity calculations used to inform the SOTs, 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 ash-free dry weight. Additionally, while there was a substantial amount 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/data sets selected to form the basis for the SOT inputs are discussed here.

In summary, fall cultivations demonstrated *P. celeri* outperforming *Monoraphidium* 26BAM and *T. striata* in September and October, achieving productivities of 30.1 and 15.1 g/m^2/day, respectively, although the strain was not carried forward into November, giving place to *T. striata*, with a productivity of 12.0 g/m^2/day. The resulting seasonal average was calculated at 19.1 g/m^2/day, an increase of 27.1% in comparison to fall FY 2020. This setup allows for the SOT to consider strain rotation only while maintaining the same culture medium, as both strains have been cultivated in high salinity (35 to 50 ppt). No significant contamination events were observed for *P. celeri*, even after 120 days of outdoor cultivation. *T. striata* cultures presented little contamination as well, though they incurred more significant flocculation, especially following pond harvest and/or reset.

Winter trials maintained the use of *T. striata* initiated in November and maintained through February as the "formal" basis for the SOT, though ultimately did not demonstrate overall gains for the winter season relative to FY 2020. The specific monthly values were 7.1 (matching those of the previous year's December), 8.1, and 9.8 g/m^2/day for December, January, and February, respectively. Such results and those obtained for other strains (no improvements were demonstrated alternatively for 26BAM and a moderate increase for *T. striata*) raise a question on where the winter productivity ceiling limit appears to be coming from: on the cultivar choice, in view of the overall climate for the AzCATI site, or from a standpoint of operational improvements for a given strain. This would require more focus on fewer strains in a season, thus limiting the exploration of new cultivars.

The spring trial presented an average productivity of 19.4 g/m^2/day compared to 18.5 g/m^2/day for FY 2020, a 5.1% increase for the spring season (based on *Monoraphidium* 26BAM used for the full spring season in FY 2021, while spring FY 2020 strains were 26BAM in March and *Scenedesmus* UTEX393 in April and May). Gains in productivity were made in both March and April (4.3% and 21.1%, respectively), but May values were lower relative to FY 2020 (−5.8%). *Monoraphidium* 26BAM outperformed all other strains in all three months of the spring season, being cultivated at 5-ppt salinity. Cultures of this strain showed multiple fungal parasitoid contamination events, although these have been managed through fungicide application and multiple restarts with fresh seeds to maximize performance. It is noteworthy that *P. celeri*, cultivated at 35-ppt salinity, was the second best strain for both April and May, presenting no issues of contamination or any significant signs of clumping through May, with cultures continuing into the summer season. An alternative spring data set making use of the *P. celeri* data in April and May, as well as continued use of *T. striata* in March, would translate to an average spring productivity of 17.1 g/m^2/day based on maintaining saline conditions at 35 ppt or more. Given the primary focus in the SOT for maximizing productivity, the brackish (5-ppt)

26BAM basis at 19.4 g/m^2/day was selected, though in reality the resultant blowdown and salt management implications for maintaining brackish conditions could ultimately outweigh the small productivity increase in terms of overall cost drivers (this is outside the scope of the SOT focus maintaining fixed salinity assumptions for all seasons, but is a consideration under further TEA modeling work conducted under DISCOVR).

Finally, summer FY 2021 seasonal average productivity was 23.8 g/m^2/day, compared to 31.6 g/m^2/day for the FY 2020 SOT, a substantial 24.8% decrease, even though *P. celeri* was used in both summer trials under similar cultivation conditions. It is hypothesized this reduction was attributed to an intolerance of *P. celeri* to monsoon weather conditions. While only a single minor rain event was observed each in fall, winter, and spring, multiple dust storms throughout July and into early August occurred due to an active monsoon over the summer season at the AzCATI site. Such events led to a significant increase in overall ash observed in ponds (at least for July), which could have contributed to some light attenuation and perhaps impacted productivity. The other main issue observed this season was the amount of diatom contamination in *P. celeri*. The confirmation of the decline in summer productivity attributable to weather conditions will be deferred to collaborators at Pacific Northwest National Laboratory, who will use parametrization methods to carry out a biophysical growth model analysis for this strain during summer FY 2021 weather conditions. As a result of this summer productivity decline, the overall annual average for FY 2021 was 17.6 g/m^2/day, a 4% reduction relative to the FY 2020 value of 18.4 g/m^2/day (detailed in Table 1).

Table 1. Monthly Cultivation Performance for FY 2021 SOT Trials (Source: John McGowen, ASU)

Season	Month	Productivity, g/m^2/day	AFDW at Harvest, g/L	Strain	Days	Season Avg.
Fall	September	30.1	0.46	*P. celeri*	30	19.1
	October	15.1	0.27	*P. celeri*	30	
	November	12.0	0.33	*T. striata*	32	
Winter	December	7.1	0.28	*T. striata*	29	8.3
	January	8.1	0.34	*T. striata*	34	
	February	9.8	0.37	*T. striata*	27	
Spring	March	14.7	0.37	26BAM	28	19.4
	April	20.7	0.46	26BAM	29	
	May	22.8	0.40	26BAM	31	
Summer	June	24.6	0.38	*P. celeri*	29	23.8
	July	23.3	0.41	*P. celeri*	30	
	August	23.4	0.36	*P. celeri*	31	

Strain IDs = *Picochlorum celeri*, *Tetraselmis striata LANL1001*, 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 2021 SOT, in comparison to prior data used in the 2015–2020 SOTs. As noted in prior SOT milestone reports, the first two 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 (solar irradiance, temperatures, seasonal swings, etc.) 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 2021 SOT as shown in Table 2, the resulting year average productivity is 17.6 g/m^2/day, which represents a slight 4% decline from the FY 2020 SOT basis of 18.4 g/m^2/day, with improvements in productivity demonstrated fall and spring ultimately outweighed by a larger decline in summer. Namely, fall and spring season average productivity increased by 27% and 5%, respectively, while winter average values remained the same. However, summer productivity (which has been a key driver in overall annual productivity over recent years) declined sharply by 25%, even though the same *P. celeri* strain under similar cultivation conditions was maintained consistently with that used in the summer 2020 season, as discussed above. While this represented the first decline (albeit minor) in overall annual productivity across historical SOT updates, it is also worth pointing out that these seasonal productivity data were tied to productive use of the ponds nearly 100% of every month, equating to 360 days of productive cultivation uptime over the full course of FY 2021 (exceeding the fixed n^{th}-plant model assumption at 330 days/year, and representing a further improvement over 353 days/year in the 2020 SOT). This latest performance level generally exceeds the best data previously reported elsewhere publicly [9–11], 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 2021 Cultivation Trials at ASU Site, Compared Against Prior Cultivation Trials at ASU and Florida Algae 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
2015 SOT (Florida Algae/ATP[3])							
Fall 2014	6.8	0.22	0.01	*Nanno*	1x	0.75	0.11
Winter 2014	5.0	0.23	0.01	*Nanno*	1x	0.75	0.11
Spring 2014	11.4	0.36	0.14	*Nanno*	1x	0.75	0.11
Summer 2014	10.9	0.25	0.02	*Nanno*	1x	0.75	0.11
Average	**8.5**	**0.27**	**0.04**				
2016 SOT (Florida Algae/ATP[3])							
Fall 2015	7.0	0.20	0.01	*Desmo*	3x	0.50	0.21
Winter 2014 [a]	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) [b]	0.74	0.9	*Scened*	5x	0.25	0.18
Summer 2015 [c]	14.1	0.32	1.2	*Desmo*	3x	0.50	0.21
Average	**10.3**	**0.43**	**0.7** [f]				
2018 SOT (ASU/ATP[3]-DISCOVR-RACER) [d]							
Fall 2016 [e]	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** [f]				
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** [f]				
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** [f]				
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** [f]				

[a] No new winter 2015 data available; winter 2014 data at Florida Algae are maintained for 2016 SOT.
[b] Algae Raceway Integrated Design.
[c] No new summer 2016 data available; summer 2015 data at ASU are maintained for 2017 SOT.
[d] RACER: Rewiring Algal Carbon Energetics for Renewables.
[e] No new fall 2017 data available; fall 2016 data at ASU are maintained for 2018 SOT.
[f] Evaporation rate set based on 2017 algae harmonization report for site nearby Phoenix, Arizona (30-year average).

The compositional data corresponding with the FY 2021 SOT productivity data shown in Tables 1 and 2 for the DISCOVR cultivation experiments are presented in Table 3. Fall data include the months of September and October 2020 for *Picochlorum celeri* and November 2020 for *Tetraselmis striata* (shown in parentheses for the fall column). Winter reflects exclusive use of *Tetraselmis* (December 2020–February 2021), followed by *Monoraphidium* 26B-AM in the spring (March–May 2021). Finally, summer data reflect the continued use of *Picochlorum celeri*. The compositional data shown in Table 3 represent measured averages across a robust data set of 239 samples analyzed. Generally, no significant trends in biomass composition across the four seasons can be observed because of the wide range of physiology underlying the harvested biomass samples. The exception in compositional trends can be found in a lower ash and correspondingly higher carbohydrate and protein content for the *Monoraphidium* 26B-AM case in the spring relative to all other strain cases, reflecting a lower salinity level run at 5 ppt (brackish conditions) for this strain relative to full saline for the other strains (35 ppt for *T. striata* and 50 ppt for *P. celeri*). Overall elemental compositions on an ash-free basis, however, are generally comparable across all cases. Further details and caveats behind the compositional values reported here are shown in the footnotes of Table 3.

Similar to previous SOTs, all cultivation experiments were conducted in nutrient-replete conditions, generally translating to similar component compositions as have been reported previously with respect to high protein and relatively low lipid and carbohydrate contents. Namely, fatty acid methyl ester (FAME) lipid content (reported here as free fatty acid) is consistently maintained between 7 and 9 dry wt %, and fermentable carbohydrates (glucose plus mannose) are between 4 and 6 dry wt % (12% in the case of *Monoraphidium*), while protein content is higher, between 35–43 dry wt %. Although such measured biomass compositions were expected given the focus on maximizing productivity supported by nutrient-replete conditions, they continue to reflect a difference relative to the future target composition exemplified by mid-harvest HCSD projected to be achieved by 2030 (Table 4), with a lower protein content (13 dry wt %) and higher lipid (26% FAME as free fatty acid) and carbohydrate (48%) content [3] (the HCSD composition shown in Table 4 is consistent with the algae farm design report [3], but with additional detail added now to reflect components not previously specified explicitly, such as glycerol and sterols [12]). The latter for mid- to late-harvest (and thus nutrient-deplete) *Scenedesmus* continues to be the SOT basis for experimental CAP conversion processes given that the experimentally cultivated high-protein material is not practical for such processes (at least based on historical CAP approaches taken to date). Thus, as noted above and 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, if the harvested compositions as shown in Table 3 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).

Table 3. Elemental and Component Compositions Based on Seasonal Average Values for Harvested Strains Reported in Table 1 (Adjusted to 100% Mass Balance Closure)

Elemental (AFDW) [a,b]	**Fall** *Pico/Tetra* [f]	**Winter** *Tetra*	**Spring** *Monor*	**Summer** *Pico*
C	46.9 (48.2)	48.1	51.5	51.5
H	7.3 (7.3)	7.3	7.9	7.6
O	34.3 (34.2)	33.9	29.5	28.4
N	10.1 (8.9)	9.2	9.7	11.1
S	0.2 (0.2)	0.2	0.2	0.2
P	1.2 (1.2)	1.2	1.2	1.2
Total	100.0%	100.0%	100.0%	100.0%
Component (dry wt) [b]				
Ash	22.7 (18.5)	20.4	6.8	21.1
Protein	37.9 (34.8)	35.2	43.3	41.9
FAME lipids [c]	7.6 (8.5)	7.5	7.3	8.6
Glycerol [c]	0.9 (1.0)	0.9	0.8	1.0
Non-fuel polar lipid impurities	4.6 (5.1)	4.5	4.4	5.2
Sterols [d]	0.5 (0.5)	0.5	0.5	0.5
Fermentable carbohydrates [e]	4.0 (5.7)	6.1	11.6	3.9
Other carbohydrates (galactose)	0.8 (1.1)	1.2	2.3	0.8
Cell mass	21.1 (24.8)	23.7	22.9	17.0
Total	100.0%	100.0%	100.0%	100.0%

[a] CHN composition is reported as measured CHN data corrected for ash content of the biomass; O was calculated as the difference from mass balance after estimating S and P (as 0.2% and 1.2%, respectively) and adjusted to 100%.

[b] SOT biomass compositions are less detailed than the HCSD basis; CHN and composition data for *Picochlorum celeri*, *Tetraselmis striata*, and *Monoraphidium minutum* cases are based on measured averaged data for a total of 239 harvested production samples (74 fall, 62 summer, 42 winter, and 61 spring samples) and are considered representative for primarily nutrient-replete growth conditions. Composition data are currently broken down to ash, protein, lipids as FAME (in this case triglyceride lipids measured as FAME, with an added estimate of 10% glycerol relative to measured FAME, and an assumed polar lipid headgroup fraction that increased the FAME content by at least 60%), and total carbohydrate content (reported here as 100% fermentable from the measured sum of monosaccharides detected, with an additional 20% non-fermentable and possibly unhydrolyzable or recalcitrant carbohydrates); a remaining component called “cell mass” accounts for between 16% and 19% of the biomass and reflects unidentified components that are not measured but are need to account for the mass balance.

[c] Lipids originally characterized as triglycerides (1:1 FAME equivalent), adjusted here to free fatty acid plus glycerol (as ~11% of the measured FAME content, and reflective of actual components in pretreated hydrolysate for algal biomass).

[d] Sterols originally included in “polar lipid impurity” fraction in prior models. Value currently estimated for HCSD, based on a representative earlier-harvest biomass sample; for SOT biomass, sterol concentration is estimated at a flat 0.5% of the biomass, consistent with earlier observations at NREL.

[e] “Fermentable carbohydrates” typically consist of 75% glucose and 25% mannose for all species analyzed.

[f] Fall: first value: *Picochlorum celeri* (Sept.–Oct.); value in parentheses: *Tetraselmis striata* (Nov.).

Table 4. 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, 12]

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, 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 2021 SOT data set 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 is identified as a key issue 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 2017–2021 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 [13, 14]. 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 in order 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 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 Florida Algae 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 5). 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 $694/ton AFDW in 2016$ for the "unlined pond" base case when reflecting ASU evaporation rates/blowdown demands, which would reduce to $611/ton if instead reflecting FA evaporation rates, as was the basis for the 2015–2016 SOTs**—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 28% to $864/ton or $781/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 tied to productivity, estimated at an annual average of 17.6 g/m^2/day (AFDW) for the DISCOVR/ASU cultivation activities described above, representing a small 4% decline in annual average cultivation productivity relative to the FY 2020 SOT basis (18.4 g/m^2/day) [15]. Although a small penalty, this represents the first time since the SOT benchmarking efforts began that the MBSP did not improve over the prior year, though this is to be expected occasionally in measuring experimental progress, and likely was tied primarily to adverse weather events outside of experimental control negatively impacting summer productivity. Notably, this still represents a 2.1-fold 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 six years, further improvements still remain 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 in order to keep progress on track over the next several 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 4% reduction in 2021), it is unlikely such substantial improvements will be sustainable on such a level moving forward indefinitely. Fortunately, a lower degree of improvement on the order of 4% year over year is all that must be demonstrated over the next 9 years in order to ultimately achieve the 2030 goal of 25 g/m^2/day. Additionally, a key further improvement moving forward will be to shift composition toward less replete, lower-protein biomass without sacrificing on productivity gains. DISCOVR is prepared to support continued improvements, with internal goals aspiring to exceed such levels over coming years. The data and resulting MBSP values presented here provide value as a public benchmark, as they are based on transparent, long-term growth trials with public documentation of a vast data set.

Additionally, for the recent FY 2017–2021 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 is maintained at $1.80/m^3$ (2016$) [16–20], consistent with the FY 2017 SOT discussion. In addition, as described previously, two other mitigation measures were also maintained, including (1) evaporation ponds on the blowdown waste stream to reduce overall volumes, 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 2021 SOT scenario based on FA evaporation rates is important to consider given that *overall, this basis reduces MBSP costs by $83/ton relative to the ASU evaporation basis*. Thus, this reiterates an important conclusion that *arid climates with high evaporation/low precipitation rates (such as the U.S. Southwest) are not ideal locations for siting algal cultivation facilities relative to lower-evaporation locations (such as the U.S. Gulf Coast), if focused on saline cultivation,* due purely to challenges in how to manage salt. While prior harmonization work had assumed this logic (i.e., in placing a high priority on minimizing water losses), the present work quantifies the TEA penalty for this issue. However, 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 (again, modeling by the Biomass Assessment Team may help resolve this in future SOTs).

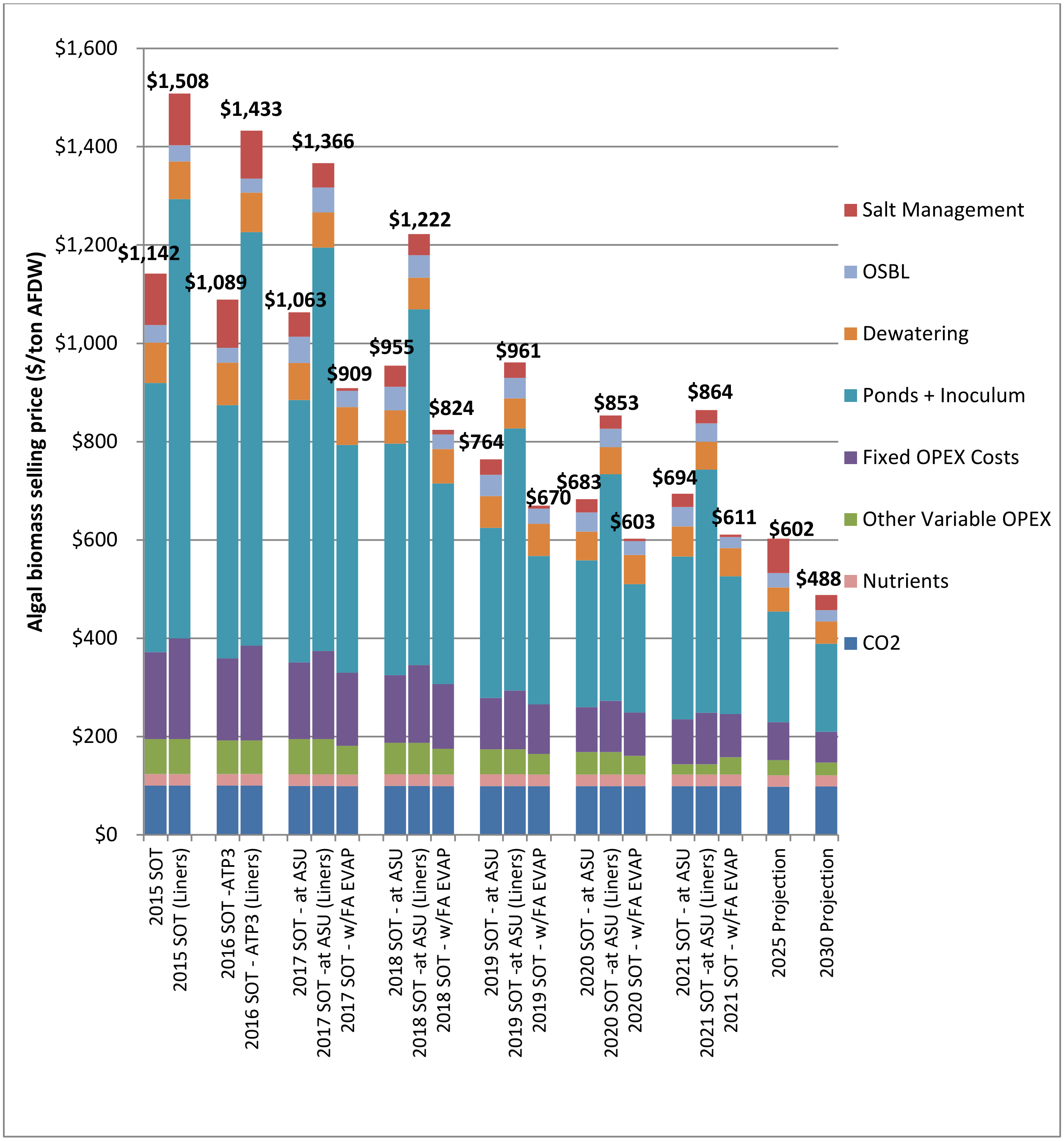

Figure 2. Biomass production MBSP results and cost breakdowns by major contributions for 2021 SOT, compared against 2015–2020 SOTs and 2025/2030 projections for reference [3] (2016$, all based on HCSD composition).

First two 2017–2021 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 5. 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 an ABY1 performer.

Processing Area Cost Contributions & Key Technical Parameters	Metric	2015 SOT [a]	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]	2025 Projection	2030 Projection
Biomass selling price (with liners)	$/ton AFDW	$1,142 ($1,508)	$1,089 ($1,433)	$960 ($1,250)	$909 ($1,211)	$824 ($1,090)	$670 ($866)	$603 ($772)	$611 ($781)	$602	$488
Production cost (with liners)	$/ton AFDW	$999 ($1,365)	$947 ($1,291)	$824 ($1,115)	$775 ($1,078)	$704 ($970)	$556 ($752)	$500 ($669)	$516 ($686)	$509	$400
Harvest/dewatering cost	$/ton AFDW	$105	$110	$107	$97	$87	$82	$75	$72	$62	$63
Other cost (facility circulation, storage)	$/ton AFDW	$38	$32	$28	$36	$33	$32	$28	$22	$32	$25
Net biomass production yield [g]	Ton AFDW/ acre-year	12.4	13.2	15.6	15.0	17.0	23.1	26.7	25.5	29.9	37.2
Cultivation productivity (annual average)	g/m^2/day	8.5	9.1	10.7	10.3	11.7	15.9	18.4	17.6	20	25
Max. seasonal production variability	Max:min productivity	2.3:1	2.6:1	3.6:1	2.6:1	2.0:1	4.2:1	3.8:1	2.9:1	3:1	3:1
Biomass harvest concentration	g/L AFDW	0.27	0.26	~0.5	0.43	0.51	0.49	0.46	0.37	0.5	0.5
Total farm power demand	kWh/ton AFDW	860	831	739	717	647	529	486	523	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] 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 GREET 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 6 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 6. Sustainability Indicators for FY 2021 SOT Biomass Model

		FY 2021 SOT Evaporation Basis	
Parameter		**ASU Evap**	**FA Evap**
Net biomass yield to conversion	ton/acre-yr AFDW [a]	25.5	25.5
Carbon efficiency to biomass	% of delivered CO_2 [b]	90%	90%
Electricity import	kWh/ton AFDW	637	523
Natural gas import	MJ/ton AFDW	N/A	N/A
Water consumption (SALINE ONLY)	gal/ton AFDW [c]	123,342	7,988
Water consumption (SALINE ONLY)	m^3/day [c]	188,968	12,273

[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 $694/ton AFDW in 2016$ for ASU site evaporation/blowdown rates, or $611/ton for Florida Algae evaporation/blowdown rates.** This represents the best available seasonal cultivation data attributed to ASU production of *Picochlorum*, *Tetraselmis*, 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 $864/ton and $781/ton for the ASU and FA evaporation cases, respectively. The SOT MBSP value is tied primarily to ASU-demonstrated productivity rates, calculated at 17.6 g/m^2/day AFDW as seasonal averages for the AzCATI site. This represents a slight 4% reduction in productivity from the FY 2020 SOT basis at 18.4 g/m^2/day, leading to a roughly 2% increase in SOT biomass cost. Although small, this increase in MBSP is attributed to a more challenging summer productivity relative to the prior year, even though the same strain and conditions were employed in the summer season (in turn hypothesized to be associated with more monsoon-type weather events in the summer). However, the reduction in summer productivity was slightly offset by an increase in spring and fall productivity rates. 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 practicality 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 ($611/ton MBSP, also a slight increase over the $603/ton benchmark in the FY 2019 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 data sets under ATP[3], the MBSP may plausibly be expected to be even lower than the $611/ton value if the FA site were still available.

As part of future SOT efforts, it is hoped that cultivation trials can credibly demonstrate substantial improvements in both productivity as well as compositional quality, in moving toward 2030 design case targets. On the latter metric, in order to improve compositional quality, particularly towards higher-carbohydrate/lower-protein biomass, *Nannochloropsis* has been eliminated from seasonal strain rotations in past SOTs, recognizing it will never achieve a suitable composition for CAP conversion, particularly around carbohydrates. 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 use of a single strain year-round would be useful moving forward. Such details as these 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 FY 2022.

Consistent with prior SOT conclusions, we reiterate that improving cultivation performance (yields/compositions) 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 in size [3], or potentially pursuing low-cost photobioreactor/pond hybrid systems, as recently published in literature [9]. Additionally, algal wastewater treatment may provide alternative cost benefits including reduced nutrient costs and water treatment credits [21]; this point has been recently reinforced through discussions with wastewater treatment technology providers in industry, who are looking to scale up algal 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 [22].

References

NREL milestone reports cited below cannot be accessed outside of NREL and DOE. Readers may contact the authors of those reports to determine if this information has been made public since publication of this report.

[1] Aspen Technology Inc. Aspen Plus. 7.2 ed. Cambridge, MA; 2007.

[2] Davis R, Kinchin C, Markham J, Tan E, Laurens L, Sexton D, et al. Process Design and Economics for the Conversion of Algal Biomass to Biofuels: Algal Biomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products. Golden, CO: National Renewable Energy Laboratory; 2014.

[3] Davis R, Markham J, Kinchin C, Grundl N, Tan E, Humbird D. Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion. Golden, CO: National Renewable Energy Laboratory; 2016.

[4] U.S. Department of Energy. Bioenergy Technologies Office Multi Year Program Plan. Washington, D.C.: Bioenergy Technologies Office; 2016.

[5] Davis R, Clippinger J. Algae Production via Open Pond Cultivation: NREL Algae Farm Excel TEA Tool (https://www.nrel.gov/extranet/biorefinery/aspen-models/). NREL; 2018.

[6] Davis R, Wiatrowski M, Kinchin C, Humbird D. Conceptual Basis and Techno-Economic Modeling for Integrated Algal Biorefinery Conversion of Microalgae to Fuels and Products. 2019 NREL TEA Update: Highlighting Paths to Future Cost Goals via a New Pathway for Combined Algal Processing. National Renewable Energy Lab, Golden, CO; 2020.

[7] Knoshaug E, Laurens L, Kinchin C, Davis R. Use of Cultivation Data from the Algae Testbed Public Private Partnership as Utilized in NREL's Algae State of Technology Assessments. National Renewable Energy Laboratory, Golden, CO; 2016.

[8] Davis R, Laurens L. Algal Biomass Production via Open Pond Algae Farm Cultivation: 2019 State of Technology and Future Research. National Renewable Energy Lab, Golden, CO; 2020.

[9] Huntley ME, Johnson ZI, Brown SL, Sills DL, Gerber L, Archibald I, et al. Demonstrated large-scale production of marine microalgae for fuels and feed. Algal Research. 2015;10:249-65.

[10] White RL, Ryan RA. Long-Term Cultivation of Algae in Open-Raceway Ponds: Lessons from the Field. Industrial Biotechnology. 2015;11:213-20.

[11] Hazlebeck D. Development of Algae Biomass Yield Improvements in an Intergrated Process Phase I. U.S. Department of Energy Bioenergy Technologies Office 2017 Project Peer Review. Denver, CO; 2017.

[12] Markham J, Davis R, Kinchin C, Grundl N. Paths to $3/GGE. Internal NREL milestone. Golden, CO; 2016.

[13] Davis R, Fishman D, Frank ED, Wigmosta MS, Aden A, Coleman AM, et al. Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model. 2012.

[14] Davis RE, Fishman DB, Frank ED, Johnson MC, Jones SB, Kinchin CM, et al. Integrated evaluation of cost, emissions, and resource potential for algal biofuels at the national scale. Environmental science & technology. 2014;48:6035-42.

[15] Davis R, Klein B. Algal Biomass Production via Open Pond Algae Farm Cultivation: 2020 State of Technology and Future Research. United States; 2021.

[16] Negewo BD. Renewable energy desalination: an emerging solution to close the water gap in the Middle East and North Africa: World Bank Publications; 2012.
[17] McCurdy R. Underground injection wells for produced water disposal. Proceedings of the Technical Workshops for the Hydraulic Fracturing Study: Water Resources Management EPA; 2011.
[18] Burnett D. Desalinating brine from oil and gas operations in Texas. Southwest Hydrology, Nov-Dec. 2005.
[19] Tultz A, Bell K. PA prefers recycling brine, Ohio favors injection. The News Outlet-Partners in Engaging Journalism.
[20] Options to Help Oklahoma Alleviate Its Emerging Oilfield Water Crisis. In: LLP BH, editor. Newsfeed; 2016.
[21] Lundquist TJ, Woertz IC, Quinn NWT, Benemann JR. A Realistic Technology and Engineering Assessment of Algae Biofuel Production. Energy Biosciences Institute, Univesiry of California Berkeley; 2010.
[22] Clippinger J, Davis R. Techno-Economic Assessment of Opportunities to Integrate Algae Farming with Wastewater Treatment. United States; 2021.

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

2021 SOT with FA Evaporation Rates
All Values in 2016$

MBSP (Minimum Biomass Selling Price):	**$611 /US Dry Ton (AFDW)**
Contributions: CO2 and Nutrients	**$119 /US Dry Ton**
Cultivation	**$383 /US Dry Ton**
Other Production	**$108 /US Dry Ton**
Total Biomass Production (AFDW Basis)	0.13 MM US Ton/yr
Total Biomass Yield (AFDW Basis)	25.6 US Ton/acre/yr
	57.4 Metric tonne/ha/yr
Internal Rate of Return (After-Tax)	10%
Equity Percent of Total Investment	40%

Capital Costs	
Production ponds	$162,400,000
Inoculum Ponds	$16,500,000
CO2 Delivery	$4,400,000
Makeup Water Delivery + On-Site Circulation	$6,700,000
Dewatering	$36,500,000
Storage	$3,300,000
Total Installed Equipment Cost	$229,800,000
Added Direct + Indirect Costs	$146,200,000
(% of TCI)	39%
Total Capital Investment (TCI)	$376,000,000
Installed Equipment Cost/Annual US dry ton biomass	$1,793
Total Capital Investment/Annual US dry ton biomass	$2,934
Loan Rate	8.0%
Term (years)	10
Capital Charge Factor (Computed)	0.123

Cost Breakdowns ($/US Ton AFDW Biomass product)	
CO2	$96.23
Ammonia	$16.38
Diammonium Phosphate	$6.48
Power	$35.69
Chilled Water Utility	$7.87
Fixed Costs	$88.03
Capital Depreciation	$87.00
Average Income Tax	$29.00
Average Return on Investment	$244.00

Cost Breakdowns ($/yr)	
CO2	$12,900,000
Ammonia	$2,200,000
Diammonium Phosphate	$900,000
Power	$4,800,000
Chilled Water Utility	$1,100,000
Fixed Costs	$11,800,000
Capital Depreciation	$11,200,000
Average Income Tax	$3,700,000
Average Return on Investment	$31,300,000

Algal Biomass Production Process Engineering Analysis

2021 SOT with ASU Evaporation Rates
All Values in 2016$

MBSP (Minimum Biomass Selling Price):	**$694 /US Dry Ton (AFDW)**
Contributions: CO2 and Nutrients	**$119 /US Dry Ton**
Cultivation	**$436 /US Dry Ton**
Other Production	**$139 /US Dry Ton**
Total Biomass Production (AFDW Basis)	0.13 MM US Ton/yr
Total Biomass Yield (AFDW Basis)	25.6 US Ton/acre/yr
	57.3 Metric tonne/ha/yr
Internal Rate of Return (After-Tax)	10%
Equity Percent of Total Investment	40%

Capital Costs	
Production ponds	$181,700,000
Inoculum Ponds	$18,500,000
CO2 Delivery	$4,400,000
Makeup Water Delivery + On-Site Circulation	$9,700,000
Dewatering	$36,700,000
Storage	$10,100,000
Total Installed Equipment Cost	$261,100,000
Added Direct + Indirect Costs	$156,900,000
(% of TCI)	38%
Total Capital Investment (TCI)	$418,000,000
Installed Equipment Cost/Annual US dry ton biomass	$2,044
Total Capital Investment/Annual US dry ton biomass	$3,272
Loan Rate	8.0%
Term (years)	10
Capital Charge Factor (Computed)	0.132

Cost Breakdowns ($/US Ton AFDW Biomass product)	
CO2	$96.51
Ammonia	$16.47
Diammonium Phosphate	$6.51
Power	$43.42
Chilled Water Utility	$7.89
Fixed Costs	$91.32
Capital Depreciation	$98.00
Average Income Tax	$32.00
Average Return on Investment	$302.00

Cost Breakdowns ($/yr)	
CO2	$12,900,000
Ammonia	$2,200,000
Diammonium Phosphate	$900,000
Power	$5,800,000
Chilled Water Utility	$1,100,000
Fixed Costs	$12,200,000
Capital Depreciation	$12,500,000
Average Income Tax	$4,100,000
Average Return on Investment	$38,600,000

Appendix B. Life Cycle Inventory for 2021 SOT Algae Farm Model

SOT Front-End Input and Output Data for the Modeled Algae Production Facility (10-Acre Average Base Case). (Note: Daily rates shown below are based on annual averages over all modeled seasons based on 24-hour day).

Products, kg/h	**Annual Average Rates FA Evap.**	**Annual Average Rates ASU Evap.**
Algal biomass (AFDW) [a]	14,675	14,632
Algal biomass (total including ash) [a]	15,038	14,994
Resource Consumption, kg/h		
CO_2 (counted as biogenic)	32,656	32,656
Ammonia	294	294
Diammonium phosphate (DAP)	142	142
Total process water input *(SALINE)* [b]	511,367	7,873,654
Electricity demand, kW	8,850	10,738
Output Streams, kg/h		
Water in biomass product stream	59,291	59,121
Water lost to blowdown	42,546	1,204,800
Algae lost in blowdown	2	46
Air Emissions, kg/h		
Water lost to evaporation	379,393	6,323,219
CO_2 outgassing from ponds (counted as biogenic)	3,279	3,279
O_2 to atmosphere	25,401	25,401

[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.