Opportunities for Utilization of Low-Cost Algae Resources: Techno-Economic Analysis Screening for Near-Term Deployment

Part 1: Algal Biomass Sourced via Wastewater Treatment

Part 2: Algal Biomass Sourced via Harmful Algal Blooms and Commercial Lipid Extraction

Matthew Wiatrowski, Bruno Klein, Christopher Kinchin,
Zhe Huang, and Ryan Davis

NREL is a national laboratory of the U.S. Department of Energy
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NREL/TP- 5100-81780
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Preface

This report presents a comprehensive techno-economic analysis (TEA) for the production, collection, or procurement of several low-cost algae resources that may otherwise be considered "waste" biomass materials today, as well as the utilization of these materials through exemplary conversion processes to produce renewable fuels and chemicals. In contrast to conventional TEA models attributed to large-scale algae "farming" approaches, which may be able to produce substantially more biomass and thus fuels/products at a national scale in the future, this assessment focuses on understanding opportunities and costs for such "waste" algal biomass resources as may be available at considerably lower cost today. Economics for base case assumptions and a range of sensitivity scenarios are presented, employing conversion technologies that are simple and well understood, and thus may be deployed at smaller community scale in the near term, as a means to support and expand a nascent algae industry on the way to employing a larger commercial algae farm approach for commodity-scale production.

Specifically, three algal biomass resources are considered in this assessment, as may be sourced from (1) municipal wastewater treatment (WWT) utilizing algae in place of more conventional technologies for nitrogen/phosphorus removal, (2) collection and removal of harmful algal bloom (HAB) biomass as proliferates in certain inland water bodies, and (3) procurement of residual biomass following commercial lipid extraction (EXT) operations performed at smaller scale by industry today focused on higher-value nutraceutical applications. These three resources are evaluated through two conversion pathways: (1) combined algal biomass processing (CAP) through a simple/low-complexity configuration, and (2) anaerobic digestion (AD). The CAP pathway produces liquid fuels and chemical coproducts (polymer for off-site upgrading to bioplastics), whereas the AD pathway produces biogas (specifically renewable natural gas [RNG]) and crop fertilizer coproducts. To streamline the discussion, this report is broken into two sections: Part 1 focuses on WWT-derived biomass, and Part 2 on HAB and EXT biomass.

Given the integrated nature of the processes spanning biomass production/collection and subsequent conversion, the TEA modeling approach taken here was different than conventional approaches, which typically solve for biomass production cost and then subsequent fuel production cost. Instead, all fuels/products were fixed at market price values, and the model solved for the required biomass "transfer" price from upstream procurement to the downstream conversion facility. This is referred to throughout this report as the "maximum biomass purchase price" (MBPP), representing the maximum value of the biomass the conversion facility would be willing to pay from the upstream provider. In the EXT case, this simply represents the price the commercial extraction entity may expect to be paid for the residual biomass material. In the WWT case, this may be compared to the cost of algal biomass production through a standard "minimum biomass selling price" (MBSP) metric when valorizing treated wastewater as a "coproduct" from algal biomass production (recognizing in reality the WWT facility would view treated water as the main output and algal biomass as a byproduct). Finally, in the HAB case, an equivalent biomass production cost (MBSP) cannot readily be calculated, as it strongly depends on revenue the HAB biomass collector receives from local governments or municipalities for performing a water treatment remediation service; however, the resulting required water treatment "credits" are instead calculated by assuming a biomass production cost (MBSP) equal to the biomass transfer price (MBPP).

Acknowledgments

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List of Acronyms

AD	anaerobic digestion
AFDW	ash-free dry weight
CAP	combined algal processing
CI	carbon intensity
CO_2	carbon dioxide
CSTR	continuous stirred-tank reactor
DAF	dissolved air flotation
EXT	lipid extraction (biomass sourcing)
GGE	gallon of gasoline equivalent
HAB	harmful algal bloom
IRR	internal rate of return
LCA	life-cycle analysis
LCFS	Low Carbon Fuel Standard
MBPP	maximum biomass purchase price
MBSP	minimum biomass selling price
MFSP	minimum fuel selling price
MGD	million gallons per day
MMBtu	million British thermal units
N	nitrogen
NREL	National Renewable Energy Laboratory
P	phosphorus
RIN	Renewable Identification Number
RNG	renewable natural gas
SOT	state of technology
TCI	total capital investment
TEA	techno-economic analysis
WWT	wastewater treatment
WWTP	wastewater treatment plant

Opportunities for Utilization of Low-Cost Algae Resources: Techno-Economic Analysis Screening for Near-Term Deployment

Part 1: Algal Biomass Sourced via Wastewater Treatment

Executive Summary

While microalgae as a biomass resource holds tremendous potential to contribute meaningful volumes of renewable fuels and bioproducts at the national and global stage, the high cost of algal biomass when sourced through "conventional" cultivation systems may limit its deployment at large commercial scales for commodity fuel production in the near term. Accordingly, to support today's nascent algae industry and seek out opportunities for it to progress along a technology learning curve toward such future scales, identifying and capitalizing on lower-cost algae resources as may exist today or in the near future adds a crucial building block toward this progression. Particularly when viewed in the context of system integration with downstream utilization in mind, techno-economic analysis (TEA) modeling can be a powerful tool to highlight opportunities and challenges for both producing/sourcing such biomass and converting it to fuels and coproducts.

As such, this report presents TEA modeling and analysis conducted for production of a low-cost algae resource, beginning in this Part 1 volume with algae cultivated for wastewater treatment (WWT). Additionally, TEA is performed for processing this biomass source through two possible conversion pathways, selected primarily with an emphasis on simplicity and local community-scale deployability in the near term—namely a simple combined algal processing (CAP) schematic, as well as conversion via anaerobic digestion (AD). In the CAP framework, biomass is converted to infrastructure-compatible liquid fuels (namely ethanol and lipids to be subsequently processed to diesel or jet fuel) and value-added coproducts (primarily residual protein valorized as a feed for downstream production of thermoplastics). In the AD scenario, the biomass is simply digested to biogas (subsequently upgraded to renewable natural gas [RNG]) while producing crop fertilizer coproducts.

TEA modeling for this biomass resource coupled with either conversion pathway was found to exhibit high potential for economic viability as may be deployed at small scale in the near term, even before factoring in potential policy incentives. This was primarily evidenced through the approach applied here to solve for the "maximum biomass purchase price" (MBPP) that a conversion facility would be willing to pay as a biomass "transfer" price from the upstream production entity, which ranged from −\$6 to \$130/ton. Although such low prices would never be achievable from conventional algae farming systems, in this context these prices were not viewed as being unreasonable given that this biomass source is not produced for purposes of selling (or necessarily even utilizing) it, but rather may be viewed as a waste byproduct that in some cases may require additional expense to merely dispose of.

This study found very strong economic viability to utilize algae for tertiary WWT for nitrogen/phosphorus mitigation, at least for moderately sized WWT facilities of roughly 5 million gallons per day (MGD) or larger, enabling a minimum biomass selling price (MBSP) for production of WWT biomass as low as *negative* \$341/ton, driven strongly by water treatment credits for nutrient mitigation. This may be compared to the downstream conversion biorefinery MBPPs of −\$6 to \$130/ton noted above, highlighting that the biomass can be produced at a much lower cost (MBSP) than is required to be purchased by the conversion facility (MBPP) in order for both entities to remain profitable.

A number of sensitivity cases were also evaluated to better understand trade-offs and key drivers on overall system economics beyond the base case scenarios. Scale was found to be a strong driver in all cases evaluated, given that the scale set as the base case here was already substantially smaller than typical commercial algae farm models envisioned in our past TEA work (roughly 16 tons/day of algal biomass in these cases compared to over 550 tons/day projected for a 5,000-acre *n*th-plant commercial algae farm reflected in prior TEA models). Additionally, applicable treatment credits for the WWT system also strongly influenced overall system economics, driven particularly by phosphorus treatment credits demonstrating a more significant impact compared to nitrogen credits, highlighting the potential for algae to reduce WWT costs compared to traditional technologies particularly for achieving phosphorus mitigation. On the conversion side, non-fuel coproduct credits (including those that may be generated by policy incentives) were also shown to exhibit strong sensitivity in supporting overall economic viability, as has also commonly been observed in algae conversion pathways sourced via conventional algae farming approaches. Finally, further opportunities to expand this assessment and address gaps/remaining questions in the future are also discussed.

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Introduction

Algal biomass has long been established as a promising feedstock for producing biofuels, bioenergy, and bioproducts, owing to a long list of unique advantages relative to other terrestrial biomass sources. Such advantages include high carbon content and correspondingly high uptake potential for carbon dioxide (CO_2) utilization/sequestration, high biomass growth rates, the ability to use non-arable or otherwise low-value land and saline or other non-freshwater resources, and compositional attributes of many algae strains that lend themselves to opportunities for producing numerous value-added products [1–4]. However, algal biomass is substantially more costly to produce than terrestrial lignocellulosic feedstocks when done through "conventional" algae farming approaches (i.e., building dedicated open pond or closed photobioreactor systems for the purpose of growing algal biomass through procurement/costing of makeup water, CO_2, and fertilizer nutrients to support biomass growth). Best-case estimates for n^{th}-plant commercial algae farms spanning thousands of acres project algal biomass costs of at least \$450–\$500/ton ash-free dry weight (AFDW) through open pond cultivation or \$600–\$700/ton (or more) through photobioreactor cultivation as a minimum floor that may be achieved in the future [5–8], compared to projections for woody or corn stover biomass less than \$80/ton [9,10].

In spite of such cost challenges for farmed microalgae, the many other unique advantages noted above still paint a promising path forward for algae to make important contributions to decarbonization via production of energy/fuels, products, food/feed, nutraceuticals, etc. at large volumes. For example, the *2016 Billion-Ton Report* published by Oak Ridge National Laboratory highlighted the future potential to supply roughly 10–20 million tons per year of algal biomass at the national scale [11]. This was subsequently shown in a multi-laboratory harmonization report [4] to be able to be expanded to roughly 100–300 million tons/yr total biomass potential when coupled with opportunities for carbon capture of existing CO_2 point sources in the United States, translating to a potential to supply 1–5 billion gallons of gasoline equivalent (GGE) per year at economically viable levels below \$3/GGE when including value-added coproducts alongside fuel production. While this is encouraging in highlighting the potential for microalgae to contribute meaningful volumes to support commodity-scale biofuel production, deployment at such scales may still be well in the future (depending on the degree of support from policy and other incentives) given a much smaller scale of the algae industry as it exists today and large risks to scale-up given substantial capital costs. For example, a 5,000-acre dedicated open pond algae farm integrated with downstream biorefinery conversion to fuels/products can be on the order of roughly \$800 million total capital investment (TCI) based on prior n^{th}-plant modeling [5,12].

In light of the above, the present assessment seeks to identify opportunities to support and grow the algae industry in the near term over coming years by avoiding such large-scale/high-cost commercial algae farming approaches, and instead focusing on low-cost algae resources as exist today or may be readily developed by leveraging existing opportunities. Primarily, this involves algal biomass that may be viewed either as a "waste" or byproduct resource as may be available typically at much smaller scale. In this Part 1 volume, we focus on algal biomass cultivated for purposes of nutrient remediation in wastewater treatment (WWT). We investigate opportunities, costs, and potential scale for procuring this type of biomass, coupled with techno-economic analysis (TEA) modeling for two possible conversion scenarios emphasizing opportunities for deployment at small community scale based on maximizing process simplicity and thus minimizing capital costs for deployment. The following sections of this volume document key TEA modeling inputs and assumptions for both biomass production and conversion to fuels/energy products (as a primary focus) and residual coproducts (as warranted), as well as resultant yields and overall economics, with a focus on understanding biomass production costs from WWT cultivation versus the maximum allowable costs of such feedstock through the conversion scenarios as necessary to achieve economic viability. Subsequently, Part 2 of this study documents a similar assessment centered around waste biomass as may be collected and removed from naturally occurring harmful algal blooms (HABs), as well as residual biomass from current algae industry activities focused on extraction (EXT) of high-value lipids such as omega-3 fatty acids.

Inputs and Assumptions

As noted above, two conversion process approaches were considered in this exercise as applied to the WWT biomass resource. One focuses on production of liquid fuels/precursors via a simplistic pathway under the National Renewable Energy Laboratory's (NREL's) combined algal processing (CAP) concept, involving wet anaerobic storage of peak seasonal biomass as warranted, followed by dilute acid pretreatment, fermentation of carbohydrates to ethanol, extraction of lipids for sale as destined for off-site upgrading to finished hydrocarbon fuels, and valorization of the residual protein fraction for coproduct credit as may be utilized for bioplastics production or alternative uses. The second conversion approach further simplifies the process to a single primary unit operation via anaerobic digestion (AD), producing biogas as the primary energy product as may be sold into renewable natural gas (RNG) markets, with AD byproduct fractions sold as fertilizer credits. A high-level overview of the conversion process schematics as reflective of processing WWT-derived algal biomass is depicted in Figure 1, followed by a description of the modeled process pathways.

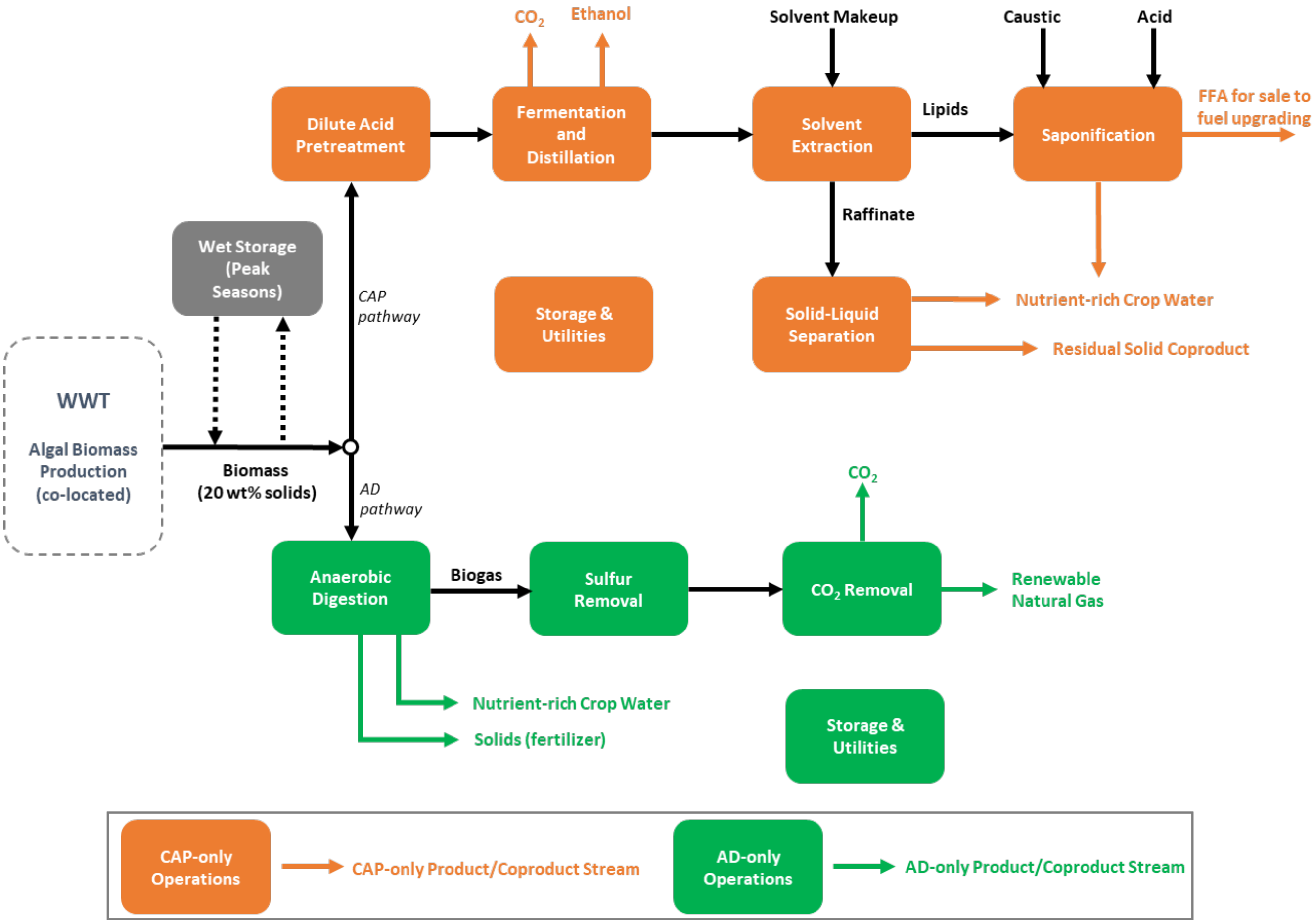

Figure 1. Process flow diagram for the CAP and AD scenarios demonstrating the conversion of algal biomass produced from WWT cultivation (FFA = free fatty acids)

Biomass Production

To evaluate process design and economic implications for algal biomass production from wastewater treatment, NREL’s previous assessment on the subject was leveraged as a starting point [13]. In that prior work, two scenarios were initially investigated as potential integration points for algal WWT systems, namely “complete” wastewater treatment focused on replacing operations downstream of primary clarification (typically involving activated sludge for biological destruction of organics and subsequent downstream operations for nitrogen [N] and phosphorus [P] removal), as well as “tertiary” treatment to specifically target mitigation of N/P to low levels as increasingly required to meet discharge permits. In the present work, only the tertiary treatment case was selected as what may likely be a more practical fit with better economics and less operability challenges for algal systems, based on feedback from industry.

The tertiary treatment schematic for algal biomass N/P removal is shown in Figure 2. In summary, an open pond algae farm is designed to meet a target wastewater flowrate (rather than typical models fixed at a target land area) and N/P loading, in this case based on secondary effluent from a co-located wastewater treatment plant (WWTP). To avoid conflating the results with multiple design scenarios and investigate “best-case” future cost potential, the scope of this analysis focuses only on open ponds for algae WWT cultivation, but it is recognized closed photobioreactors are currently being pursued by multiple commercial companies in the algal WWT industry. Photobioreactors also may play a role in this context, allowing for a smaller footprint as may be dictated by land availability constraints near WWTPs commonly located in populated areas, though typically at a trade-off of higher capital costs versus open ponds (ultimately dependent on cost considerations for land, water, CO_2 [including CO_2 retention efficiencies], and culture stability/contamination events [mitigated substantially with photobioreactors]) [6]. Photobioreactors also enable algal cultivation in higher latitudes by supporting better temperature control and better access to available light, potentially also enabling 24-hour illumination for extended cultivation (and thus WWT) capacity as is also being pursued commercially.

The algae farm scale is set based on the required degree of N/P removal given incoming concentrations versus target discharge levels for both N and P components, with the difference taken up during algae cultivation. In most seasons, supplementary nutrients are added in order to meet the stoichiometric requirements of the algae, with N being the more limiting component and thus supplementary N outweighing P. The exception to this is in winter, when no additional P is fed. The area requirement in winter effectively sets the size of the ponds due to the lower biomass productivity. In higher productivity seasons, both N and P are added in order to support the full biomass potential of the ponds beyond the availability of N/P in the wastewater (assumed constant all year). Given low residual organics in WWT secondary effluent, all carbon demands are assumed to be met through externally supplied CO_2, similar to standard algae cultivation (while wastewater nutrients are provided at no cost). The TEA then solves for the minimum biomass selling price (MBSP) given coproduct treatment credits applied for N/P mitigation, valorized based on what it would otherwise cost the WWTP to meet final N/P discharge limits through standard incumbent technologies (more costly, both in terms of capital and operating expenses).

The reader is referred to the above-cited algae WWT report for further details on the process specifics and approach/assumptions applied for TEA modeling [13]. Relative to that initial framework, a number of details have been further refined in the present work. First, the secondary effluent flowrate was set equal to an assumed raw wastewater flowrate of 10 million gallons per day (MGD), reflective of a large WWTP facility, updating to a more typically realistic N content of 20 mg/L, P content of 4 mg/L, and a chemical oxygen demand (COD) of 30 mg/L based on secondary treatment standards [14] and feedback from industry. Second, the treated water discharge limits for N and P were updated to 10 mg/L and 1 mg/L, respectively, as more typical parameters based on the U.S. Environmental Protection Agency’s discharge monitoring report [15]. The discharge limits for N and P assumed in the present study represent common levels for many U.S. treatment plants, although some states may set more stringent nutrient discharge levels (e.g., Massachusetts requires a 0.1-mg/L discharge limit for total P). Third, rather than lumping N and P treatment credits together as was assumed previously [13], in this study we apply individual N and P treatment credits of \$3/lb N removal and \$50/lb P removal based on published tertiary N and P removal costs for conventional technologies, as an “opportunity cost” that the WWT facility would instead pay to the co-located algae facility to perform this remediation service [16,17]. Cultivation productivity rates were maintained consistent with the prior WWT study at an annual average of 25 g/m^2/day, varying seasonally at values of 31.3, 25.0, 15.7, and 28.2 g/m^2/day across summer, fall, winter, and spring, respectively (assuming a maximum seasonal variability of 2:1). To evaluate the economic sensitivity to productivity recognizing current state of technology (SOT) performance is not yet at 25 g/m^2/day, a sensitivity case with an average productivity of 18 g/m^2/day was also considered reflective of recent SOT levels demonstrated outdoors [18].

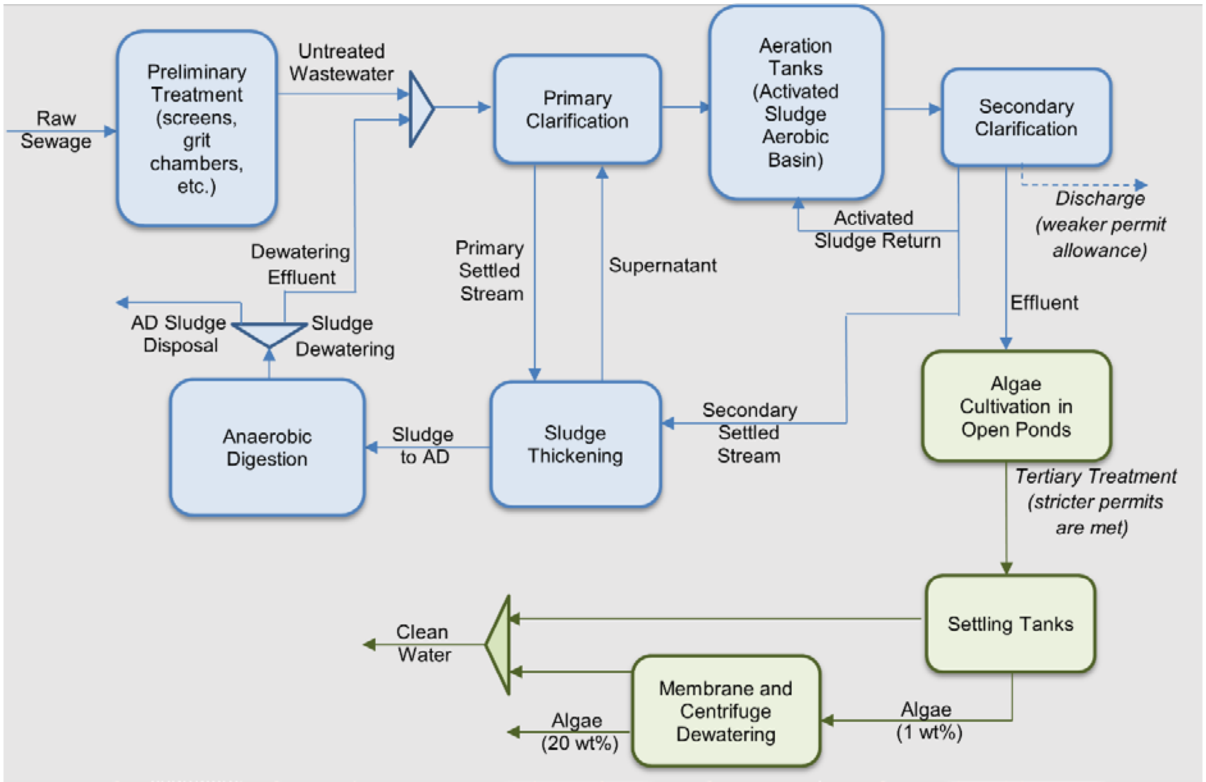

Figure 2. Schematic diagram of WWT integrated with algae cultivation for tertiary N/P removal [13]

Biomass Composition

The biochemical and elemental compositions of the biomass for the WWT case are shown in Table 1. The composition for key biochemical components (carbohydrates, lipids, and protein) is based on analysis of algae cultivated from wastewater (obtained from an industry collaborator). The remaining compositional fractions are assumed to be present in proportions equal to those observed for high-protein biomass cultivated under the Development of Integrated Screening, Cultivar Optimization, and Verification Research (DISCOVR) consortium [19]. For example, the average ash content in a DISCOVR high-protein biomass cultivation trial was measured at 11.0% of the total biomass (varying seasonally from 9%–16% of the biomass), adjusted down in this case to 10.4% for the WWT biomass based on a slightly higher fraction of carbohydrates, lipids, and proteins. From this basis, the associated elemental composition of the biomass is based on interpolation from NREL and other published biomass compositions [20–22]. Elemental composition was determined as follows:

- N: Determined by correlation of N to protein content (linear regression of high-carbohydrate and high-lipid *Scenedesmus* [HCSD/HLSD] and 2019/2020 state-of-technology (SOT) compositions), translating to a ratio of 3.8:1 for protein vs. N wt % in biomass [18,21].

- P: Determined by assuming a constant N:P ratio, consistent with published high-protein biomass compositions, at 8.2:1 [18,21].
- Balance (C/H/O): Assumed to be present in equal proportions to published high-protein biomass compositions at 6.8:1.0:3.8 [18,21].

Table 1. Modeled Biochemical and Elemental Compositions for Algal WWT Biomass.
Protein/carbohydrate/lipid composition determined by analysis of commercial biomass from WWT collaborator; remainder of composition set proportionally as consistent with [20].

Biochemical Composition (dry wt %)	
Fermentable carbohydrates	22.2
Protein	39.0
Lipids	9.1
Ash	10.4
Non-fermentable carbohydrates	3.4
Non-fuel polar lipid impurities	5.2
Cell mass	10.8
Elemental Composition (ash-free dry wt %)	
C	52.8
H	7.8
O	29.3
N	8.9
S	0.0
P	1.1

Biomass Conversion – Combined Algal Processing

The scale of algal biomass availability from a single WWT facility (or similarly for other waste algae resources discussed in Volume 2) is significantly lower than production rates typically assumed in NREL *n*th-plant models for a dedicated commercial algae farm spanning thousands of acres; therefore, a substantial simplification of the process design is warranted to minimize economy-of-scale penalties for an overly complex biorefinery. The process design for the CAP scenario follows the general approach of fractionating and valorizing each of the three major fractions of the biomass; namely, carbohydrates (fermented to ethanol), lipids (extracted and sold as a precursor for fuels), and proteins (sold as a solid coproduct along with any other residual solid components). Key parameters for each processing operation are summarized in Table 2 alongside parameters for the AD pathway.

Dewatered algal biomass from the WWTP is fed to the conversion facility, maintained at a constant rate despite variations in seasonal biomass productivity by using a wet anaerobic storage system for diversion of peak seasonal biomass for storage and blending during low-production seasons. Assumptions regarding biomass degradation and compositional changes during storage are consistent with recent work [12,23]. Algal biomass is then sent to a dilute acid pretreatment step to hydrolyze carbohydrates and make lipids amenable to extraction. Process design assumptions regarding dilute acid pretreatment and ethanol fermentation are also consistent with those published in our prior work [12,24]. One exception to this is the pretreatment reactor design, simplified from a reactor with relatively complex internals assumed in previous analyses (as designed originally for use with corn stover [25]) to a continuous stirred-tank reactor (CSTR) design, costed as an agitated pressure vessel maintaining the same operating conditions and metallurgy premiums. At the biomass feed rates considered here (roughly 2%–3% of rates considered in typical models for a dedicated algae biorefinery [12,20]), as well as the fact that algal biomass in general may not require such a complex pretreatment reactor given lower viscosity and likely easier access of acid into the biomass compared with raw corn stover, this simplified design was deemed appropriate for this work.

The pretreated biomass is next sent to whole-slurry fermentation, where liberated sugars undergo bioconversion to ethanol using standard fermentation operations described in previous NREL reports [24] and as summarized in Table 2. Other options also exist for conversion of carbohydrates—for example, via fermentation to other fuels/products, or alternatively digestion to biogas (given several near-term opportunities for biogas/renewable natural gas discussed below in the AD scenario)—but ethanol was selected in the present scope owing to its simplicity and potential to contribute to liquid fuels as per the focus of this case. Following fermentation, lipids are separated from the slurry by utilizing three sequential agitation and centrifugation steps in the presence of two solvents (hexane and ethanol). The solvents are recovered from the extract and raffinate phases, respectively, via distillation and recycled. Assumptions regarding the solvent extraction operation are also consistent with those used in our preceding analyses [12,20]. Lipids undergo saponification, utilizing water and caustic to remove the polar impurities (given that the majority of extracted lipids from these generally nutrient-replete/high-protein biomass sources are initially expected to be polar/membrane-bound lipids more than neutral lipids), followed by neutralization with a strong acid. The resultant fatty acid lipids should then be suitable for upgrading to hydrocarbon fuels via hydrotreating; however, the relatively small scale of the conversion facility would result in significant economy-of-scale penalties and precludes the use of a local catalytic hydrotreating operation. Instead, the recovered lipids are sold off-site to a refinery, where they can be coprocessed alongside petroleum products.

The value of the extracted lipids is inherently less than a finished fuel product due to the additional processing required. In order to properly assign a discounted valuation to the lipids, a separate TEA was performed that considered a larger commercial-scale algae biorefinery processing algal biomass from a 5,000-acre algae farm more typical of prior NREL models, reflecting a process design equivalent to the CAP scenario specified here. The TEA for this facility, however, considered an on-site hydrodeoxygenation step to upgrade the lipids to finished fuels. Costs associated with the lipid hydrotreating operations were then subtracted out from the market value of the fuel, fixed at $2.50/GGE, using assumptions reflective of a centralized upgrading facility that could process lipids from various regional sources at a production scale of 8.2 million GGE of liquid fuels per year. Costs for the transportation of the lipids are not included. An adjustment was also made to account for the energy content difference between the feed lipids and the finished fuels. This resulted in a lipid "intermediate" valuation of $2.22/GGE following extraction and purification, implying downstream upgrading cost allowances of $0.28/GGE of lipids to reach a $2.50/GGE-equivalent cost of finished fuel. Accordingly, the recovered/purified lipid product from the conversion facility evaluated here was valorized at $2.22/GGE. Given some uncertainty in this valuation, a sensitivity analysis that considers a lipid price variation of ±25% is considered later in this report.

The raffinate from extraction, an aqueous slurry, is separated via vacuum belt filtration. The aqueous phase, containing N from partially hydrolyzed algal proteins, is utilized as crop water for nearby farms. The aqueous phase from saponification, rich in phosphorus, is used in a similar manner; both are sold at a value of $0.15/lb (dry basis). Residual solids are dried further and sold as a coproduct, in this case for example purposes reflecting a protein-enriched material sold and subsequently utilized as a co-feed for the synthesis of bioplastics at a rate of $818/ton (an average price for such a material as supported by commercial collaborator Algix for such a process) [26]. It is recognized this represents a high value (considerably exceeding values for the fuel/energy products), but such reliance on value-added coproducts is a common necessity for algal-based processes in order to achieve economic viability. The overall sensitivity in the TEA results to the value of the residual solids is explored later in the sensitivity analysis.

The labor force required for operating the CAP facility is significantly reduced compared to what is typical for published NREL commercial-scale algal biorefineries due to a much smaller plant size in the present work. However, additional personnel are assumed for the CAP scenario compared to the AD scenario due to a relatively higher complexity for the CAP process. The labor requirements are summarized in Table 2.

Table 2. Assumed Conversion Parameters for the CAP and AD Conversion Facilities

Parameter	Fixed Value	Reference
CAP & AD: Common Parameters		
Seasonal storage		
Storage degradation losses (wt %)	13%	[12,23]
CAP Pathway Parameters		
Labor requirements		
Plant engineer	1	Reduced from [12,24]
Maintenance technician	1	Reduced from [12,24]
Shift supervisor	1	Reduced from [12,24]
Shift operators	6	Reduced from [12,24]
Dilute acid pretreatment		
Acid loading (wt % vs. feed)	2%	[12,24]
Fermentable sugar release (%)	90%	[24]
Temperature (°C)	150	[12,24]
Pressure (atm)	4.6	[12,24]
Fermentation to ethanol		
Total batch time (days)	1.5	[24]
Organism	*S. cerevisiae*	[24]
Inoculum level (vol %)	10%	[24]
Temperature (°C)	37	[24]
Number of trains	2	[24]
Maximum vessel size	20,000 gallons	Adjusted from [24] based on required volume
Number of vessel stages	4	Adjusted from [24] based on required volume
Metabolic yield (g ethanol/g hexose sugars)	0.48	[24]
Glucose to biomass growth	2%	[24]
Lipid extraction		
Extraction configuration	3-stage CSTR + centrifugation with 2 solvents	[12,20]
Solvent loading (hexane: EtOH: dry biomass, wt)	2.7: 1.1: 1 g/g/g	[12,20]
CSTR extraction residence time (min)	15	[12,20]
Overall lipid extraction yield	96%	[12,20]
AD Pathway Parameters		
Labor requirements		
Maintenance technician	1	Reduced from [12,24]
Shift operators	3	Reduced from [12,24]
Anaerobic digestion		
Carbon destruction to biogas	48.2%	[4,24]
% CH_4 in biogas	67%	[4,24]
Biogas upgrading		
Capital and operating costs	Based on cost factors from Saur and Jalalzadeh-Azar	[27]

Biomass Conversion – Anaerobic Digestion

A second conversion scenario involving anaerobic digestion of algal biomass was also considered. This process, shown in Figure 1, maximizes simplicity by reducing the process design down to one primary unit operation for conversion. As in the CAP scenario, biomass is fed at a constant rate by way of seasonal storage. The digestible portions of the biomass are converted by a mixed consortia of organisms to biogas (primarily methane and CO_2).

Biogas can be used on-site directly but requires further processing to meet the standard for pipeline-quality natural gas. Heating requirements for the process are minimal and are met by directly utilizing ~10% of the biogas; the remaining biogas is upgraded to pipeline-quality biomethane on-site. Biogas upgrading costs are calculated using cost factors supplied by Saur and Jalalzadeh-Azar [27] and were also compared to other sources [28] to confirm their validity. CO_2 from the conversion facility (sourced from both the purified biogas and the steam boiler) is recycled to the WWTP to supplement algal biomass growth. Alternatively, biogas may be piped to a centralized facility to minimize upgrading costs; this is considered later on in the sensitivity analysis.

The modeled value of the upgraded RNG ($4.12 per million British thermal units [MMBtu]) is based on a 5-year average of industrial natural gas prices in the United States [29]. However, recent market prices for RNG are in the range of $15–$100/MMBtu due to policy incentives associated with CO_2 emissions reduction [30–32]. These policy incentives, including Renewable Identification Numbers (RINs) and Low Carbon Fuel Standard (LCFS) credits, help offset the high production costs for RNG (estimated at $19/MMBtu by the International Energy Agency [33], though varying depending on feedstock and production strategy). There is also a substantial market for this RNG; according to a database from Argonne National Laboratory [34], there were 230 operational RNG production facilities in the United States in 2021, with a total annual RNG production of 73,850,947 MMBtu (658 million GGE).

This separate market for RNG is influenced by the generation of LCFS credits for RNG purchasers, which are calculated based on avoided carbon emissions compared to the status quo energy source. RNG offers a significantly lower carbon intensity (CI) compared to conventional natural gas and can serve as a drop-in replacement; therefore, adopting RNG is an easy way for a natural gas user to reduce their greenhouse gas emissions. Depending on the feedstock used (e.g., landfill gas, dairy waste, wastewater sludge, or food waste), the resulting RNG can have net-negative CI values below −100 gCO_2e/MJ [32,35], promising the potential for significant LCFS credit generation when compared to the CI of conventional natural gas (50 gCO_2e/MJ [36]). For some users, the credits generated from this difference in CI can have a significant impact on economics. Producers of green hydrogen, for example, can reduce their overall CI by 70%–90% by using a biomethane-based steam reforming process compared to the electrolysis of water using grid electricity [37], imparting significant value on RNG beyond its use as an energy source.

Clearly, RNG holds a value greater than that of conventional natural gas. However, in order to avoid incorporating policy implications and to enable a valid comparison with the CAP case, an RNG market price consistent with petroleum-derived natural gas is used in the base case. Given the wide range of reported RNG market prices, this variable is considered in more detail in the sensitivity analysis.

Other coproducts from AD include a nutrient-rich aqueous stream (utilized as crop water) and digestate (utilized as a fertilizer). Both products are valued at $0.15/lb dry weight based on guidance from industry. Additional labor reductions are assumed for the AD scenario compared to the CAP scenario due to the relative simplicity of the AD process, as indicated in Table 2.

Table 3. Summary of Key Process Design Parameters for Modeled Conversion Facilities

Process Design Parameters	
Feed rate basis (base case)	10-MGD wastewater facility
Average feed rate (U.S. tons/day AFDW)	16.4
Seasonal biomass availability variation ratio (high:low)	2:1 (productivities = 31.3, 25.0, 15.7, and 28.2 $g/m^2/day$ for summer, fall, winter, and spring, respectively)
CAP Conversion	
Pretreatment	Dilute acid
Fuel products	Ethanol, purified lipids for coprocessing
Coproducts	• Protein-enriched solids (thermoplastic co-feed) • Nutrient-enriched crop water
CO_2 end use	Recycle to cultivation facility
AD Conversion	
Pretreatment	None
Fuel (energy) products	Renewable natural gas
Coproducts	• Digestate for land application • Nutrient-enriched crop water
CO_2 end use	Recycle to cultivation facility

TEA Approach

The TEA methodology applied to the cases presented in this report follows the broad assumptions outlined in prior NREL TEA reports, such as Davis et al. [5]. In short, the assessment is carried out through establishing discounted cash flows, thus combining capital expenditures, operational expenses, and selling prices of multiple coproducts (Table 4). However, in the present approach, most scenarios assume fixed selling prices for all products (rather than solving for a minimum selling price for one targeted product) while instead solving for an upstream attribute such as required biomass "transfer" cost or associated biomass production parameter, described later. Table 5 presents additional financial parameters employed in the assessment.

Table 4. Selling Prices of the Main Products in CAP and AD Biorefineries

Products	Value
Ethanol	$2.50/GGE
Lipids	$2.22/GGE
RNG (biomethane)	$4.12/MMBtu
Solid coproduct (CAP residual protein)	$817.5/ton dry weight
Crop water (CAP/AD residual aqueous)	$0.15/lb solids
CO_2	$40.82/ton
Solid fertilizer (AD digestate)	$0.15/lb solids

Table 5. Financial Assumptions Used in the TEA, Based on a Mature *n*th Plant [20,38]

Financial Assumptions	Value
Plant life	30 years
Cost year dollar	2016$
Capacity factor	90%
Discount rate	10%
Plant depreciation	Modified accelerated cost recovery
Plant recovery period	7 years (general); 20 years (steam plant)
Federal tax rate	21%
Financing	40% equity
Loan terms	10-year loan at 8% annual percentage rate
Construction period	3 years
Construction expenditure phasing (year 1 – 2 – 3)	*8% – 60% – 32%*
Working capital	5% of fixed capital investment
Startup time	6 months
Revenues during startup	50%
Variable costs during startup	75%

Two separate TEA metrics are used to assess the economics for the integrated system. The minimum biomass selling price (MBSP) represents the price that *the upstream producer must sell* the biomass for in order to achieve the specified 10% internal rate of return (IRR), when evaluating the algal WWTP economics based on solving for MBSP at a given coproduct credit for water treatment. This may be compared to the maximum biomass purchase price (MBPP), representing a biomass "transfer" price that the *downstream conversion facility can afford to pay* while still achieving the 10% IRR at fixed prices for all conversion end products. Common parameters between the models such as algae composition and seasonal flowrates are calculated based on the parameters of the biomass cultivation TEA module, which include WWT facility size, wastewater flowrate, N/P removal rates, and algae growth characteristics. This workflow is depicted in Figure 3 and summarized below:

1. A dedicated TEA calculation is used to estimate the biomass production facility's MBSP ($/ton AFDW) arising from using a given set of cultivation conditions reflected above.
2. The biomass flowrates from the cultivation module are employed to define and size the operations in the biomass conversion module (CAP or AD biorefinery).
3. A separate TEA calculation is used to estimate the conversion facility's MBPP ($/ton AFDW) reflecting the biomass characteristics from cultivation applied across target conversion parameters, as required to sell all fuels/products at fixed market levels. This may then be compared against the upstream MBSP, with economic viability of the integrated process achieved when MBPP > MBSP.

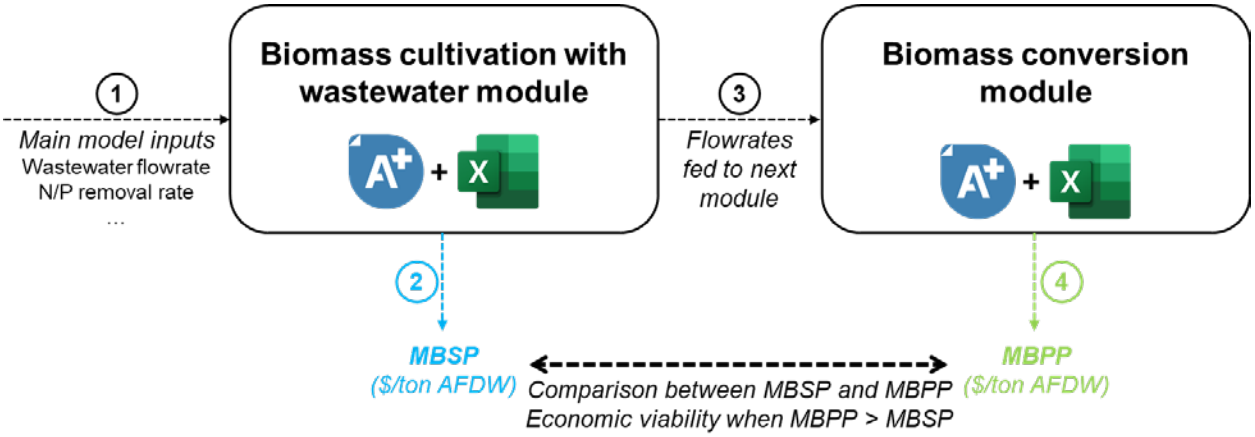

Figure 3. Representation of the iterative processes to determine overall economic viability comparing the production facility's MBSP against the conversion facility's MBPP for the WWT case

Results and Discussion

The TEA approaches discussed previously were applied to the procurement and conversion of the WWT-derived biomass. Broadly speaking, the economic potential of algae production from WWT showed great potential. Biomass production costs (Table 6) were outweighed by the water treatment credits, resulting in a negative calculated minimum biomass selling price for the WWT facility (meaning that the WWT entity could theoretically *pay* $341/ton of biomass and still maintain a 10% IRR at the base treatment credit levels applied here). When biomass production was combined with conversion, both base case scenarios considered showed good near-term potential for economic viability, with exceptionally strong results demonstrated for cases that considered increased biomass availability and elevated credits associated with nutrient removal, as well as inclusion of low-carbon fuel policies. Results for each conversion pathway are shown in Table 7. Following discussions of biomass procurement and conversion for each scenario, sensitivity analyses on critical parameters are presented.

Table 6. Summary of TEA Results for the Modeled Biomass Production Base Case

	WWT	**Units**
Minimum biomass selling price	−$341	$/ton AFDW
Biomass yield	1.6	tons/million gallons water AFDW
	5,400	tons/year AFDW
Total capital investment [a]	$13,772,000	$
Variable operating costs [a]	$1,142,000	$/year
Fixed operating costs [a]	$1,173,000	$/year
Water treatment credits [a]	$5,937,000	$/year

[a] Includes costs for the algal WWT system (excluding upstream WWTP costs) only.

Table 7. Summary of TEA Results for the Modeled Algae Conversion Base Cases.
Costs for production not included here.

	WWT-CAP	WWT-AD	Units
Maximum biomass purchase price	\$130	−\$6	\$/ton AFDW
Total fuel/energy yield [a]	42.5 (0.23)	75.4 (0.41)	GGE/ton AFDW (million GGE/year)
Liquid fuel yield	42.5 (0.23)	0 (0)	GGE/ton AFDW (million GGE/year)
Purified lipids [b]	25.1 (0.14)	0 (0)	GGE/ton AFDW (million GGE/year)
Ethanol	17.4 (0.09)	0 (0)	GGE/ton AFDW (million GGE/year)
RNG yield [c]	0 (0)	75.4 (0.41)	GGE/ton AFDW (million GGE/year)
	0 (0)	8.8 (47,400)	MMBtu/ton AFDW (MMBtu/year)
Biomass feed rate (seasonal average)	16.4	16.4	tons/day AFDW
Solid coproduct/digestate production	8.2	8.4	tons/day
Total capital investment [d]	\$9,804,000	\$4,873,000	\$
Non-feedstock variable operating costs [d]	\$586,000	\$143,000	\$/year
Fixed operating costs [d]	\$1,040,000	\$441,000	\$/year
Coproduct credits [d]	\$3,047,000	\$981,000	\$/year

[a] Includes both liquid fuels and renewable natural gas heating content.

[b] Purified lipids are discounted from a finished hydrocarbon fuel (\$2.22/GGE) and are assumed to be sold/upgraded at a central processing facility for ultimately achieving \$2.5/GGE final fuel selling price after central hydrotreating.

[c] The RNG yield is given in GGE to represent the energy content of the gas fuel (no liquid fuel production in AD scenarios).

[d] Includes costs for the conversion facility only.

Water Treatment and Biomass Production

Based on the refinements described above to the previously published algae WWT model framework [13], for the baseline WWT scenario evaluated here (10-MGD WWT scale, \$3/lb N and \$50/lb P removal credits), the resulting MBSP is calculated to be *negative* \$341/ton, a major reduction compared to the traditional algae cultivation farm model at a targeted \$488/ton MBSP [5]. To accommodate larger WWTP capacities, increasing the WWT scale from 10 to 50 MGD further reduces the MBSP to *negative* \$522/ton. For both WWT scales, decreasing nutrient removal credits by 50% (\$1.5/lb N and \$25/lb P) would lead to a dramatic increase in MBSP by \$550/ton, while increasing nutrient removal credits by 50% (\$4.5/lb N and \$75/lb P) would similarly reduce MBSP by \$550/ton—thus highlighting N/P mitigation credits as a very strong driver on overall economics for algae-based WWT. Similar effects are seen at a reduced average biomass productivity of 18 g/m^2/day as may be closer to current SOT performance, compared to 25 g/m^2/day targeted for the base case. This productivity reduction generally resulted in an MBSP increase of \$120/ton-140/ton, but with the same overall trends still demonstrating promising economics – for example, the baseline case (10 MGD WWT scale, \$3/lb N and \$50/lb P removal credits) translates to an MBSP of negative \$211/ton, compared to negative \$341/ton at 25 g/m^2/day (a favorable outcome in either case).

These results are highlighted in Figure 4 and Table 8, with highly favorable economics showing production MBSP well below conversion MBPP for all scenarios except for 10 MGD and 50% nutrient treatment credit reductions, while 50 MGD and 50% nutrient treatment credit reductions achieve a roughly equivalent MBSP versus MBPP. In practice, these treatment credits will be site- and region-specific: in states with stricter discharge limits, the value of mitigation credits may be significantly higher than states with less stringent limits.

It was also demonstrated that an algae yield of 1.6 tons per million gallons of wastewater treated can be achieved based on the N/P content in secondary effluent and resultant water discharge limits described in the Inputs and Assumptions section. Following previous work [13], as a high-level estimate, if 50% of the existing 34.5-billion-gallon/day WWT capacity in the United States could be integrated with tertiary algal treatment using the base case algae yield found here, *the total algal biomass potential could be as high as 28.3 million tons/yr for this scenario, translating to a national biofuel potential of 1.2 billion GGE/yr* when coupled with the 42.5-GGE/ton fuel yield shown in Table 7 for this scenario.

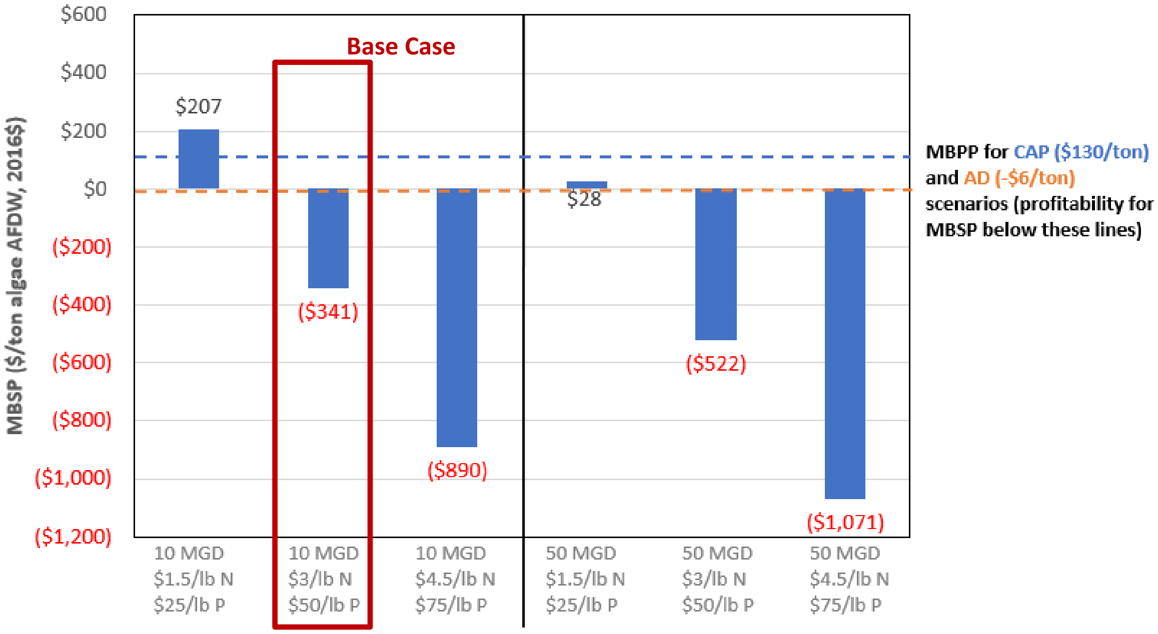

Figure 4. Algae WWT TEA results for tertiary N/P removal. Blue bars represent the MBSP calculated for the biomass production facility at various scales and nutrient credits, while dotted lines represent the MBPP calculated for the base case conversion facilities. Overall profitability is achieved when MBSP < MBPP.

Table 8. Summary of TEA Results for Algal Biomass Production at Various Scales and Nutrient Credit Values. Includes costs for the algal WWT system (excluding upstream WWTP costs) only. Base case scenario shown with red border.

	10 MGD $1.5/lb N $25/lb P	10 MGD $3/lb N $50/lb P	10 MGD $4.5/lb N $75/lb P	50 MGD $1.5/lb N $25/lb P	50 MGD $3/lb N $50/lb P	50 MGD $4.5/lb N $75/lb P	Units
MBSP	207	−341	−890	28	−522	−1,071	$/ton AFDW
Capital expenditures	328	328	328	283	283	283	$/ton AFDW
Variable operating costs	428	428	428	294	294	294	$/ton AFDW
WWT credits	−549	−1,098	−1,647	−549	−1,099	−1,648	$/ton AFDW

Conversion Results: WWT-CAP and WWT-AD

As noted above, the TEA for the WWT-CAP and WWT-AD conversion processes takes the approach of setting product prices to their market values and solving for the required MBPP, which can be compared to the calculated MBSP from the WWT facility to determine economic viability for the overall integrated system. An alternative approach is also considered, where the biomass feedstock cost to conversion is set by the baseline WWT cultivation case, and the minimum fuel selling price (MFSP) (accounting for energy content of both the ethanol and extracted lipids) is calculated.

The WWT-CAP scenario resulted in an MBPP of $130/ton, demonstrating a very promising case for economic viability when compared to the MBSP of −$341/ton determined from the WWT cultivation. *Alternatively, when considering the cultivation and conversion facilities together, a hypothetical MFSP of −$8.49/GGE is calculated*. Of course, this large negative value of MFSP would not be practical (a biorefinery would not be paying their customers over $8/GGE to offload their fuel products); rather, it should be interpreted as an indication that fuel and/or coproducts could be sold for less than the asserted market prices while still maintaining profitability given large revenues incurred for upstream WWT nutrient mitigation. Thus, the base case would achieve an IRR higher than the assumed 10% (in this case, achieving a 36% IRR when fuel and coproduct prices are set to their market values). Given the significant revenues associated with the solid coproduct in the CAP case, an additional scenario was also considered that included an integrated facility (MBSP = −$341/ton) and fixed fuel prices and solved for the minimum solid coproduct selling price. In this case, a solid selling price of −$115/ton was found, demonstrating that profitability could still be achieved even without the added revenue of the solid coproduct. Finally, another version of the WWT-CAP scenario was also considered, which processed the biomass without a lipid extraction step. This change, which simplifies the process considerably, had the detrimental effect of lowering fuel yields by 60%, a key focus area for this study. However, despite lower fuel production, this case was shown to be slightly more profitable than the base case, demonstrating an MBPP of $187/ton due to relegating the lipids to the higher-value residual solid coproduct.

The WWT-AD scenario resulted in an MBPP of −$6/ton; here, a lower value is less favorable than the WWT-CAP scenario but still exhibits a clear potential for economic viability when compared to the calculated MBSP of −$341/ton. Alternatively, an MFSP of −$34/MMBtu (equivalent to −\$3.93/GGE on a heating value basis) for the RNG product is calculated when considering the combined cultivation-conversion facility. As in the WWT-CAP case, this negative MFSP should be taken as an indication of the profitability of the process even if the sale of RNG was excluded. Alternatively, the combined facility with fixed product prices can achieve an IRR of 44%. This value is notably higher than the IRR calculated for the WWT-CAP scenario due to the lower capital intensity of the WWT-AD case.

Sensitivity to Scale and Nutrient Credits

Having demonstrated the significant effects that WWTP facility size and nutrient credits can incur on process economics, these effects are investigated in further granularity. Figure 5 depicts the effect of varying N and P credits independently on MBSP, while scale impacts are discussed in more depth concurrently with biomass conversion (Figure 6).

Though N and P mitigation credits each play an important role in achieving favorable economics, Figure 5 particularly illuminates the importance of the P credit. When P credits are removed as a revenue stream (with N credits set at the baseline value of \$3/lb), the MBSP rises to \$512/ton, well above even the target price of algal biomass cultivated in a dedicated farm [12]. Conversely, removing N credits from the analysis (while maintaining the baseline P credit of \$50/lb) results in an MBSP of −\$98/ton, still below the MBPP for both the WWT-CAP and WWT-AD scenarios, thus enabling an economically viable process even with P credits alone. This sensitivity to P removal credits suggests that discharge limits on P drive the economic viability of WWT with algae as a clearly superior means of enabling N/P removal in WWT applications. As noted above, in localities with stricter P discharge limits, and thus more costly operations to meet such limits through conventional methods, the associated coproduct credit value for algal P mitigation could be much greater than the base case reflected here (Wisconsin is one such state, though other factors would also need to be considered in that case such as colder climates, lower cultivation productivities, and/or the need for photobioreactors or alternative cultivation system designs).

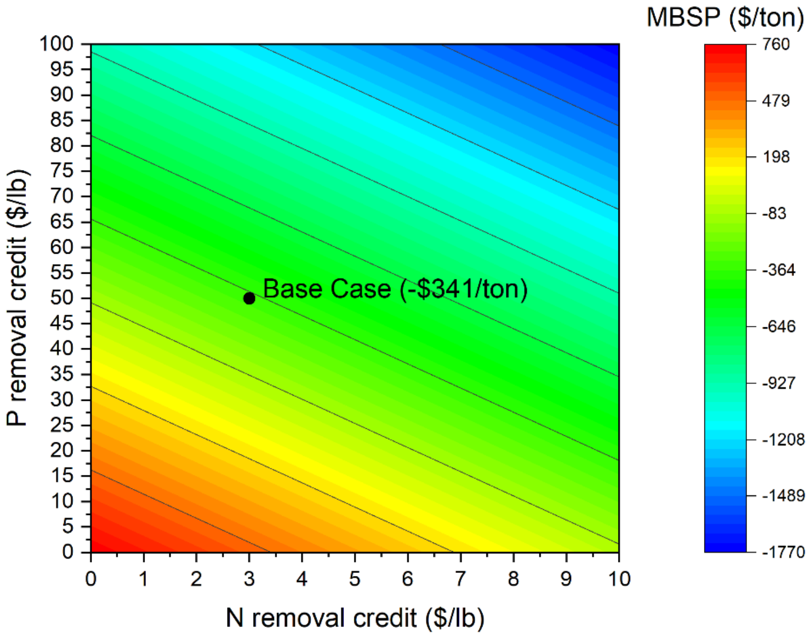

Figure 5. Contour plot showing impact of nitrogen (x-axis) and phosphorus (y-axis) remediation credits on minimum biomass selling price for the WWT algae cultivation base case (10 MGD)

Results for all WWT cases (including the front-end WWT as well as both conversion pathways) vary considerably depending on the scale of the WWTP considered. While approximately 90% of the WWTPs in the United States are considered small- to medium-sized (<10 MGD) [39], the majority of wastewater in the United States is processed in large facilities. According to a 2008 survey from the U.S. Environmental Protection Agency [39], WWTPs in the United States with a capacity of 10 MGD or greater process a total of 21,600 MGD, accounting for 67% of the total cumulative wastewater flow (32,300 MGD). The wastewater capacity of some facilities is significantly greater than 10 MGD; for example, the Stickney Water Reclamation Plant in Chicago, Illinois, processes 700 MGD, with capacity to process up to 1,444 MGD [40]. Larger facilities would be a logical place to implement treatment with and conversion of algae; however, even the small- to medium-sized facilities could implement the described treatment and conversion processes.

Profitability is predicted for both the WWT-CAP and WWT-AD scenarios at scales >5 MGD, indicated in Figure 6 by the point where the base case MBSP for the WWTP begins to drop below the MBPPs calculated for the conversion facility. This demonstrates the importance of WWTP scale to the economics of a conversion process; at smaller scales below roughly 5 MGD, the cost of cultivating, harvesting, and converting the biomass does not make economic sense at base case assumptions for nutrient removal credits. Note the curves on this plot are inclusive of all costs (capital and operating) over the varying scales for both algal biomass production (MBSP curves) and conversion (MBPP curves) but do not include upstream WWTP costs prior to the algal WWT operations.

The effect of scale was also considered in the context of varying nutrient credits. At low nutrient credits (−50% of the base case values), both the CAP and AD conversion pathways require higher scales to achieve economic viability (12 MGD and 20 MGD, respectively). At higher nutrient credits (+50% of the base case values), the viability of employing treatment with algae is greatly improved, allowing CAP and AD conversion pathways to be viable down to scales of 3 MGD. However, due to the steep economy-of-scale penalties observed below ~3 MGD, smaller facilities below that scale are still not predicted to be viable.

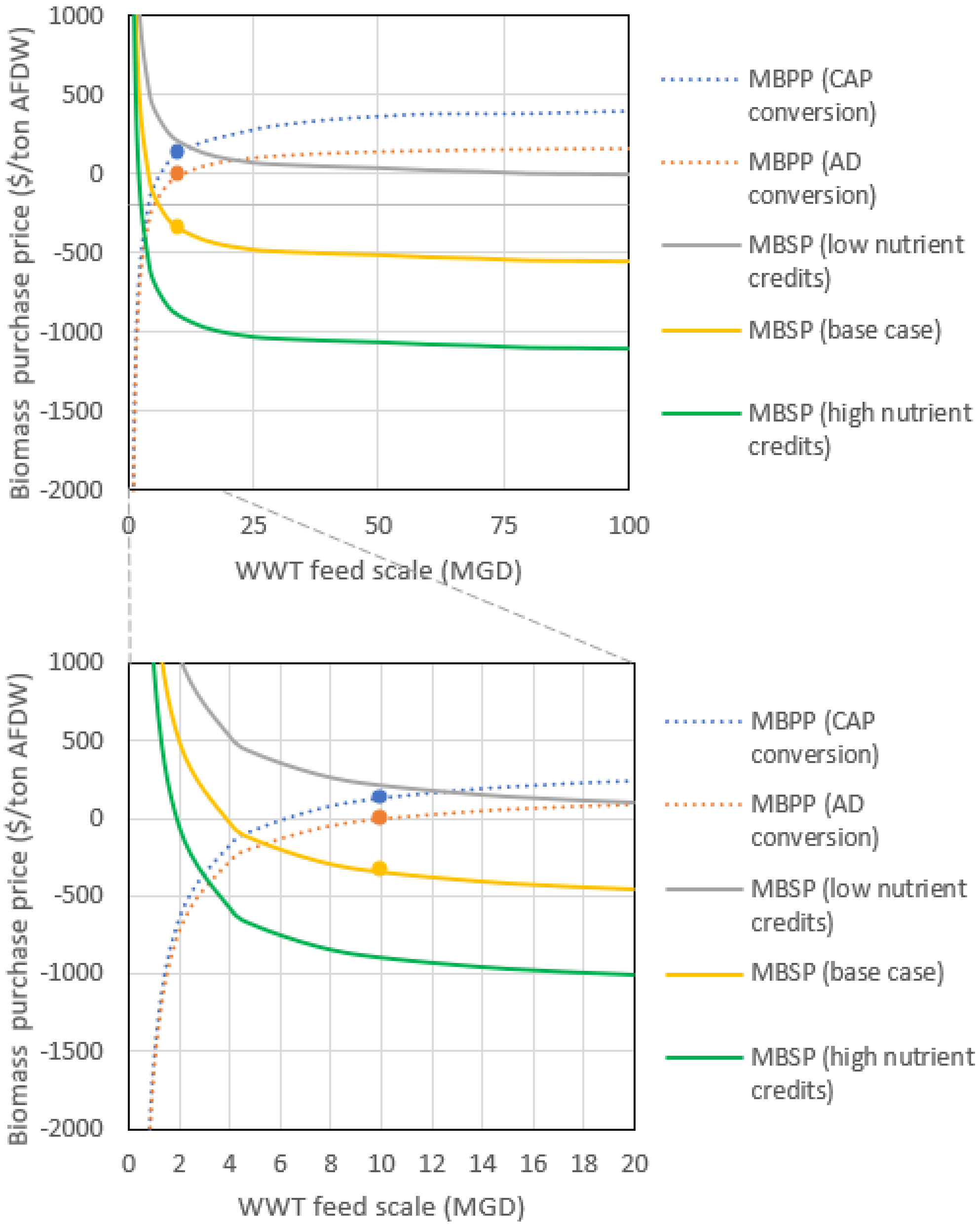

Figure 6. Plot of MBPP (as determined by a conversion facility with fixed product prices) and MBSP (as determined by WWT facility with fixed nutrient credits). Results of base case scenarios are indicated with a marked data point. Areas where MBPP > MBSP represent scenarios with the potential for profitability. High and low nutrient credit cases represent +50% and −50% nutrient credits for N and P compared to the base case, respectively. The bottom plot shows a zoomed-in view over smaller scales for additional detail.

Comparison of WWT-CAP and WWT-AD Conversion Scenarios

Both the CAP and AD conversion pathways demonstrate a strong potential for profitability when paired with biomass sourced from WWT. The WWT-CAP scenario enabled a higher MBPP (\$130/ton) than the WWT-AD scenario (−\$6/ton) due to the production of more valuable products, including liquid fuels and a solid co-feed for thermoplastic production. Liquid fuels are much more versatile than the RNG produced in the AD pathway, and thus are associated with a higher value on an energy content basis; here, we have assumed a liquid fuel value of \$2.50/GGE, whereas RNG is priced at \$4.12/MMBtu (equivalent to \$0.48/GGE). Additionally, the CAP pathway produces significant amounts of solid coproduct selling at a price of \$818/dry ton, accounting for ~60% of annual revenue, compared to AD digestate solid coproduct sold at \$300/ton. Revenues from nutrient coproducts (sold as crop water/digestate) and recycled CO_2 also account for a considerable portion of the revenue for each process.

These higher product/coproduct revenues for the CAP process offset the increased capital and operating costs, resulting in a higher (more favorable) overall MBPP than the AD pathway. However, the AD pathway is not without its merits. Capital costs for the AD pathway are roughly half that of the CAP process, owing to the simplicity of the process; the benefit of this can be seen when taking the TEA approach of solving for IRR. Using this approach, the AD pathway outperforms the CAP pathway (IRR of 44% vs. 36%, respectively, when setting the biomass purchase price equal to the MBSP). Additional capital savings may be realized for WWT facilities that can leverage existing AD operations. Lower costs are also observed compared to the CAP pathway for variable operating costs (i.e., raw materials), as well as fixed costs (a result of lower capital and labor requirements). These low capital and operating costs may make the AD pathway a more attractive option to a municipality with tight margins and a low budget for large capital expenditures; additionally, rather than purifying/selling the biogas as RNG, it could also simply be used on-site as generator fuel to support power demands. Policy credits may also more strongly benefit the AD case; this is discussed in greater detail in the sensitivity analysis sections below. It should also be noted that the economic advantages of the CAP process fade at smaller scales, ultimately being matched by the AD pathways at scales <2 MGD due to the more simplistic process design and lower capital intensity (though again noting that profitability is not predicted for either pathway below 4.5 MGD under base case assumptions). Additionally, the AD pathway shows a much lower economic sensitivity to biomass composition, discussed in more detail below.

Compositional Sensitivity Analysis

Given wide compositional variability expected for these types of algal biomass resources, a compositional sensitivity analysis was performed for each conversion process. The results of the compositional sensitivity analysis are depicted in the ternary diagrams in Figure 7. Each corner of the ternary diagram represents a biomass composition that contains elevated levels of either carbohydrates, lipids, or proteins. The compositions of the high-carbohydrate and high-lipid biomass are reflective of mid- and late-stage nutrient depletion harvests of *Scenedesmus*, respectively [20,41]. To ensure that a broad compositional spectrum was covered, the high-protein biomass composition was based on the actual harvested composition from our previous SOT trials [22].

The compositional sensitivity analysis provided valuable insights on how the biomass composition can affect conversion economics. Within the CAP process, the calculated MBPP can range from −\$69/ton to \$174/ton, with high-protein biomass producing more favorable results. This can be attributed to a disparity in value between the various products of the process within this currently reflected CAP configuration; while the carbohydrate and lipid constituents of the biomass serve as precursors for fuels (ethanol and hydrocarbons, respectively), protein contributes to solid coproduct yields, which fetch a higher value than the fuel products. Alternative CAP configurations and product suites may be more optimal for biomass compositions at higher levels of carbohydrates or lipids, which would change these trends.

Significantly less variability is seen for the CAP-AD scenario when considering the same range of feedstock compositions, with the calculated MBPP ranging from −\$73/ton to −\$3/ton. The most favorable results are again associated with the high-protein composition due to increased coproduct credits for digestate and crop water (since high-protein biomass has an inherently higher N content, which receives a coproduct credit from the back end through conversion without incurring a cost for front-end cultivation given N/P nutrients available at no cost for WWT). As a whole, however, economic results for the WWT-AD scenario are relatively consistent across a range of compositions and are more favorable than the WWT-CAP scenario when there is a relatively lower amount of protein. This result highlights the merits of the AD approach when the biomass composition is unknown or variable over time.

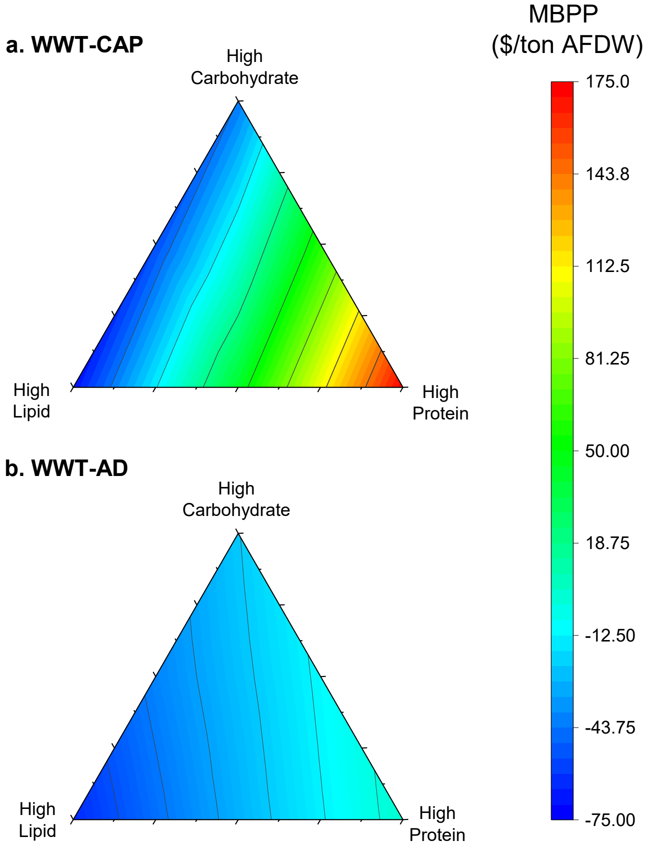

Figure 7. Ternary diagrams showing effect of composition on MBPP for WWT-CAP and WWT-AD scenarios. A higher MBPP reflects more favorable economics (a biorefinery is willing to accept a higher cost of biomass while still maintaining profitability through conversion).

Single-Point Sensitivity Analysis: CAP Conversion

A single-point sensitivity analysis was performed on the CAP and AD conversion processes. For each parameter considered, an MBPP is calculated at a high and a low value with all other variables held constant. Each MBPP is then compared to the base case MBPP for the corresponding scenario to determine the change in MBPP, which is used as a measurement of economic sensitivity. The parameters considered in the sensitivity analyses, along with the upper and lower bounds, are shown in Table 9; results are shown in Figure 8 and Figure 9 for the CAP and AD processes, respectively.

Table 9. Parameters Varied in the Single-Point Sensitivity Analysis for Biomass Conversion

Assumption	Unfavorable	Baseline	Favorable
CAP & AD			
Fuel selling price [a]	−25%	Varies	+25%
Fertilizer/crop water selling price	−25%	$0.15/lb dry weight	+25%
Total capital investment	+25%	-	−25%
Labor costs	+50%	-	−50%
Solid coproduct selling price	−25%	$818/ton dry weight	+25%
RIN credits	-	None	$0.78/gal ethanol equivalent (energy basis)
CAP Only			
Dilute acid pretreatment carbohydrate solubilization	95%	80%	65%
Dilute acid pretreatment protein solubilization	70%	50%	30%
AD Only			
Biogas cleanup cost	+50%	-	−50%
Biogas upgrading facility	-	Local upgrading	Centralized upgrading

[a] Applies to all fuel products for the process (may include ethanol, clean lipids, and/or RNG).

Revenue from Fuels, Coproducts, and Policy Credits

The most impactful conversion parameter for the WWT-CAP scenario was solid coproduct selling price, referring to the value of the solids as a co-feed for thermoplastic production as an example case considered in this study. It is understood that the suitability of the solids for co-feeding relies on the compositional profile of the solids, requiring sufficiently high protein content while limiting the composition of other fractions such as carbohydrates, lipids, and ash [26]. Solids with ideal compositions may achieve higher values of up to $1,088/ton, while lower-quality solids may sell for as low as $725/ton [26].

The MBPP showed a high sensitivity to variations in solid coproduct selling price, with fluctuations of ±$103/ton observed for coproduct selling prices ±25% of the baseline value ($818/ton). Effects for variations in the crop water and fuel selling prices had a considerably smaller effect on economics than the price of the solid coproduct. Crop water price, varied by ±25%, resulted in a change in MBPP of ±$29/ton; fuel price, also varied by ±25%, resulted in a change in MBPP of ±$27/ton. These lesser impacts compared to the solid coproduct are a result of the crop water and fuel selling at relatively low value ($300/ton and $500–$600/ton, respectively) compared to the solid coproduct ($818/ton) and highlight an important reliance of CAP process economics on revenue from a non-fuel coproduct stream, particularly for coproducts of a higher value than fuels. This imparts some risk to the economic stability of such a process but is a theme also observed in algal biorefineries with more conventionally cultivated biomass as an unavoidable requirement to offset the cost of algal biomass in order to achieve economic viability for simultaneous production of low-cost fuels [12,42].

Alternatively, policy incentives crediting carbon intensity reductions as may be possible through algae conversion technologies may also (or additionally) provide such cost offsets. An alternative case considering the inclusion of RIN credits was thus also considered. As outlined in the Renewable Fuel Standard, RIN credits are generated from renewable fuel production and can be sold to petroleum fuel producers to meet their annual obligations. The generation of RINs depends on the process meeting certain greenhouse gas reduction targets and feedstock requirements, and the value of a RIN credit depends on which renewable fuel category it falls into; here, we have assumed a RIN value of $0.78/gal (ethanol equivalent, calculated on an energy basis). This value was determined from a 5-year average of historical D4 RIN prices for 2017–2021 [43]; however, it is worth noting that these credits can also trade significantly higher, and that the average D4 RIN value in 2021 was $1.32/gal. Generation of these RINs resulted in an MBPP increase of $51/ton, showing the significant effect that public policies can have on economics. Further benefits may also be observed in localities that have implemented additional renewable fuel policies, such as California's LCFS.

Labor Costs

Labor costs, referring to the annual operating expenditure for conversion plant personnel, had a significant effect on process economics. When labor costs were varied by ±50%, a variation in MBPP ranging from ±$80/ton was observed. Due to the relatively small biomass feed rate of the process compared to a conventional biorefinery, the effect of labor costs on process economics was especially pronounced, reflecting economy-of-scale penalties compared to larger commercial biorefineries typically investigated in prior NREL TEA studies.

Total Capital Investment

TCI was varied by ±50%. This resulted in varied levels of impact for each feedstock, at around ±$51/ton for the case presented herein.

Pretreatment Efficiency

The efficiency of the dilute acid pretreatment strategy on carbohydrate and protein solubilization was considered due to the significant effect these variables can have on fermentation and solid product yields. Protein solubilization had a measurable effect on MBPP, with protein solubility of 30% and 70% associated with respective changes of +$36/ton and −$34/ton for the MBPP. At higher protein solubilization, more protein is lost from the residual solids, resulting in a lower yield of the highest-value solid coproduct.

Variability in carbohydrate solubilization had the effect of impacting ethanol yields in fermentation, which makes direct use of soluble sugars for conversion. However, this effect was less pronounced than that observed for proteins, with carbohydrate solubility of 65% and 95% associated with respective changes of +\$17 and −\$14/ton for the MBPP. This is due to a higher value associated with the solid coproduct compared to the fuel products.

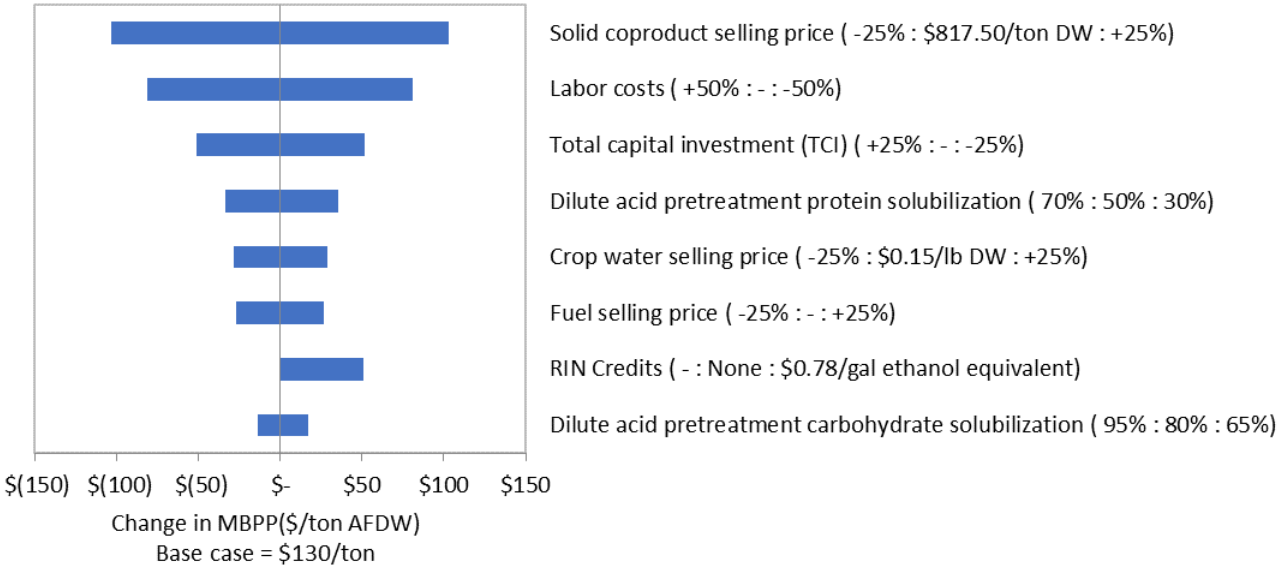

Figure 8. Single-point sensitivity analysis for key parameters of the CAP conversion process

Single-Point Sensitivity Analysis: AD Conversion

Revenue from Fuels, Coproducts, and Policy Credits

One notable difference between the CAP and AD cases is that the AD case has a much higher sensitivity to the inclusion of RIN credits. Including these credits had the substantial effect of increasing the MBPP by \$90/ton, compared to a \$51/ton increase in the CAP case. Multiple factors drive this difference; the CAP process has significantly higher capital and operating costs than the AD case, but this is compensated by the revenue from the solid coproduct. In contrast, the AD case has lower capital and operating costs but significantly less revenue generation. Thus, the inclusion of RIN credits results in a 41% increase in revenue generation (compared to an 8% increase for the CAP case) and increases the MBPP to \$84/ton.

The implications of this impact are important to highlight; assuming that the WWT-AD case qualifies for RIN generation, the economics are substantially more promising, even when compared to the favorable base case. Of course, the fuels produced in each case are not equivalent because the AD case produces RNG while the CAP case produces liquid fuels. This has implications on the eligibility for RINs; however, if the RNG is used as a transportation fuel and meets the required greenhouse gas reduction requirements, it can qualify for RINs. In fact, it is possible that the RINs produced in the AD case fall into the D3 category and therefore actually command more value (5-year average of $2.05/gal, with average 2021 prices of $2.65 [43]). Although this category is generally reserved for cellulosic fuels, RNG produced from landfills and anaerobic digestors also qualifies for this higher-value RIN, suggesting that the advantages for the AD case could be even greater when considering policy credits [44,45]. When D3 RIN generation is considered at a value of $2.05/gal, an MBPP of $231/ton (an increase of $237 vs. the base case) is observed, showing the potential for very strong profitability.

This high economic impact of policy credits is also substantiated by the current market for RNG. As discussed previously, recent market prices for RNG range from $15–$100/MMBtu [30–32], driven by policy incentives for RNG production and utilization. Considering a conservative RNG selling price of $10/MMBtu for the WWT-AD case results in an MBPP of $46/ton, an increase of $52/ton compared to the base case. Further, RNG selling prices of $15/MMBtu and $30/MMBtu result in MBPPs of $90/ton and $222/ton, respectively. This green premium, driven by policy credit incentives, can dramatically improve near-term economic viability for deployment of this approach.

Fertilizer and crop water selling price also had pronounced effects on MBPP, with variations of ±25% resulting in a change of ±$42/ton for the MBPP, evidence that the AD conversion pathway is also reliant on coproduct revenue. Conversely, a less significant effect was seen when varying the fuel selling price by the same amount. When fuel selling price was varied by ±25%, a change in MBPP of ±$9/ton was observed. This lesser effect is again due to relatively lower fuel revenue compared to the revenue from coproducts, driven by a relatively low value of the fuel product (in this case, RNG) and higher overall yields of coproducts.

Labor Costs

As in the CAP case, variations in labor costs can significantly affect process economics, with variations of ±50% in labor costs resulting in a change in MBPP of $33/ton. This effect is seen despite the further reduced personnel numbers assumed for the AD scenario, highlighting the importance of optimizing labor needs for small-scale biorefinery operations such as this one.

Biogas Cleanup Costs

Biogas cleanup accounts for more than two-thirds of the total installed equipment cost the AD case. Additionally, biogas cleanup costs can vary significantly depending on the upgrading strategy used [28]. To evaluate the economic sensitivity of the process to these costs, biogas cleanup costs (including both capital and operating costs, which are linked to capital costs as described by Saur and Jalalzadeh-Azar [27]) were varied by ±50%. This resulted in associated changes of ±$51/ton for the MBPP, among the highest of the parameters considered and exceeded only by the inclusion of RIN credits. This demonstrated economic sensitivity to upgrading costs suggests that the upgrading strategy is a major cost driver for the overall conversion process and that it should be chosen prudently based on the scale and specific requirements of the process. Given the variety of different upgrading technologies available, more detailed modeling of the biogas upgrading process may be warranted in future analyses.

To further evaluate sensitivity to the assumptions behind the biogas upgrading costs, a scenario including a centralized upgrading facility was considered. In the base case, the biogas produced is assumed to be upgraded directly on-site to RNG. Alternatively, biogas may be transported to a centralized upgrading facility via pipeline for RNG production. In this scenario, transportation and upgrading costs are divided among a group of local biogas producers. Pipeline costs were calculated to be \$0.0605/Nm^3 and follow the methodology laid out in Hengeveld et al. [46]. This cost is calculated by assuming 16 biogas producers each feeding an average 300 Nm^3/h of biogas to a centralized upgrading facility, with the side of the square source area equal to 30 km (18.4 miles). Upgrading costs for the centralized facility are calculated using cost factors supplied by Saur and Jalalzadeh-Azar [27], with the costs shared by all biogas producers. Costs for compressing and storing the CO_2 removed from the biogas are also considered, which is sold as a coproduct (as opposed to the CO_2 from the biogas utilized at the conversion facility, which is recycled to the WWTP to supplement algal biomass growth).

The consideration of a centralized facility resulted in moderately improved economics, with the MBPP increasing by \$20/ton. The centralized facility was associated with significant capital cost savings; the installed cost of the biogas cleanup infrastructure was reduced by nearly 75% compared to the local upgrading case. However, these benefits are dampened by significant costs for installing pipeline and compressing the CO_2 removed at the centralized upgrading facility.

Total Capital Investment

A variation of ±50% in TCI resulted in an impact of ±\$25/ton over MBPP.

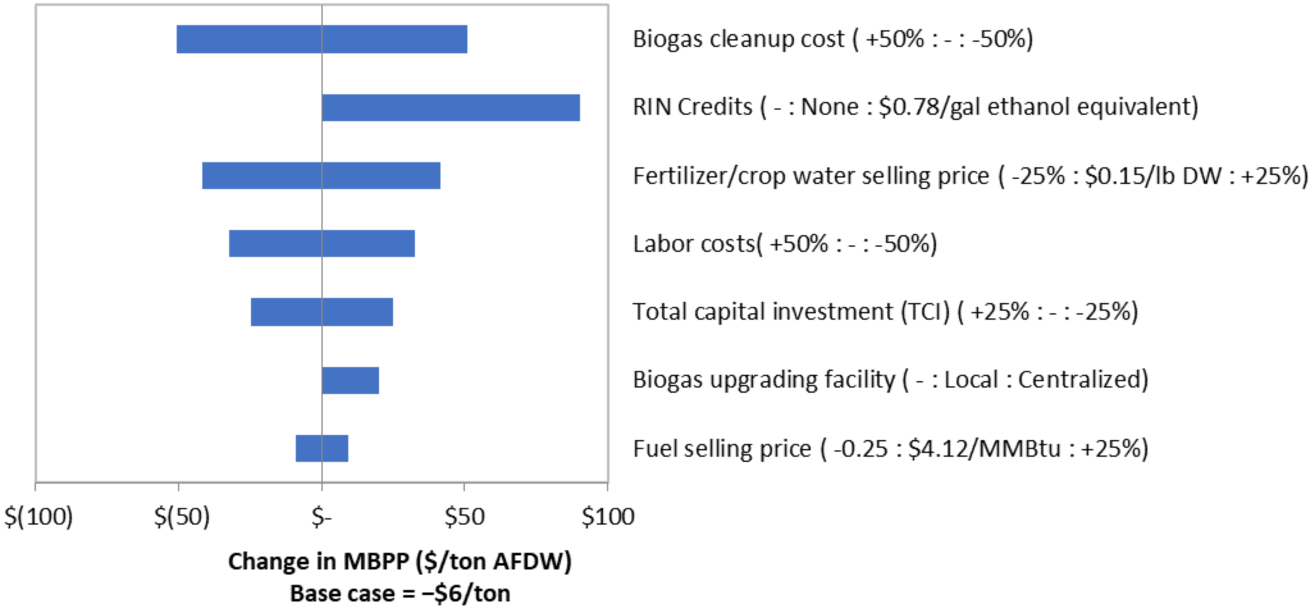

Figure 9. Single-point sensitivity analysis for key parameters of the AD conversion process

Concluding Remarks

The analyses conducted here provide valuable insights on the opportunities and challenges for the production and use of algal biomass cultivated for wastewater treatment. Not only may these resources be procured at reasonable costs in the near term, but technologies for their conversion to renewable fuels and products may also be deployed in the near term at smaller community scale, leveraging relatively established and low-risk conversion processes. While such algae resources may be limited in their scalability (i.e., will not alone contribute billions of gallons to the national fuel infrastructure, as commercial algae farms may one day be able to support [4]), the significantly lower cost of algal biomass envisioned through these pathways could support important early expansion of the industry to begin "getting off the ground" and develop learning curves for producing, harvesting, and processing algal biomass as could be applied to commercial algae farming and more complex algal biorefineries further into the future. Namely, the TEA modeling conducted here highlights example pathways for conversion of algal biomass produced from wastewater treatment via processing through simple CAP or AD conversion operations—with good potential for economical production of infrastructure-compatible fuels (ethanol, lipids for hydroprocessing to diesel or sustainable aviation fuels [SAF], and renewable natural gas for use as an energy source and/or subsequent upgrading for renewable hydrogen generation) and large-market coproducts (feed for bioplastics, crop fertilizers, and captured CO_2) even before the inclusion of policy incentives. When policy incentives such as RIN credits are also considered, the economic potential of these approaches is considerably increased; however, the qualification for these credits must be certified by comprehensive life cycle assessment (LCA), which is outside of the scope of this analysis. Future work should expand on this assessment to include LCA also for purposes of better understanding the decarbonization potential for these strategies, in light of favorable economic potential demonstrated here.

Comparing between conversion technologies, the CAP pathway produces liquid fuels as well as a more valuable solid residual coproduct that may be utilized for thermoplastics, but at higher capital/operating expenses. Conversely, the AD pathway requires a significantly lower capital investment (50% of the CAP facility) and annual operating costs (36% of CAP facility total operating costs) but produces a less valuable RNG product and AD effluent/digestate fertilizer materials—though opportunities may exist for higher-value RNG outlets in the near term through policy incentives, as well as potential implications on subsequent carbon capture options from RNG that would not apply for vehicle fuel use. Overall, the trade-offs between processing costs and product/coproduct revenues translate to more favorable economics for CAP conversion in the case of WWT-derived biomass in comparison to AD.

For the WWT scenario, TEA modeling expanded from previous work indicates strong economic potential for coupling algae with wastewater treatment, in this case tertiary treatment of wastewater to achieve N/P reduction down to regulatory discharge limits (which in some cases are becoming more stringent over recent years and moving forward, as a key opportunity for algae to support). In particular, algal WWT for this purpose has been shown to be economically viable for facility scales of at least roughly 5 MGD, provided sufficient treatment credits may be applied on the order of \$3/lb N and \$50/lb P reduction with the majority of economic incentives driven by P mitigation. Under those parameters, algal WWT may even be economically viable without depending on any revenue from sale or use of the algal biomass, with further profitability that may be realized by incorporating either conversion process to upgrade the biomass into fuels and products. This scenario indicates a large potential profit margin, with the base case minimum biomass selling price for biomass production calculated at *negative* $341/ton, while allowing a maximum purchase price up to $130/ton by the conversion facility. Further options also exist to unlock more locations for algal WWT through the use of photobioreactor cultivation, particularly in more northern climates or land-constrained WWT facilities.

Moving forward, further opportunities exist to expand on the feasibility analyses conducted here, both to continue exploring the most promising findings as well as to address knowledge gaps identified during this work. These are summarized as follows:

- Collaborate with WWT stakeholders (ideally processing >5 MGD) to further understand how the industry views nutrient removal credits and what the primary barriers are for adoption of algal WWT technology. Focus on opportunities in areas with more stringent discharge limits.
- Consult with companies performing algal WWT to expand analysis and assess alternative treatment technologies (as are being pursued in industry beyond standard raceway pond designs—e.g., in light of other factors such as land availability constraints) combined with CAP and AD conversion processes described here.
- Incorporate experimental data regarding additional biomass compositions from production, as well as data on conversion of biomass (pretreatment/fermentation/AD performance) to confirm details assumed here.
- Perform detailed LCA on each process to identify the key drivers of carbon intensity, opportunities for decarbonization, and the associated implications on policy incentives such as RIN and LCFS credits.

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Opportunities for Utilization of Low-Cost Algae Resources: Techno-Economic Analysis Screening for Near-Term Deployment

Part 2: Algal Biomass Sourced via Harmful Algal Blooms and Commercial Lipid Extraction

Executive Summary

While microalgae as a biomass resource holds tremendous potential to contribute meaningful volumes of renewable fuels and bioproducts at the national and global stage, the high cost of algal biomass when sourced through "conventional" cultivation systems may limit its deployment at large commercial scales for commodity fuel production in the near term. Accordingly, to support today's nascent algae industry and seek out opportunities for it to progress along a technology learning curve toward such future scales, identifying and capitalizing on lower-cost algae resources as may exist today or in the near future adds a crucial building block toward this progression. Particularly when viewed in the context of system integration with downstream utilization in mind, techno-economic analysis (TEA) modeling can be a powerful tool to highlight opportunities and challenges for both producing/sourcing such biomass and converting it to fuels and coproducts.

As such, this report presents TEA modeling and analysis conducted for collection/procurement of existing low-cost algae resources as generally may be viewed as waste or byproduct biomass. In this Part 2 volume, we focus on biomass that may be collected from harmful algal blooms (HABs) and residual biomass remaining after lipid extraction (EXT) as done at limited scale in industry today for higher-value algal lipid components. As in Part 1, TEA is performed for processing these two biomass sources through two possible conversion pathways, selected primarily with an emphasis on simplicity and local community-scale deployability in the near term—namely a simple combined algal processing (CAP) schematic, as well as conversion via anaerobic digestion (AD). In the CAP framework, biomass is converted to infrastructure-compatible liquid fuels (namely ethanol and lipids to be subsequently processed to diesel or jet fuel) as well as value-added coproducts (primarily residual protein valorized as a feed for downstream production of thermoplastics). In the AD scenario, the biomass is simply digested to biogas (subsequently upgraded to renewable natural gas [RNG]) while producing crop fertilizer coproducts.

The scenarios for biomass resources and conversion pathways were found to exhibit high potential for economic viability as may be deployed at small scale in the near term primarily for CAP conversion of either biomass resource, even before factoring in potential policy incentives. AD conversion also may be a viable approach upon inclusion of such policy incentive credits, which are particularly valuable for RNG produced from the AD pathway. This was primarily evidenced through the TEA modeling approach applied here to solve for the "maximum biomass purchase price" (MBPP) that a conversion facility would be willing to pay as a biomass "transfer" price from the upstream production/collection entity, ranging up to $140/ton for CAP conversion. Although such low prices would never be achievable from conventional algae farming systems, in this context these prices were not viewed as being unreasonable given that these biomass sources are not produced for purposes of selling (or necessarily even utilizing) the biomass, but rather may be viewed as a waste or an environmental nuisance that would otherwise require additional expense to merely dispose of.

Specifically, the HAB and EXT scenarios indicated good economics for conversion through CAP, translating to a required MBPP of $21/ton for HAB and $139/ton for EXT (here, a higher MBPP indicates a better economic result). The former cost could be reached for HAB biomass collection/harvesting given sufficient water "treatment" credits on the order of $840 per million gallons, payable to the HAB biomass collector from a local government or municipality with a vested interest in removing HAB to improve the local ecosystem (in some cases as may also be tied directly to the local economy). Results were somewhat less favorable for AD conversion, translating to MBPPs of –$177/ton and –$83/ton for HAB and EXT biomass sources, respectively (generally exceeding costs for landfilling disposal at a tipping fee of –$35/ton). In the HAB case, this MBPP would in turn require water treatment remediation credits of $1,450 per million gallons for HAB biomass collection. However, the AD configuration also exhibited merit with much lower capital and operating costs, thus potentially being more readily deployable at small scale based on mature technology (though producing lower-value RNG and fertilizer products).

Beyond base case economics investigated for the above biomass sourcing/conversion scenarios, a number of sensitivity cases were also evaluated to better understand trade-offs and key drivers on overall system economics. Scale was found to be a strong driver in all cases evaluated, given that the scales set as the base cases here were already substantially smaller than typical commercial algae farm models envisioned in our past TEA work (roughly 13–16 tons/day of algal biomass in these cases compared to over 550 tons/day projected for a 5,000-acre *n*th-plant commercial algae farm reflected in prior TEA models). Additionally, applicable treatment credits for the HAB case also strongly influenced overall system economics. On the conversion side, non-fuel coproduct credits (including those that may be generated by policy incentives) were also shown to exhibit strong sensitivity in supporting overall economic viability, as has also commonly been observed in algae conversion pathways sourced via conventional algae farming approaches. Finally, further opportunities to expand this assessment and address gaps/remaining questions in the future are also discussed.

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Introduction

Part 1 of this report introduced the promising potential of algae, as well as the cost challenges of large-scale biomass production through dedicated algae farms. In light of these considerations, the present assessment again seeks to identify opportunities to support and grow the algae industry in the more near term over coming years by avoiding such large-scale/high-cost commercial algae farming approaches, and instead focusing on low-cost algae resources as exist today or may be readily developed by leveraging existing opportunities. Primarily, this involves algal biomass that may be viewed either as a "waste" or byproduct resource as may be available typically at much smaller scale. In this Part 2 volume, we focus on (1) biomass as may be collected and removed from naturally occurring harmful algal blooms (HABs) and (2) residual biomass from current algae industry activities focused on extraction (EXT) of high-value lipids such as omega-3 fatty acids.

As carried out in Part 1 of this report for algal biomass obtained by integration with wastewater treatment (WWT) systems, we investigate opportunities, costs, and potential scale for procuring each of these two additional resources, coupled with techno-economic analysis (TEA) modeling for two possible conversion scenarios emphasizing opportunities for deployment at small community scale based on maximizing process simplicity and thus minimizing capital costs for deployment. The following sections of this report document key TEA modeling inputs and assumptions for both biomass production/collection and conversion to fuels/energy products (as a primary focus) and residual coproducts (as warranted), as well as resultant yields and overall economics with a focus on understanding biomass production/collection costs versus the maximum allowable costs of such feedstocks through the conversion scenarios as necessary to achieve economic viability.

Inputs and Assumptions

As in Part 1 of this report, two conversion process approaches were considered in this exercise as applied across the biomass resources of interest. One focuses on production of liquid fuels/precursors via a simplistic combined algal processing (CAP) pathway, fermenting carbohydrates to ethanol and valorizing residual biomass as a co-feed for thermoplastic production (lipids may also be extracted for coprocessing to hydrocarbons, as described in Part 1; however, low lipid content of HAB and EXT biomass does not justify the inclusion of this step for the CAP approach considered here in Part 2). The second conversion approach further simplifies the process to a single primary unit operation via anaerobic digestion (AD), producing biogas as the primary energy product as may be upgraded and sold into renewable natural gas (RNG) markets, with AD byproduct fractions sold as fertilizer credits. A high-level overview of the conversion process schematics as reflective of processing HAB- and EXT-derived algal biomass is depicted in Figure 1 and Figure 2, followed by a brief description of the modeled process pathways.

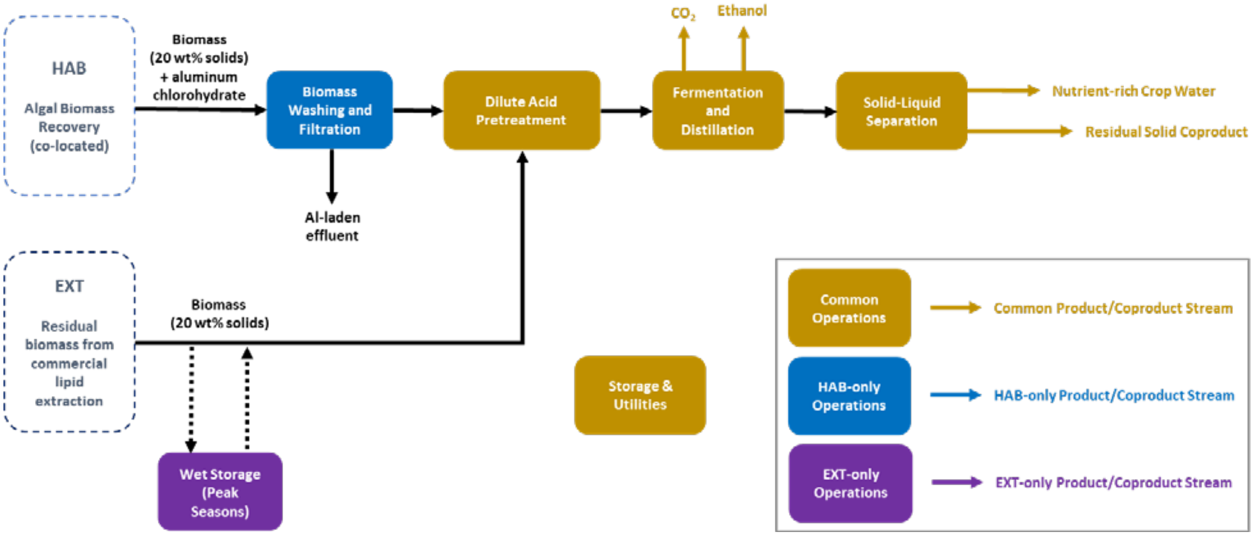


Figure 1. Process flow diagram for the CAP scenario demonstrating the conversion of algal biomass recovered from HABs and available after lipid extraction in industrial units (EXT)

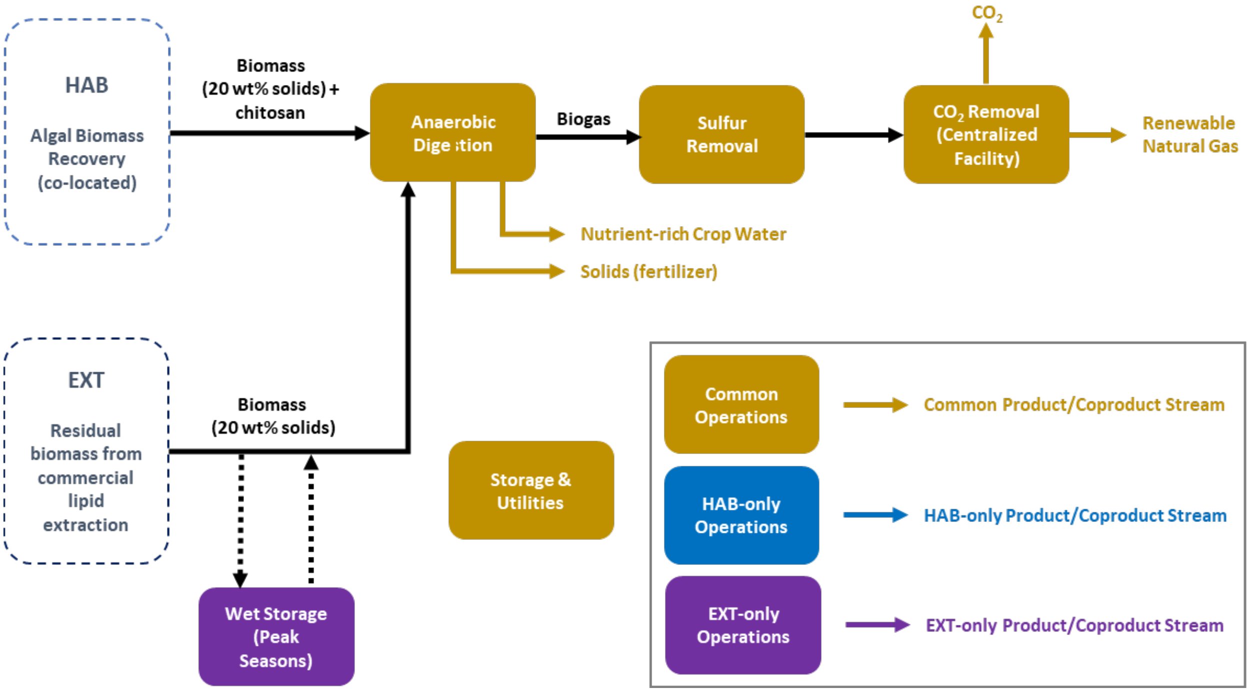


Figure 2. Process flow diagram for the AD scenario demonstrating the conversion of algal biomass recovered from HABs and available after lipid extraction in industrial units (EXT)

Harmful Algal Bloom Biomass

Biomass Sourcing

Under normal conditions, naturally occurring algae production in nutrient-rich, saline, or freshwater environments ranges from 2–6 tons/hectare/year [1]. When an excessive amount of nutrients (namely nitrogen [N] and phosphorus [P] compounds leached from upstream agricultural lands) reaches local water bodies, microalgae can flourish in an uncontrolled manner, giving rise to algal blooms. In such events, microalgae productivity can increase by an order of magnitude up to 60 tons/hectare/year (though the referenced study was not clear whether this is based on dry weight or ash-free dry weight [AFDW] biomass) [1]. Since the production of toxins is a common secondary feature of certain species in algal blooms (usually microcystin in parts-per-billion levels), such events can also be deemed harmful algal blooms. HABs can impact water quality for human consumption, tourism, recreation, health of animals and wildlife, and fishery activities and ultimately lead to hypoxia—a severe depletion of oxygen, critical to higher levels of the food chain [2]. It is estimated that HABs in Lake Okeechobee (Florida, USA) alone incur annual economic losses in the order of $60 million [3]. Accordingly, HABs have gained significant recent attention, and local governments and environmental remediation agencies are increasing efforts to control these events and identify ways to harvest (and potentially utilize) the resulting biomass [4].

This section provides insights toward the removal of microalgal biomass from HABs in a large freshwater body to mitigate the negative economic and environmental effects of such phenomena through a preliminary screening TEA. Instead of considering the algae cultivation ("farm") stage usually reflected in conventional microalgae TEA studies [5–8], the following framework proposes a three-step process for remediation of bodies of water following the proliferation of a HAB event: interception of HAB biomass with a passive collection system, dewatering of the suspension using established technologies, and conversion of the obtained biomass, again utilizing either AD or CAP approaches similar to those described in Part 1. Sensitivity analyses toward critical technical and economic parameters are carried out to identify feasible operation ranges of such ventures. Additionally, this report simplistically refers to "microalgae" as the group of organisms found in HABs, which include green microalgae, cyanobacteria, and diatoms. Other problematic or nuisance biomass proliferation events also occur through macroalgae blooms (e.g., seaweeds such as *Sargassum* in saline environments) and may offer further opportunity for collection and use, but this is outside the scope of the present analysis.

The assessment presented in this report considers a fixed (stationary or nonmobile) unit to remove microalgal biomass from a large lake with recurring HAB events and a simple, efficient business model to exploit the algal biomass recovered in this way. While mobile units for HAB biomass collection are also the subject of present study for bloom remediation, a fixed facility has been chosen as the baseline case due to some similarities in comparison to a conventional wastewater treatment plant (as is the subject of Part 1) and to lower the uncertainties associated with estimating the economic parameters for its deployment. It is also assumed that the lake includes infrastructure for the controlled release of excess water, also known as a spillway or overflow channel, and that the system is designed to accommodate high algal concentrations that can form a film or scum on the surface. Figure 3 depicts the method for treating water from a lake with a significant HAB event and recovering microalgal biomass in the process. The system comprises pre-concentrating the algae in a given region of the water body, further dewatering until the biomass reaches an acceptable concentration, and ozonation of the treated water prior to discharge back to the lake. Since the process of removing algae from the lake is designed to have a significant (positive) impact on water quality, the plant is effectively a water treatment operation: the main product of the process is "clean" water returned to the water body (or spillway downstream), while microalgal biomass remains as a coproduct of industrial interest. An ideal site for establishing such facilities would incur a reliable annual HAB event in the same location with high microalgae concentration, high productivity, and which maximizes the number of operating days per year. The following pages detail such steps following recent efforts and guidance from industry collaborators (AECOM).

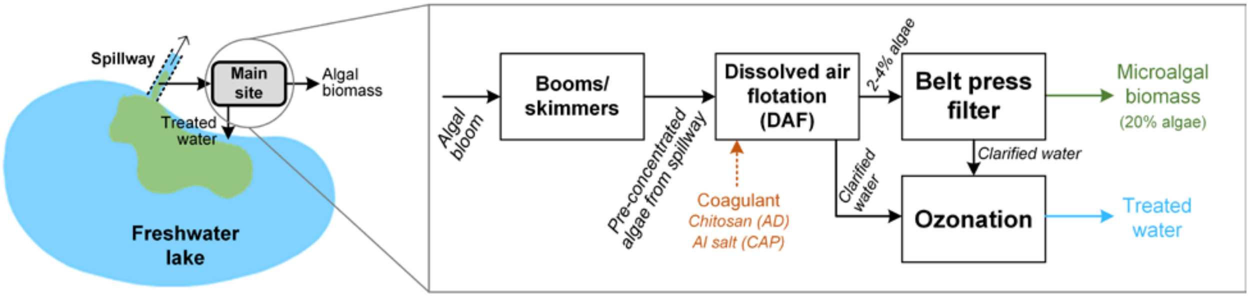


Figure 3. Schematics of the process for interception of HABs, biomass collection and recovery, and water treatment

Algal Bloom Interception

As microalgal cells often tend to concentrate close to the surface of water bodies during HABs, the initial step for recovery may consist of a "boom and skimmer" approach. In this design, a series of booms can contain the surface microalgae traveling down the spillway, and static skimmers are able to collect a thickened algal film—thus mimicking oil spill response structures. Floating weir skimmers are a promising option when the material to be collected forms a thick layer on the water surface [3], thus being the option chosen in this assessment. The floating weir skimmer design used in this assessment is based on tests performed by the U.S. Army Corp of Engineers Engineer Research and Development Center (ERDC) [3,9].

Each skimmer is coupled with a centrifugal pump to deliver the algal suspension to the dewatering section. This stationary collection method is ideal for algal blooms that occur reliably in the same location annually. For algal blooms that occur less reliably or move around lakes, mobile collection methods are necessary. The current assessment assumes a stationary skimmer weir collection strategy; therefore, details on the mobile collection methods are summarized for the sake of completeness, as the stationary design may be appropriate for a number of locations in the United States.

Most mobile collection strategies consist of a boat or fleet of boats with algae separation and dewatering equipment on board. The boats can be small enough to be loaded onto a trailer and moved across land to collect algae from multiple bodies of water, or large enough to be dedicated to one body of water. For example, large lakes such as Lake Erie produce consistent blooms annually, but the location of the bloom often varies throughout a single year. Algae collection boats have been designed by several research institutions including Utah Valley

University [10], University of Sheffield [11], University of Illinois at Urbana-Champaign [12], and others. Proposed collection methods include trawling nets and screens to partially dewater algae as it is collected, while other designs simply pump water containing algae directly to a dewatering unit. The most recent and detailed design of a mobile collection system is currently being tested at pilot scale by the U.S. Army Corp of Engineers ERDC [9]. The design includes five boats. Two lead boats use floating booms to tow a dissolved air flotation (DAF) barge. The two booms focus algae on the water surface into an intake weir on the DAF barge. Behind the DAF barge is a utility barge that provides power to the DAF unit. A fifth vessel is used to ferry the concentrated solids to shore, where solids processing operations are located.

Dewatering

As reported by one of the few field experiments related to the remediation of HABs coupled with microalgal biomass recovery [3], the first step of dewatering consists of carrying out DAF for algae/water separation, accordingly assumed in this study as well. The concentration factor of such systems is usually in the range of 400–600 times, yielding 2–3 wt % algae suspensions from very dilute initial conditions on the order of 25–100 mg/L (5–20 times more dilute than typical biomass harvested from commercial algae ponds). This operation requires the use of a coagulant to ensure an efficient aggregation of microalgal cells. When scaled up to industrial production levels, the coagulant choice should be made depending on the biomass conversion plant further downstream. When AD is the chosen conversion process, the coagulant used in the recovery is selected as chitosan, a naturally occurring biopolymer with high carbon content that could be converted to biogas along with the algae biomass to boost methane yields in AD reactors [13,14]. This also avoids the buildup of inorganics in the resulting biomass (already with high ash content) serving as feedstock for fuel production [3], as well as any potential toxicity effects for AD as may be incurred at high flocculant loadings. Alternatively, other coagulant types (such as starch-based ones) could be employed in large-scale facilities in an attempt to reduce the high costs associated with chitosan while still ensuring its ability to break down to biogas in AD reactors. However, when a CAP biorefinery is considered for the conversion of HAB biomass, an aluminum salt (aluminum chlorohydrate) is employed due to its lower cost in comparison to chitosan ($0.90/kg vs. $18/kg, respectively). It is assumed that both coagulants are recovered with the same efficiency as that for microalgal cells. In the end, the algal biomass is collected along with a significant amount of coagulant; when considering the baseline HAB microalgae concentration of 50 mg/L and the base coagulant loadings of 30 mg/L and 10 mg/L of aluminum chlorohydrate and chitosan, respectively, the recovered biomass/coagulant mix is composed of 39% aluminum chlorohydrate in the CAP case and 17% chitosan in the AD case.

Following DAF concentration, a belt press filter is the unit operation of choice for final dewatering of the microalgae due to potential advantages over centrifuges in terms of capital expenditures, operational expenses, and algal recovery efficiency. This process is assumed to yield a 20% solids suspension of microalgal biomass. Alternative unit operations to filtering are centrifugation and screw pressing (not assessed in this report).

Advanced Oxidation of Water Prior to Discharge

To ensure adequate water treatment through the process, an ozonation system is included as a polishing operation as the final step prior to discharge back to the water body to ensure the elimination of HAB-derived toxins such as microcystins [3]. Ozone dosing is proportional to the algal concentration of the HAB (higher microalgae amount in the water body could potentially mean higher microcystin concentrations, so the tertiary treatment is adjusted accordingly). The inclusion of this operation in the HAB biomass collection system is a conservative assumption of the present report. Recent studies have determined that this polishing step is often not necessary for water discharged from HAB collection to meet water quality for recreational use [9]. Since this is a costly process that significantly impacts the economics of the integrated system, sensitivity analyses are included to determine the influence of removing the ozonation unit from the HAB biomass collection plant. The outcomes from these analyses are presented in the Results and Discussion section.

Table 1. Main Technical Parameters Used To Model the HAB Biomass Recovery Facility

Parameter	Value	Reference
General parameters		
Microalgae concentration (mg/L)	50	General magnitude in [3,15] [a]
HAB event duration (days)	180	Assumption
Plant processing capacity (million gallons per day [MGD])	100	[3]
Floating weir skimmer capacity (m^3/h)	100	[16]
Dewatering operations		
DAF algae recovery efficiency	95%	[5]
DAF electricity consumption (kWh/kg microalgae)	0.133	[5]
Aluminum chlorohydrate dosage (mg/L) [b]	30	[3]
Chitosan dosage (mg/L) [c]	10	General magnitude in [17,18]
Belt press filter algae recovery efficiency	98%	[5]
Belt press filter electricity consumption (kWh/m^3)	0.3	[5]
Ozonation		
O_3 dosing (g/g algae in algal bloom)	0.1	General magnitude in [3]
O_3 generation electricity consumption (kWh/kg O_3)	12.5	[19]

[a] Average concentration considered for the large volume of water drawn from a lake. Peak concentrations at the surface, where HAB-causing algae often accumulate, could reach values that are orders of magnitude higher.

[b] Coagulant used when biomass processing is carried out with CAP.

[c] Coagulant used when biomass processing is carried out with AD.

Biomass Composition

For the HAB case, the estimated HAB biomass composition is based on available studies in the literature that perform a compositional analysis of such material [20–23]. The profile shown in Table 2 is an average of five distinct probed HAB events, presented alongside the composition for the EXT case. It is also worth highlighting that the compositions vary significantly between different HAB events and are highly dependent on the microalgae species in that specific body of water, the amount and ratio of nutrients available to microalgae growth, the temperature of the local water, the incidence of sunlight, and wind characteristics, among others [24]. For example, ash content varies between 6%–38% (average of 19.5%, standard deviation of 11.3%), while protein is observed to vary between 26%–60% (average of 37.6%, standard deviation of 12.5%).

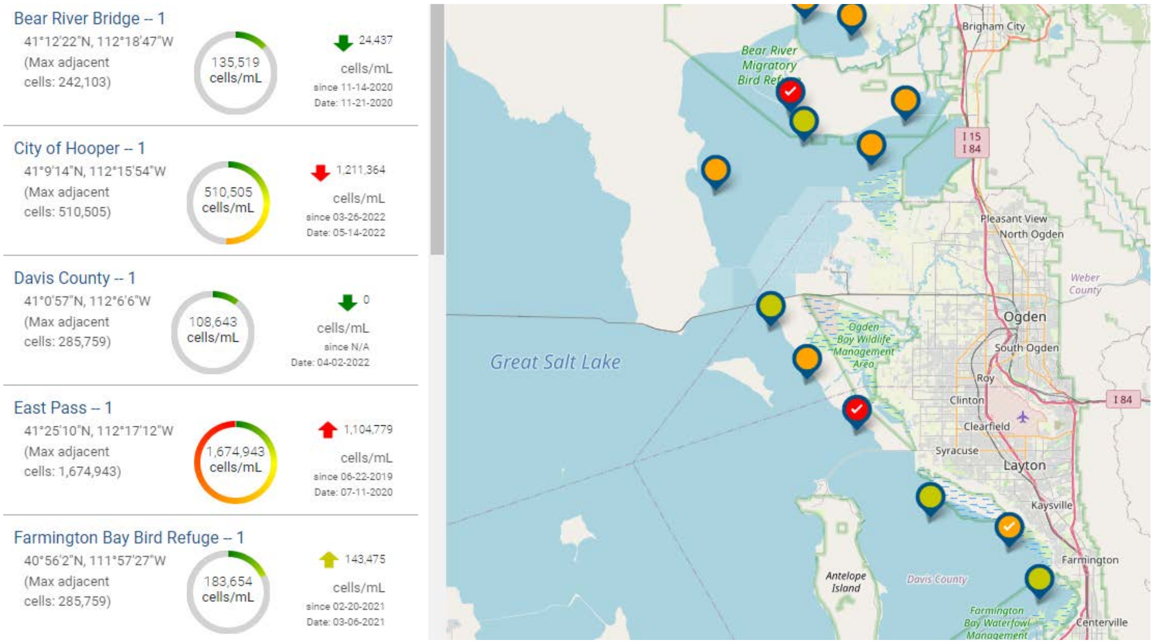
Table 2. Modeled Biochemical and Elemental Compositions for Each Source of Biomass

	HAB [a]	EXT [b]
Fermentable carbohydrates	15.1	21.3
Protein	37.6	44.2
Lipids	5.0	3.8
Ash	19.5	12.2
Non-fermentable carbohydrates	2.7	4.0
Non-fuel polar lipid impurities	6.4	1.9
Cell mass	13.7	12.6
C	53.0	51.5
H	7.9	7.6
O	29.5	30.2
N	8.6	9.3
S	0.0	0.2
P	1.0	1.2

[a] HAB composition determined by average composition of algal bloom biomass from literature [20–23].
[b] EXT composition determined by 75% lipid depletion of [25].

Biomass Availability

Estimating how much HAB biomass is available for recovery is an essential but difficult task in the effort to deploy multiple facilities that use this biomass as a feedstock. Several resources can be accessed to aid in this process, such as the National Lakes Assessment (published every 5 years by the U.S. Environmental Protection Agency and other partners [26]), local bulletins (such as those published for Western Lake Erie HAB events [27]), or the U.S. Environmental Protection Agency's Cyanobacteria Assessment Network (CyAN) app [15]. The latter option has a user-friendly interface that allows for the determination of real-time microalgae concentrations in several bodies of water greater than 1 km^2 in the United States (Figure 4).



Bear River Bridge -- 1
41°12'22"N, 112°18'47"W
(Max adjacent cells: 242,103)
135,519 cells/mL
24,437 cells/mL
since 11-14-2020
Date: 11-21-2020

City of Hooper -- 1
41°9'14"N, 112°15'54"W
(Max adjacent cells: 510,505)
510,505 cells/mL
1,211,364 cells/mL
since 03-26-2022
Date: 05-14-2022

Davis County -- 1
41°0'57"N, 112°6'6"W
(Max adjacent cells: 285,759)
108,643 cells/mL
0 cells/mL
since N/A
Date: 04-02-2022

East Pass -- 1
41°25'10"N, 112°17'12"W
(Max adjacent cells: 1,674,943)
1,674,943 cells/mL
1,104,779 cells/mL
since 06-22-2019
Date: 07-11-2020

Farmington Bay Bird Refuge -- 1
40°56'2"N, 111°57'27"W
(Max adjacent cells: 285,759)
183,654 cells/mL
143,475 cells/mL
since 02-20-2021
Date: 03-06-2021

Figure 4. Overview of the U.S. Environmental Protection Agency's CyAN tool for the retrieval of information related to HAB events. Researchers can pinpoint locations on the map to consult up-to-date cell counts (in cells/mL) estimated through satellite measurements [15].

While extremely useful for an in-depth understanding of HABs, relying on in situ evaluation of algae concentrations to supply parameters for TEA work is risky due to the ever-shifting characteristics of these events over time, such as composition, species distribution, concentration, and extension. Satellite-based measurements on the other hand, such as those used in the CyAN app, allow for probing large areas simultaneously and monitoring the dynamics of HABs [28]. Such an approach employs the fluorescence of multiple pigments in microalgae, such as chlorophylls (*a* and *b*) and phycocyanin to estimate algal abundance in a given body of water. As a second step, translating cell counts into biomass concentrations (in mg/L or g/L) is contingent on having species-dependent correlations (such as their biovolume). Using individual cell weights [29] might lead to significantly underestimating the amount of biomass in real-life HAB events, as lab-scale microalgae cultivations are much more homogeneous than the microalgae suspensions found in open waters. In this way, this report relies on a ratio of 1 g of dry algae biomass per 10 million cells in a HAB event, estimated by Dr. Kevin Shurtleff [10]. Using this conversion parameter as an estimate, common microalgae concentrations in HABs may be estimated in the range of 25 mg/L up to several hundred mg/L in some cases. For simplification purposes, this report considers that the baseline HAB event occurs for 180 days per year and has an average biomass concentration of 50 mg/L (or 500,000 cells/mL). The biomass recovery facility operates for the duration of the HAB event with a capacity of processing 100 MGD of water.

Biomass Conversion – Combined Algal Processing

In general, processing HAB-derived biomass through CAP follows a similar configuration as that considered for WWT algae biomass described in Part 1. Three main changes have been carried out to better fit the specifics of this feedstock. The first is the removal of the wet storage of biomass for off-season processing, with the operational period for the conversion facility set to match that of the biomass recovery facility (which is in turn equal to the duration of the HAB event), as it was found here that the operation period of a conversion plant (either part of the year or year-round) has little effect on the final economic result derived from the assessment. Moreover, this choice also draws from the lack of experimental data for the storage of HAB biomass for long periods when mixed with the coagulants used in the collection step. Additionally, a biomass washing and filtration step was assumed upfront (before the dilute acid pretreatment section) to remove most (80%) of the aluminum chlorohydrate mixed with the algae biomass from the recovery facility. This is required so the downstream residual solid coproduct obtained in this biorefinery is not off-spec with more mineral content than allowed by potential buyers (<35% based on feedback from industry) [30], especially when microalgae concentrations in the HABs are low. This is important since biomass from HABs often has a rather elevated ash content (Table 2). Finally, the lipid extraction unit considered in the WWT-CAP biorefinery (shown in Part 1) was removed for this feedstock due to the very low lipid content typically present in this type of feedstock not justifying the added cost for lipid recovery.

Biomass Conversion – Anaerobic Digestion

As for the CAP conversion of HAB biomass, the AD-based biorefinery in this case does not utilize a system for wet seasonal storage of microalgae (all biomass is processed in the conversion facility as it is harvested from the body of water with the HAB event, and then the AD facility is shut down). As an additional note, chitosan (the coagulant used in the biomass recovery facility) is considered to be converted to biogas/CO_2 with the same assumptions as for the incoming algae biomass based on incoming carbon (presented in Table 3). Biogas is again upgraded on-site to remove CO_2 for production of RNG. Costs for compressing and storing the CO_2 removed from the biogas are also included in this case, and the CO_2 is sold as a coproduct.

Table 3. Assumed Conversion Parameters for the CAP and AD Conversion Facilities (Applies to Both Cases)

Parameter	Fixed Value	Reference
CAP & AD: Common Parameters		
Seasonal storage		
Storage degradation losses (wt %)	13%	[31,32]
CAP Pathway Parameters		
Labor requirements		
Plant engineer	1	Reduced from [31,33]
Maintenance technician	1	Reduced from [31,33]
Shift supervisor	1	Reduced from [31,33]
Shift operators	6	Reduced from [31,33]
Dilute acid pretreatment		
Acid loading (wt % vs. feed)	2%	[31,33]
Fermentable sugar release (%)	90%	[33]
Temperature (°C)	150	[31,33]
Pressure (atm)	4.6	[31,33]
Fermentation to ethanol		
Total batch time (days)	1.5	[33]
Organism	*S. cerevisiae*	[33]
Inoculum level (vol %)	10%	[33]
Temperature (°C)	37	[33]
Number of trains	2	[33]
Maximum vessel size	20,000 gallons	Adjusted from [33] based on required volume
Number of vessel stages	4	Adjusted from [33] based on required volume
Metabolic yield (g ethanol/g hexose sugars)	0.48	[33]
Glucose to biomass growth	2%	[33]
Lipid extraction		
Extraction configuration	3-stage CSTR [a] + centrifugation with 2 solvents	[31,34]
Solvent loading (hexane: EtOH: dry biomass, wt)	2.7: 1.1: 1 g/g/g	[31,34]
CSTR extraction residence time (min)	15	[31,34]
Overall lipid extraction yield	96%	[31,34]
AD Pathway Parameters		
Labor requirements		
Maintenance technician	1	Reduced from [31,33]
Shift operators	3	Reduced from [31,33]
Anaerobic digestion		
Carbon destruction to biogas	48.2%	[33,35]
% CH_4 in biogas	67%	[33,35]
Biogas upgrading		
Capital and operating costs	Based on cost factors from Saur and Jalalzadeh-Azar	[36]

[a] Continuous stirred-tank reactor.

Residual Biomass From Commercial Lipid Extraction

Biomass Sourcing

An additional source of low-cost algal biomass was also considered, as may be available from commercial lipid extraction employed in industry today. While it is well established that lipids from microalgae can be used as precursor for biofuels, the current algae industry as exists today operates at smaller scales than those envisioned for biofuel production and focuses on higher-value products such as nutraceuticals and cosmetics. Omega-3 fatty acids are one set of particularly high-value products that are commonly sold as nutritional supplements. For this study, residual biomass is assumed to come from a generic algae facility focused on cultivating algae and extracting the lipid content for such high-value purposes, but otherwise without a use for the remaining biomass.

Biomass Composition

The biomass composition for the lipid-extracted biomass was determined by assuming lipid depletion (75% lipid reduction) of high-protein biomass associated with harvested compositions from prior 2019 state-of-technology (SOT) cultivation trials [25], shown previously in Table 2. High-protein biomass was assumed due to experimental observations that omega-3 fatty acids accumulate better in high-protein (nutrient-replete) algae. Although it is commonly understood that subjecting microalgae to nutrient deprivation induces an increase in algal lipid content, these lipids tend to contain predominantly saturated and monounsaturated fatty acids. Elemental composition is estimated by the same method as described in Part 1.

Biomass Availability

One key economic variable for the conversion of lipid-extracted biomass from commercial industry is the scale at which the residual biomass is available. This will vary greatly depending on the state of the algae industry. For this exercise, we have assumed a biomass availability that could be reasonably achieved by a single facility representative of the present commercial algae industry. Specifically, we assume a cultivation area of 150 acres (equivalent to an industry facility currently operating in Columbus, New Mexico, previously operated by Sapphire Energy [37,38]). A second facility in Texas, currently sized at 50 acres, also has announced plans to scale up to 150–200 acres in the near term [39]. The 150-acre facility is assumed to achieve an average productivity of 25 $g/m^2/day$ (consistent with targets set by the U.S. Department of Energy and the Bioenergy Technologies Office [40]) and a 75% lipid extraction efficiency. These assumptions, paired with the high-protein biomass composition described above, result in a biomass availability of roughly 12.5 U.S. tons/day. Seasonal variability is assumed to be equivalent to the modeled variability for the wastewater treatment algae facility described in Part 1. This scale could be increased substantially if similar assumptions were applied to a 5,000-acre farm size (consistent with an envisioned commercial farm size for an integrated algal biorefinery producing fuels, as considered in prior NREL models [35]), or if the biomass was sourced from multiple commercial facilities. Accordingly, a sensitivity on the scale of biomass availability for lipid-extracted biomass is also considered.

Biomass Conversion – Residual Biomass From Commercial Lipid Extraction

Two scenarios are considered for the conversion of the lipid-extracted biomass, following the general process designs established for the conversion of biomass from the other resources considered in this study. The EXT-CAP scenario follows the same general process design as the HAB-CAP process; the biomass undergoes a dilute acid pretreatment followed by fermentation to ethanol. Residual solids from fermentation are dried and sold as a solid coproduct for thermoplastic production, forgoing any further extraction due again to the low remaining lipid content of the biomass. The EXT-AD scenario also follows the same process design as was described for the HAB-AD scenario, producing biogas that is upgraded to RNG for use in the natural gas grid (or as may be used for other purposes such as renewable hydrogen). As in the HAB scenario, CO_2 cannot be simply recycled to the algae cultivation operation; therefore, costs for CO_2 compression and storage are considered to enable sale of CO_2 as a coproduct. Contrary to the HAB scenario, the EXT cases are assumed to operate year-long and utilize a wet anaerobic storage step to maintain a consistent biomass throughput through the facility, applied to both CAP and AD conversion cases.

Table 4. Summary of Key Process Design Parameters for Modeled Conversion Facilities

Process Design Parameters	**HAB**	**EXT**
Feed rate basis (base case)	HAB event with 50 mg/L occurring for 180 days; recovery facility processing 100 MGD	150-acre commercial algae farm
Average feed rate (U.S. tons/day AFDW)	15.6	12.5
Seasonal biomass availability variation ratio (high:low)	n/a (all biomass processed during the occurrence of the HAB event)	2:1
CAP Conversion		
Pretreatment	Dilute acid	Dilute acid
Fuel products	Ethanol	Ethanol
Coproducts	• Protein-enriched solids (thermoplastic co-feed) • Nutrient-enriched crop water	• Protein-enriched solids (thermoplastic co-feed) • Nutrient-enriched crop water
CO_2 end use	Compression, cleanup, and sale	Compression, cleanup, and sale
AD Conversion		
Pretreatment	None	None
Fuel (energy) products	Renewable natural gas	Renewable natural gas
Coproducts	• Nutrient-enriched crop water • Digestate for land application	• Nutrient-enriched crop water • Digestate for land application
CO_2 end use	Compression, cleanup, and sale	Compression, cleanup, and sale

TEA Approach

The TEA methodology applied to the cases presented in this report follows the broad assumptions outlined in prior NREL TEA reports, such as Davis et al. [5], and detailed in Part 1 of this study. In short, the assessment is carried out through establishing discounted cash flows, thus combining capital expenditures, operational expenses, and selling prices of multiple coproducts (Table 5). Again, most scenarios assume fixed selling prices for all products (rather than solving for a minimum selling price for one targeted product such as fuel) while instead solving for an upstream attribute such as required biomass "transfer" cost or associated biomass production/recovery parameter, described later.

Table 5. Selling Prices of the Main Products in CAP and AD Biorefineries

Products	Value
Ethanol	$2.50/gallon of gasoline equivalent (GGE)
Lipids	$2.22/GGE
RNG (biomethane)	$4.12/million British thermal units (MMBtu)
Solid coproduct (CAP residual protein)	$817.5/ton dry weight
Crop water (CAP residual aqueous)	$0.15/lb solids
CO_2	$40.82/ton
Solid fertilizer (AD digestate)	$0.15/lb solids

An iterative process is used to determine the main metrics associated with each biomass supply chain, including minimum biomass selling price (MBSP) (i.e., the cost of biomass production/collection from the upstream producer/collector's perspective), maximum biomass purchase price (MBPP) (the "value" of the biomass required to achieve economic viability for processing from the downstream conversion facility's perspective), and water credits. Figure 5 shows this approach for the HAB biomass. A short description of the process as applied to the HAB and EXT systems is provided as follows.

HAB Biomass

1. The main parameters required by the biomass collection and water treatment TEA module are retrieved and employed, such as microalgae concentration in the body of water, HAB event duration, nameplate capacity of the recovery facility, and coagulant dosage, among others.
1. The biomass and coagulant flowrates from the collection module are used to define and size the operations in the biomass conversion module (CAP or AD biorefinery).
2. A dedicated TEA calculation is used to estimate the conversion facility's MBPP ($/ton AFDW) arising from using a given set of biomass characteristics, coagulant loading, and conversion parameters to achieve fixed fuel/product output selling prices.
3. The MBPP is fed back to the first module to guide the analysis of the biomass collection facility. In this step, the water credits ($/million gallons) are varied until biomass collection MBSP is equal to biomass conversion MBPP. In this way, the economic viability of the integrated process is established.

4. A distinct TEA calculation is used to determine the resultant water credits ($/million gallons) required to satisfy the rationale above.

EXT Biomass

The TEA for the conversion of lipid-extracted biomass is rather straightforward, comprising a single processing step, as this feedstock is provided from the industrial unit at a fixed price to the conversion unit (not shown in Figure 5). Accordingly, there is no MBSP for this case, and the analysis solves for MBPP as required to achieve conversion biorefinery economic viability based on selling all products at fixed market prices.

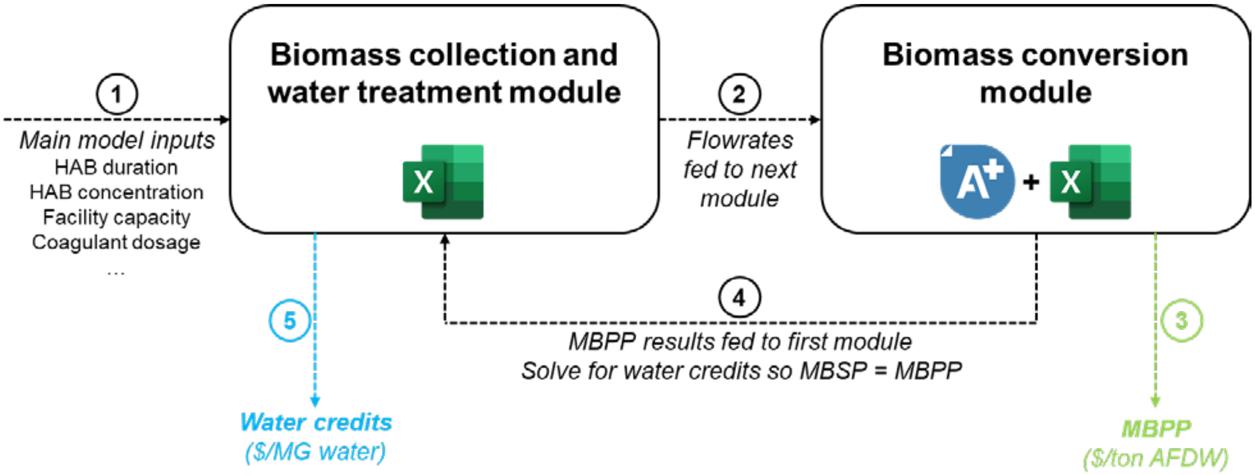


Figure 5. Representation of the iterative processes to determine collection facility's MBSP, conversion facility's MBPP, and water credits needed for MBSP to equal MBPP for the HAB case

Results and Discussion

The TEA approaches discussed previously were applied to the procurement and conversion of both biomass resources considered. Broadly speaking, the base case scenarios utilizing CAP conversion showed good near-term potential for economic viability, with exceptionally strong results demonstrated for cases that considered increased biomass availability and elevated credits associated with either environmental remediation (HAB) or solid waste management (EXT). The AD cases translate to comparatively more challenging economics (lower MBPPs, where higher MBPPs indicate more favorable economic viability) under the absence of policy incentive credits (considered further below). Due to the unique methods of biomass procurement considered, results of each scenario (Table 6) will be discussed separately, with discussion of each conversion pathway following. Results of all conversion pathways, which generally follow consistent approaches between cases in solving for maximum allowable biomass purchase price to enable achievement of fixed fuel/product selling prices at a 10% biorefinery internal rate of return (IRR), are shown in Figure 6 and Table 7. Following discussions of biomass procurement and conversion for each scenario, sensitivity analyses on critical parameters are presented.

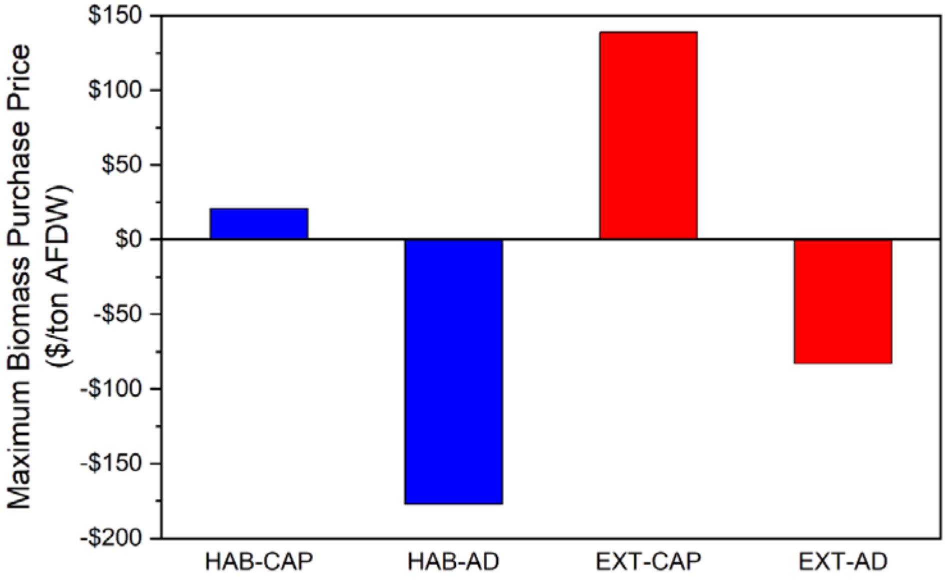


Figure 6. Maximum biomass purchase price allowable for each modeled conversion pathway in order to achieve market fuel prices ($2.50/GGE for hydrocarbon fuels/ethanol and $4.12/MMBtu for RNG). A higher MBPP reflects more favorable economics (a biorefinery is willing to accept a higher cost of biomass while still maintaining profitability through conversion).

Table 6. Summary of TEA Results for the Modeled Algae *Collection* Base Cases (HAB)

	HAB-CAP	HAB-AD	Units
Minimum biomass selling price	\$21	−\$177	\$/ton AFDW
Biomass yield	0.25	0.25	tons/million gallons water
Total capital investment [a]	\$79,518,000	\$79,518,000	\$
Variable operating costs [a]	\$2,788,000	\$13,132,000	\$/year
Fixed operating costs [a]	\$3,039,000	\$3,039,000	\$/year
Water treatment credits [a,b]	\$15,090,000	\$26,120,000	\$/year

[a] Includes costs for the HAB biomass collection facility only.

[b] Total revenue calculated using baseline water treatment credits of \$838/million gallons of water for the HAB-CAP scenario and \$1,452/million gallons of water for the HAB-AD scenario (further discussed in the Algal Bloom Biomass subsection).

Table 7. Summary of TEA Results for the Modeled Algae *Conversion* Base Cases.
Costs for collection not included here.

	HAB-CAP	HAB-AD	EXT-CAP	EXT-AD	Units
Maximum biomass purchase price	$21	−$177	$139	−$83	$/ton AFDW
Total fuel/energy yield [a]	13.1 (0.04)	93.0 (0.26)	18.1 (0.07)	73.2 (0.30)	GGE/ton AFDW (million GGE/year)
Liquid fuel yield	13.1 (0.04)	0 (0)	18.1 (0.07)	0 (0)	GGE/ton AFDW (million GGE/year)
Purified lipids [b]	0 (0)	0 (0)	0 (0)	0 (0)	GGE/ton AFDW (million GGE/year)
Ethanol	13.1 (0.04)	0 (0)	18.1 (0.07)	0 (0)	GGE/ton AFDW (million GGE/year)
RNG yield [c]	0 (0)	93.0 (0.26)	0 (0)	73.2 (0.30)	GGE/ton AFDW (million GGE/year) total feedstock
	0 (0)	10.8 (30,400)	0 (0)	8.5 (35,100)	MMBtu/ton AFDW (MMBtu/year) total feedstock
Biomass feed rate (seasonal average)	15.6	15.6	12.5	12.5	tons/day AFDW
Solid coproduct/digestate production	8.2	10.9	7.3	6.7	tons/day
Total capital investment [d]	$9,714,000	$7,233,000	$6,916,000	$5,398,000	$
Non-feedstock variable operating costs [d]	$294,000	$230,000	$250,000	$130,000	$/year
Fixed operating costs [d]	$613,000	$320,000	$984,000	$320,000	$/year
Coproduct credits [d]	$2,109,000	$746,000	$2,512,000	$750,000	$/year

[a] Includes both liquid fuels and renewable natural gas heating content.

[b] Purified lipids are discounted from a finished hydrocarbon fuel ($2.22/GGE) and are assumed to be sold/upgraded at a central processing facility for ultimately achieving $2.5/GGE final fuel selling price after central hydrotreating.

[c] The RNG yield is given in GGE to represent the energy content of the gas fuel (no liquid fuel production in AD scenarios).

[d] Includes costs for the conversion facility only.

Algal Bloom Biomass

Conversion: HAB-CAP

The conversion of biomass from HABs via a CAP-based biorefinery can be economically viable when the microalgae biomass is available at a price (MBPP) of up to \$21/ton AFDW to achieve a 10% IRR while selling all fuels/products at their asserted market values. From the perspective of the HAB collection facility, the required water credits to achieve a biomass collection cost (MBSP) equal to this MBPP value of \$21/ton would amount to \$838 per million gallons, which (as a frame of reference) stands at a fraction of an estimated \$2,600 per million gallons for conventional municipal WWT operation and maintenance costs [41], as the biomass recovery facility is ultimately a water treatment facility as well. In this case, the water treatment credits would be paid by local governments or municipalities as appropriate for performing an environmental remediation service to improve the local ecology (in some instances tied to the local economy), rather than a municipal WWT model where water treatment is paid for by individual customers. Figure 7 depicts the required water treatment credits in order to achieve economic feasibility (MBSP = MBPP) for both HAB conversion cases.

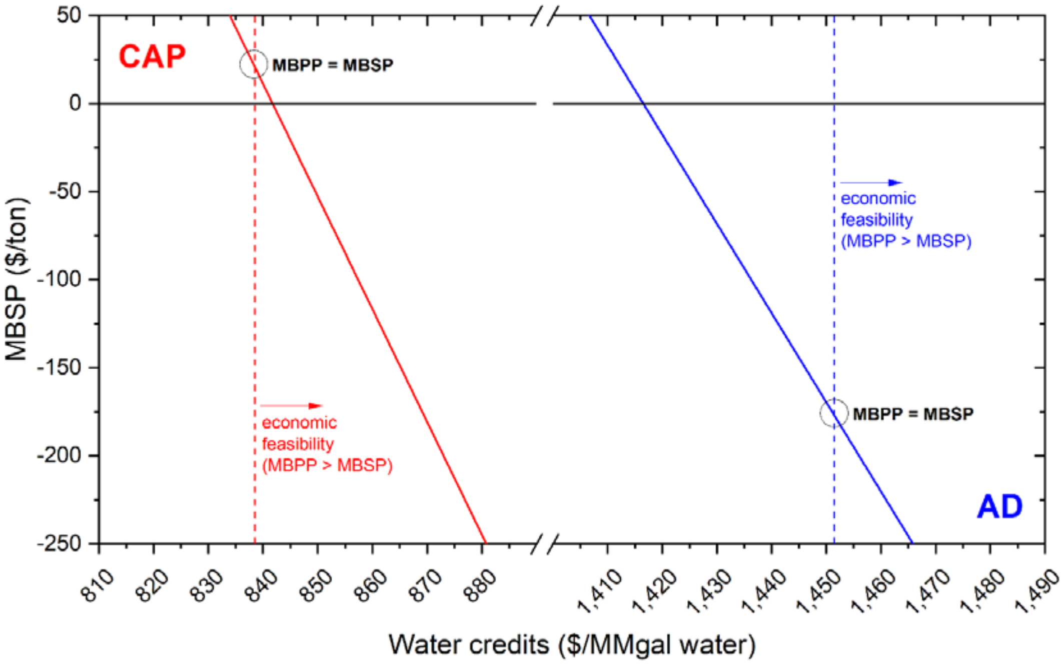


Figure 7. Variation of MBSP as a function of the water credits paid to the HAB biomass recovery facility for the CAP and AD conversion cases. Economic viability is achieved when the costs for HAB biomass collection (MBSP) equal the conversion facility's maximum allowable purchase price (MBPP).

In view of the dynamic characteristics present in HABs, a plot scan has been carried out for selected parameters to understand their influence over the economic performance of the conversion facility through the MBPP metric, namely the duration of the HAB event (90 to 270 days), its average microalgae concentration (25 to 100 mg/L), and the processing capacity of the collection facility (50 to 150 MGD). Figure 8 depicts three contour plots with the main results for the analysis, one dedicated to each of the assumed algae concentrations (25, 50, and 100 mg/L). In an overall analysis, an increase in either of these three parameters leads to higher (more favorable) MBPPs in the conversion plant, which will in turn allow for lower water credit requirements in the biomass recovery facility. At microalgae concentrations of 50 mg/L or higher, the collection of biomass from HABs occurring for more than 180 days would yield MBPPs that are positive if processing capacity is at least 100 MGD. The effect of having HABs with higher microalgae concentrations (e.g., 100 mg/L) is also clear, and the influence of HAB duration becomes the predominant variable in such cases.

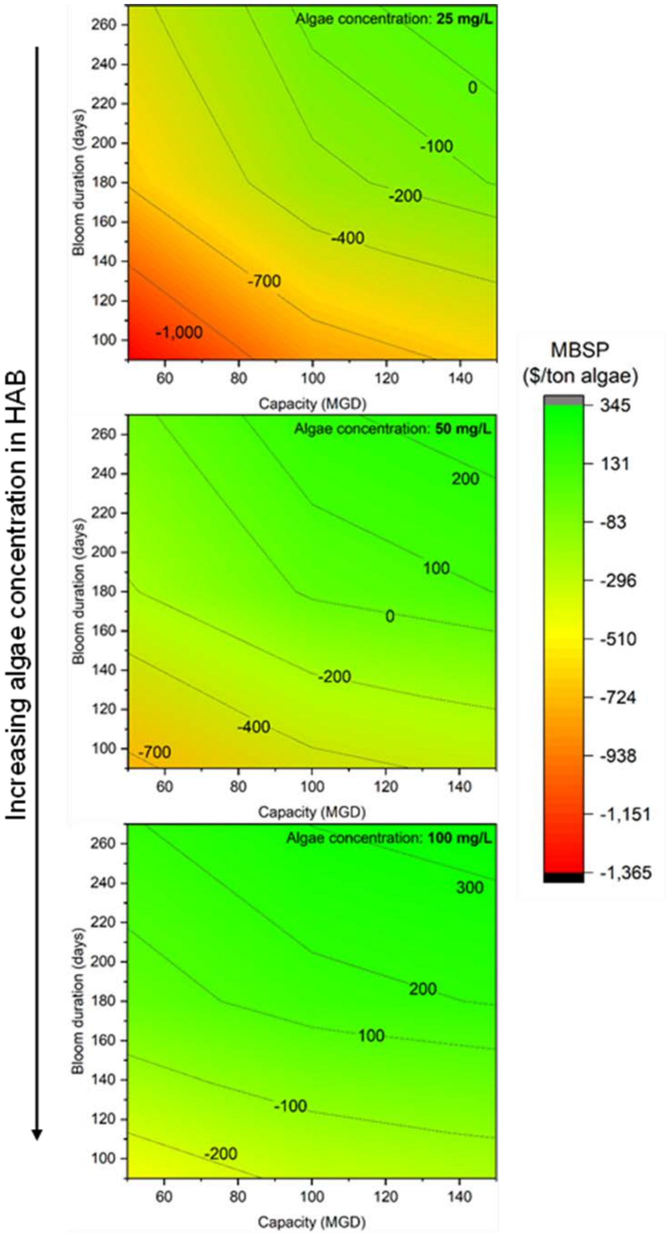


Figure 8. Contour plots for MBPP of the HAB-CAP case, varying HAB duration and capacity of the biomass recovery facility for three different microalgae concentrations: 25 mg/L, 50 mg/L, and 100 mg/L. A higher MBPP reflects more favorable economics (a biorefinery is willing to accept a higher cost of biomass while still maintaining profitability through conversion).

More severe bloom events could provide more biomass as a result of higher algae concentrations and/or longer bloom occurrences, which would also impact the economics of the recovery and conversion facilities. To better understand this, an analysis was carried out for higher potential microalgae concentrations in HABs, namely 0.5 and 1.0 g/L, over MBPP and associated water credits for a biomass recovery facility processing 25 MGD (Figure 9) for a varying HAB event duration. Positive MBPPs and reasonable water credits are achievable even in the case of a much lower processing capacity (25% of the size of the baseline previously defined) when HAB events occur for 180 days or more. If a HAB event were able to sustain microalgae concentrations 1.0 g/L for more than 220 days, the required water credits to support economic viability of the process would be less than $200 per million gallons, approaching $0 per million gallons for HABs with a duration of 270 days as an upper limit. Additionally, if higher microalgae concentrations are seen in recurring HAB events, the upfront biomass washing and filtration unit to remove aluminum chlorohydrate from the biomass prior to CAP conversion could be eliminated altogether; the higher proportion of biomass to coagulant could lead to a solid coproduct that lies within specifications in regard to ash/inorganic content (<35%). It is also noteworthy that if an ozonation unit is not required in a HAB biomass collection plant, the required water credits drop by a significant amount for any of the assessed cases.

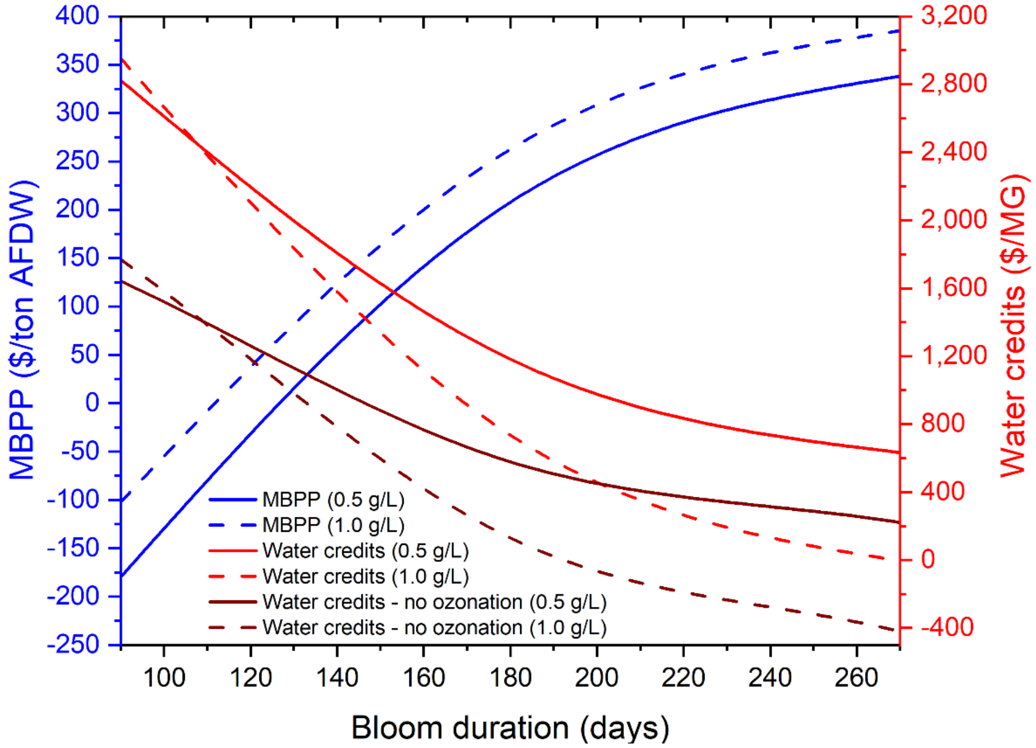


Figure 9. Variation of MBPP and water credits associated with the integrated HAB-CAP process when algae concentration in HABs achieve 0.5 and 1.0 g/L. The biomass recovery facility processes a fixed 25 MGD in this sensitivity case.

Conversion: HAB-AD

In the HAB-AD case, the RNG yield is increased due to the algal biomass being mixed with chitosan, an organic polysaccharide with high carbon content, as the flocculant utilized in HAB collection. In this case study for HAB-AD, the HAB remediation water treatment credits required to enable an economically viable operation (MBSP = MBPP) are estimated at $1,452 per million gallons. On the conversion side, the combination of capital and operating expenses, as well as coproduct revenues, translates to a considerably less favorable (lower) MBPP of *negative* $177/ton for the HAB-AD scenario compared to $21/ton for HAB-CAP (mirroring a similar trend favoring CAP conversion over AD for the EXT biomass sourcing case), as shown in Table 7. This may be compared to simply disposing of the biomass to a landfill for a cost of $35/ton (i.e., equivalent to a −$35/ton MBPP, though it should be noted that landfill tipping fees can vary dramatically depending on geographic location [42]), indicating that AD may not be an optimal choice for processing HAB-derived biomass, at least under base case conditions. However, additional policy credits could considerably improve AD economics, as presented further below. The operational expenses in the biomass recovery facility are significantly higher for HAB-AD than for HAB-CAP (mainly because of the much higher price of chitosan in comparison to aluminum chlorohydrate—$18/kg vs. $0.90/kg, respectively), thus driving the required credit for water treatment up to offset these operating expenses in achieving a lower HAB biomass collection cost as necessary for satisfying conversion economics. Figure 7 also shows the threshold for economic viability of the HAB-AD base case, highlighting the considerably higher water treatment credits required relative to the HAB-CAP pathway in view of the high costs involved with the use of chitosan as the coagulant of choice for HAB biomass recovery.

A similar plot scan as for the HAB-CAP case was carried out for the HAB-AD system. Figure 10 presents the contour plots for MBPP as a function of HAB duration, microalgae concentration in HABs, and capacity of the biomass recovery facility. Results follow the same general trends as those for the HAB-CAP case, though now reaching positive MBPPs only for 100-mg/L algae concentrations and for HAB events occurring for 220 days or longer at a capacity of 100 MGD.

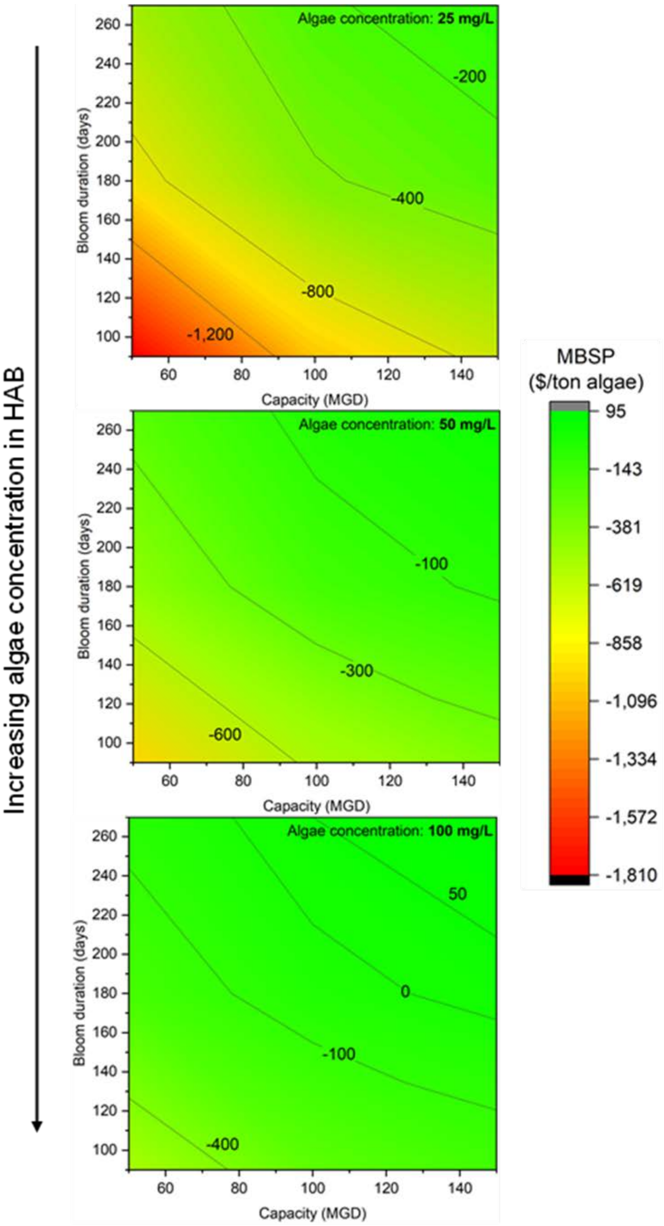


Figure 10. Contour plots for MBPP of the HAB-AD case, varying HAB duration and capacity of the biomass recovery facility for three different microalgae concentrations: 25 mg/L, 50 mg/L, and 100 mg/L. A higher MBPP reflects more favorable economics (a biorefinery is willing to accept a higher cost of biomass while still maintaining profitability through conversion).

As for the HAB-CAP example, a high biomass concentration sensitivity scan was carried out for the HAB-AD case assuming a lower processing capacity of 25 MGD in the biomass collection facility. Figure 11 presents the results for MBPP and water credits in the HAB-AD system when microalgae is present at 0.5 g/L and 1.0 g/L in HABs. The behavior of the curves follows the same trend as for the HAB-CAP case, albeit across lower (less favorable) MBPP values. Again, the use of chitosan as the coagulant of choice demands water credits at higher values in comparison to the CAP biorefinery setup. Finally, the removal of the ozonation unit from a HAB biomass collection plant would again enable a substantial reduction in the required water credits for the integrated system to attain economic viability.

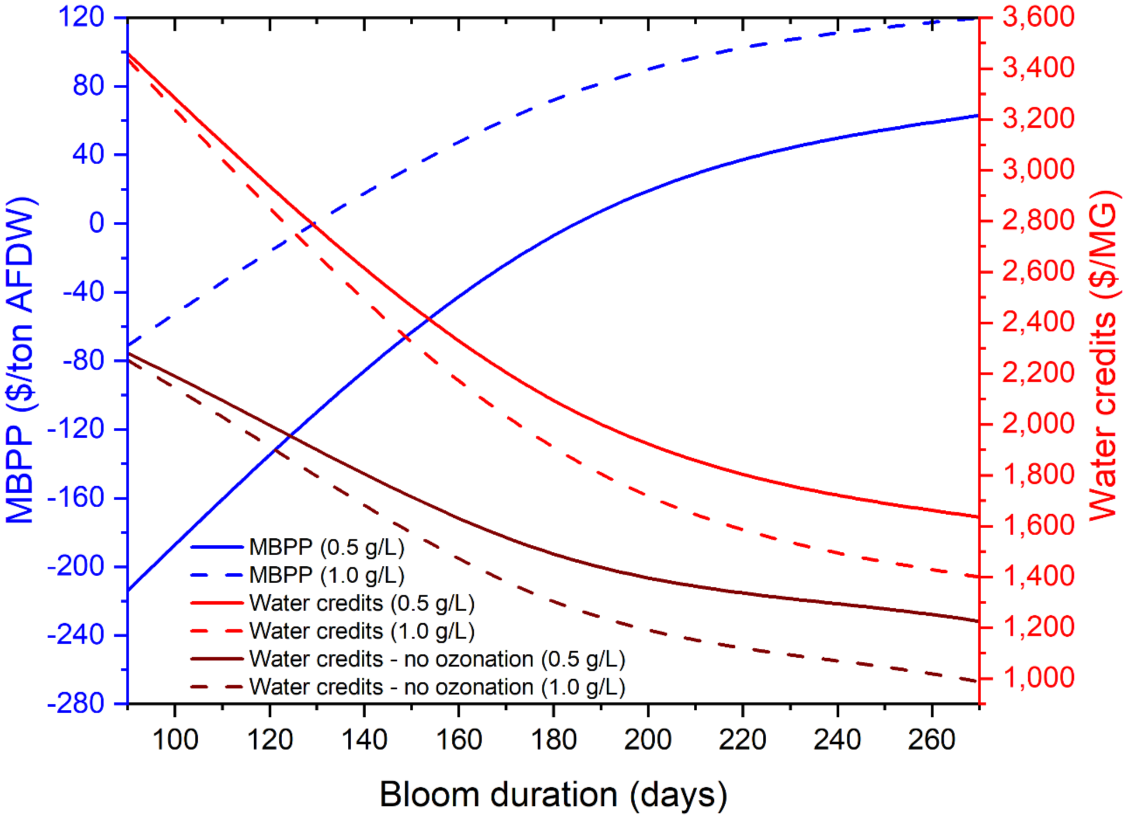


Figure 11. Variation of MBPP and water credits associated with the integrated HAB-AD process when algae concentrations in HABs achieve 0.5 and 1.0 g/L. The biomass recovery facility processes a fixed 25 MGD in this sensitivity case.

Residual Biomass From Commercial Lipid Extraction

The TEA for the EXT-CAP and EXT-AD conversion processes takes a consistent approach in setting product prices to their market values and solving for the maximum allowable biomass purchase price (MBPP) to achieve economic viability at a 10% IRR. In the case of residual biomass from commercial lipid extraction, this number represents the maximum purchase price at which it would be economically practical to convert the residual biomass. This can be compared to the current end use of the residual biomass (assumed here to be disposal in a landfill at an additional tipping fee) to determine if the EXT-CAP and EXT-AD processes have the potential to provide further economic benefit.

The EXT-CAP scenario resulted in an MBPP of $139/ton, demonstrating a promising case for economic viability when compared to an assumed landfill disposal *cost* of $35/ton as presented above. Similar to HAB-AD, the EXT-AD scenario showed challenges in surpassing assumed disposal cost at the base scale, with an MBPP of −$83/ton. When considering higher disposal costs or facility scales (noting that the modeled 150-acre facility is considerably smaller than the 5,000-acre algae farm facilities envisioned in previous *n*th-plant analyses), this approach could still achieve improvement over landfilling. Again, additional revenue from policy credits could also help improve the economic viability of both cases as presented further below.

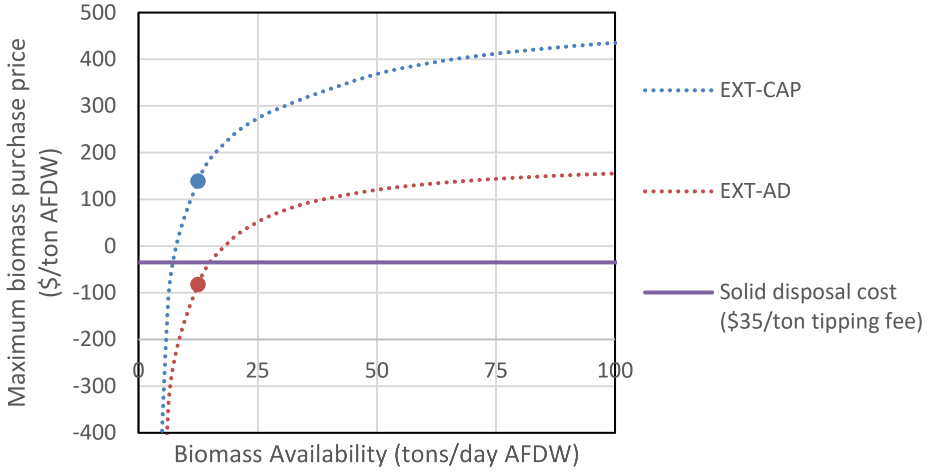


Figure 12. MBPP of the EXT-CAP and EXT-AD scenarios as a function of facility size. Biomass disposal cost for a typical landfill is also shown for comparison as a presumed base case disposition for extracted biomass at present.

Compared to the HAB biomass cases, the EXT cases yield moderately more favorable economics—i.e., higher MBPPs for both CAP and AD conversion approaches, generally reflecting lower capital and operating costs for EXT than HAB biomass conversion. Additionally, the EXT case achieves higher total fuel yields per ton of biomass than the HAB case for CAP conversion, while for AD conversion, RNG yields per ton are lower, but resultant coproduct credits are higher for EXT than HAB biomass. More generally, both biomass sources yield positive MBPPs for CAP conversion and thus are likely to be economically profitable relative to simply disposing the biomass to landfills at the assumed −$35/ton tipping fee basis considered here, while both biomass sources are unfavorable through AD conversion versus landfill disposal, but less significantly so for EXT biomass under base case assumptions. Interestingly, the economics of the EXT-CAP conversion scenario were predicted to be slightly more favorable than the WWT-CAP conversion scenario (presented in Part 1) despite a slightly smaller conversion facility. This is a result of a difference in process design between the two facilities: due to the low lipid content of the residual EXT biomass, the biomass is not subjected to lipid extraction. Despite a decrease in fuel yields, this change results in lower capital and operating costs in addition to increased revenues from the (more valuable) solid coproduct, thus resulting in a higher MBPP. Conversely, the EXT-AD case shows a less favorable MBPP compared to the WWT-AD scenario. This is driven by smaller facility scale and increased costs associated with CO_2 compression and storage, which are not required for the CO_2 recycle design of the WWT-AD scenario discussed in Part 1.

As was observed for the HAB case, scale has a significant effect on process economics (Figure 12). For the CAP pathway, scales above 8 dry tons/day indicate better economics compared to the costs of landfilling the residual biomass, whereas the AD pathway required scales above 16 dry tons/day to achieve the same break-even point with landfill disposal (equivalent to a 100-acre algal biomass production facility [CAP pathway] or a 190-acre facility [AD pathway] operating with the same assumptions discussed previously). These scales should be readily achievable by algae cultivation farms of the future dedicated to commercial lipid extraction operations, with envisioned facilities much larger than the current 150-acre scales considered here for near-term extraction processing activities.

Sensitivity Analysis

Compositional Sensitivity Analysis

Part 1 of this study contains a sensitivity analysis on the biomass composition (i.e., relative levels of carbohydrates, lipids, and proteins) and how it affects the economics of the CAP and AD conversion processes. This analysis was performed specifically for the conversion of biomass produced from wastewater treatment, but the broad conclusions can qualitatively be applied to the HAB and EXT scenarios as well due to the similarity in the conversion processes. On a high level, it was found that the CAP process had a wider range of variability when composition was varied; high-protein compositions demonstrated promising economics due to elevated solid coproduct yields (a key revenue driver), while high-carbohydrate and high-lipid compositions showed less favorable economics due to higher fuel production (a less valuable product relative to the solid coproduct). Conversely, the AD conversion process showed that economics did not vary significantly over a range of compositions due to the ability of AD to utilize a broad range of components. These results highlight the merits of the AD approach when the biomass composition is unknown or variable over time.

Single-Point Sensitivity Analysis: CAP Conversion

A single-point sensitivity analysis was performed on the CAP and AD conversion processes for both sources of biomass considered. For each parameter considered, an MBPP is calculated at a high and a low value with all other variables held constant. Each MBPP is then compared to the base case MBPP for the corresponding scenario to determine the change in MBPP, which is used as a measurement of economic sensitivity. The parameters considered in the sensitivity analyses, along with the upper and lower bounds, are shown in Table 8; results are shown in Figure 13 and Figure 14 for the CAP and AD processes, respectively.

Table 8. Parameters Varied in the Single-Point Sensitivity Analysis for Biomass Conversion

Assumption	Unfavorable	Baseline	Favorable
CAP & AD			
Fuel selling price [a]	−25%	Varies	+25%
Fertilizer/crop water selling price	−25%	\$0.15/lb dry weight	+25%
Total capital investment	+25%	-	−25%
Labor costs	+50%	-	−50%
Solid coproduct selling price	−25%	\$818/ton dry weight	+25%
RIN Credits	-	None	\$0.78/gal ethanol equivalent (energy basis)
CAP Only			
Dilute acid pretreatment carbohydrate solubilization	95%	80%	65%
Dilute acid pretreatment protein solubilization	70%	50%	30%
AD Only			
Biogas cleanup cost	+50%	-	−50%
Biogas upgrading facility	-	Local upgrading	Centralized upgrading

[a] Applies to all fuel products for the process (may include ethanol or RNG).

Revenue From Fuels, Coproducts, and Policy Credits

The most impactful CAP conversion parameter for both feedstocks considered was solid coproduct selling price, referring to the value of the solids as a co-feed for thermoplastic production. It is understood that the suitability of the solids for co-feeding relies on the compositional profile of the solids, requiring sufficiently high protein content while limiting the composition of other fractions such as carbohydrates, lipids, and ash [30]. Solids with ideal compositions may achieve higher values of up to \$1,088/ton, while lower-quality solids may sell for as low as \$725/ton [30].

The MBPP for both feedstocks showed a high sensitivity to variations in solid coproduct selling price, with fluctuations of ±\$120–\$141/ton observed for coproduct selling prices ±25% of the baseline value (\$818/ton). Effects for variations in the crop water and fuel selling prices had a considerably smaller effect on economics than the price of the solid coproduct. Crop water price, varied by ±25%, resulted in a change in MBPP of ±\$28–\$43/ton for the cases; fuel price, also varied by ±25%, resulted in a change in MBPP of ±\$9–\$11/ton. This smaller impact compared to the solid coproduct is a result of the crop water and fuel selling at relatively low values (\$300/ton and \$500–\$600/ton, respectively) compared to the solid coproduct (\$818/lb) and highlights an important reliance of process economics on revenue from a non-fuel coproduct stream, particularly for coproducts of a higher value than fuels. This imparts some risk to the economic stability of such a process but is a theme also observed in algal biorefineries with more conventionally cultivated biomass as an unavoidable requirement to offset the cost of algal biomass in order to achieve economic viability for simultaneous production of low-cost fuels [31,43].

Alternatively, policy incentives crediting carbon intensity reductions as may be possible through algae conversion technologies may also (or additionally) provide such cost offsets. An alternative case including Renewable Identification Number (RIN) credits was thus also considered. As outlined in the Renewable Fuel Standard, RIN credits are generated from renewable fuel production and can be sold to petroleum fuel producers to meet their annual obligations. The generation of RINs depends on the process meeting certain greenhouse gas reduction targets and feedstock requirements, and the value of a RIN credit depends on which renewable fuel category it falls into; here, we have assumed a RIN value of $0.78/gal (ethanol basis according to energy content). This value was determined from a 5-year average of historical D4 RIN prices for 2017–2021 [44]; however, it is worth noting that these credits can also trade significantly higher, and that the average D4 RIN value in 2021 was $1.32/gal.

Generation of these RINs resulted in an MBPP increase of $15–$22/ton between HAB versus EXT biomass sources. Though not insignificant, these impacts are fairly low compared to the impacts observed in the WWT-CAP case presented in Part 1 due to overall lower fuel yields associated with the low-lipid HAB and EXT biomass. Further benefits may also be observed in localities that have implemented additional renewable fuel policies such as California's Low Carbon Fuel Standard (LCFS).

Labor Costs

Labor costs, referring to the annual operating expenditure for conversion plant personnel, had a significant effect on process economics. When labor costs were varied by ±50%, a variation in MBPP ranging from ±$77–$106/ton was observed between the two biomass sources. Due to the relatively small biomass feed rate of either process compared to a conventional biorefinery, the effect of labor costs on process economics was especially pronounced, reflecting significant economy-of-scale penalties compared to larger commercial biorefineries typically investigated in prior n^{th}-plant algae farm TEA studies.

Total Capital Investment

The total capital investment (TCI) for each conversion scenario was varied by ±50%. This resulted in varied levels of impact for each feedstock. For the HAB case, the sensitivity to TCI was large (±$113/ton) due to the seasonal nature of the HAB operation, which results in a higher capital cost per ton of algae processed from the facility being idled for half the year, as assumed for this study. For the EXT case, a lower impact of ±$47/ton was observed.

Pretreatment Efficiency

The efficiency of the dilute acid pretreatment strategy on carbohydrate and protein solubilization was considered due to the significant effect these variables can have on fermentation and solid product yields. Protein solubilization had a measurable effect on MBPP, with variability of ±20% protein solubility associated with changes of ±$30–$40/ton for the MBPP. At higher protein solubilization, more protein is removed from the residual solids, resulting in a lower yield of the highest-value solid coproduct.

Variability in carbohydrate solubilization had the effect of impacting ethanol yields in fermentation, which makes direct use of soluble sugars for conversion. However, this effect was less pronounced than that observed for proteins, with variability of ±15% carbohydrate solubility associated with changes of ±$14–$17/ton for the MBPP. This is due to a higher value associated with the solid coproduct compared to the fuel products.

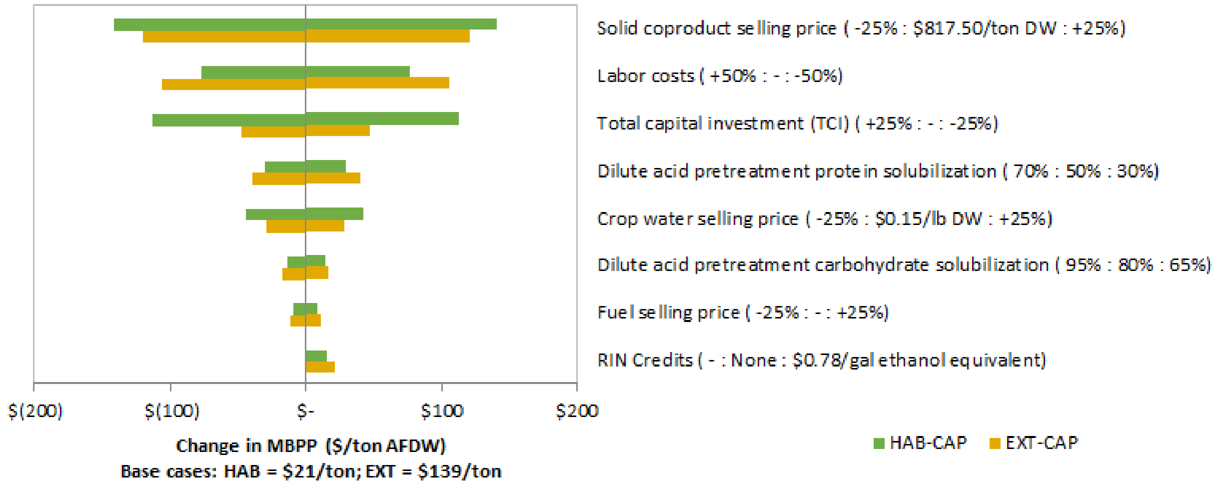


Figure 13. Single-point sensitivity analysis for key parameters of the CAP conversion process across either biomass source (HAB and EXT)

Single-Point Sensitivity Analysis: AD Conversion

Revenue From Fuels, Coproducts, and Policy Credits

One notable difference between the CAP and AD cases is that the AD case has a much higher sensitivity to the inclusion of RIN credits. Including these credits had the substantial effect of increasing the MBPP by $88–$111/ton, compared to a $15–$22/ton increase in the CAP case. Multiple factors drive this difference; the CAP process has significantly higher capital and operating costs than the AD case, but this is compensated by the revenue from the solid coproduct. In contrast, the AD case has lower capital and operating costs but significantly less revenue generation. Fuel yields for the AD scenarios are also 4–7 times higher than their corresponding CAP scenarios. Thus, the inclusion of RIN credits results in a 36%–38% increase in revenue generation (compared to a 2%–3% increase for the CAP case), ultimately resulting in much stronger economic impacts.

The implications of this impact are important to highlight; assuming that the AD case qualifies for RIN generation, the economics become substantially more promising. Of course, the fuels produced in each case are not equivalent because the AD case produces RNG, while the CAP case produces liquid fuels. This has implications on the eligibility for RINs; however, if the RNG is used as a transportation fuel and meets the required greenhouse gas reduction requirements, it can qualify for RINs. In fact, it is possible that the RINs produced in the AD case fall into the D3 category and therefore actually command more value (5-year average of $2.05/gal, with average 2021 prices of $2.65 [44]). Although this category is generally reserved for cellulosic fuels, RNG produced from landfills and anaerobic digestors also qualifies for this higher-value RIN, suggesting that the advantages for the AD case could be even greater in the near term when considering policy credits [45,46]. When D3 RIN generation is considered at a value of

$2.05/gal, an MBPP of $115–$147/ton (an increase of $230–$292/ton vs. the base case) is observed, showing the potential for considerably improved profitability relative to base case values presented previously.

This high economic impact of policy credits is also substantiated by the current market for RNG. As discussed previously, recent market prices for RNG range from $15–$100/MMBtu [47–49], driven by policy incentives for RNG production and utilization. Considering a conservative RNG selling price of $10/MMBtu results in an MBPP of −$113 to −$32/ton, an increase of $51–$64/ton compared to the base case for either biomass source. Further, an RNG selling price of $30/MMBtu results in an MBPP of $104–$139/ton. This green premium, driven by policy credit incentives, can dramatically improve near-term economic viability for deployment of this approach, in contrast to the unfavorable economics for AD conversion reflected in the base case scenarios excluding any policy credits.

For both cases, fertilizer and crop water selling price also had pronounced effects on MBPP, with variations of ±25% resulting in a change of ±$44–$62/ton for the MBPP, evidence that the AD conversion pathway is also reliant on coproduct revenue. Conversely, a less significant effect was seen when varying the fuel selling price by the same amount. When fuel selling price was varied by ±25%, a change in MBPP of ±$9–$11/ton was observed. This lesser effect is again due to relatively lower fuel revenue compared to the revenue from coproducts, driven by a relatively low value of the fuel product (in this case, RNG) and higher overall yields of coproducts.

Labor Costs

As in the CAP case, variations in labor costs can significantly affect process economics, with variations of ±50% in labor costs resulting in a change in MBPP of ±$30–$43/ton. This effect is seen despite the further reduced personnel numbers assumed for the AD scenario, highlighting the importance of optimizing labor needs for small-scale biorefinery operations such as this one.

Biogas Cleanup Costs

Biogas cleanup accounts for more than two-thirds of the total installed equipment cost in the AD cases. Additionally, biogas cleanup costs can vary significantly depending on the upgrading strategy used [50]. To evaluate the economic sensitivity of the process to this consideration, biogas cleanup costs (including both capital and operating costs, which are linked to capital costs as described by Saur and Jalalzadeh-Azar [36]) were varied by ±50%. This resulted in associated changes of ±$62–$102/ton for the MBPP, among the highest of the parameters considered and exceeded only by the inclusion of RIN credits. This demonstrated economic sensitivity to upgrading costs suggests that the upgrading strategy is a major driver for the overall conversion process and that it should be chosen prudently based on the scale and specific requirements of the process. Given the variety of different upgrading technologies available, more detailed modeling of the biogas upgrading process may be warranted in future analyses.

To further evaluate sensitivity to the assumptions behind the biogas upgrading costs, a scenario including a centralized upgrading facility was considered. In the base case, the biogas produced is assumed to be upgraded directly on-site to RNG. Alternatively, biogas may be transported to a centralized upgrading facility via pipeline for RNG production. In this scenario, transportation and upgrading costs are divided among a group of local biogas producers. Pipeline costs were calculated to be $0.0605/Nm^3 and follow the methodology laid out in Hengeveld et al. [51]. This cost is calculated by assuming 16 biogas producers each feeding an average 300 Nm^3/h of biogas to a centralized upgrading facility, with the side of the square source area equal to 30 km (18.4 miles). Upgrading costs for the centralized facility are calculated using cost factors supplied by Saur and Jalalzadeh-Azar [36], with the costs shared by all biogas producers. Costs for compressing and storing the CO_2 removed from the biogas are also considered, which is sold as a coproduct.

The consideration of a centralized facility resulted in significantly improved economics, with the MBPP increasing by \$43–\$112/ton. The centralized facility was associated with significant capital cost savings; the installed cost of the biogas cleanup infrastructure was reduced by nearly 50% compared to the local upgrading case. The highest impacts were observed for the HAB case, which had the highest capital intensity of the cases due to the seasonal nature of the biomass harvesting and accordingly lower utilization efficiency of installed capital costs. The significant impacts observed demonstrate the value of centralized biogas upgrading in either HAB or EXT cases processing biomass through AD conversion.

Total Capital Investment

The TCI for each conversion scenario was varied by ±50%. This resulted in varied levels of impact for each feedstock; for the EXT case, an impact of ±\$36/ton was observed. For the HAB case, however, this effect was slightly higher (±\$83/ton), again due to the seasonal nature of the harvesting operation, resulting in a higher capital intensity per ton of biomass processed.

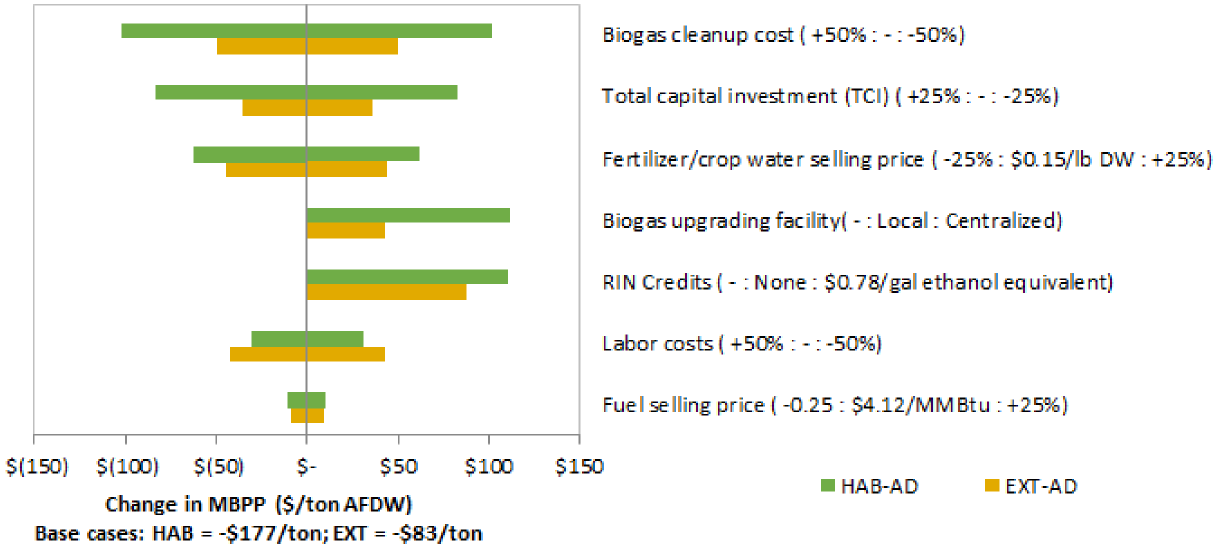


Figure 14. Single-point sensitivity analysis for key parameters of the AD conversion process across either biomass source (HAB and EXT)

Single-Point Sensitivity Analysis: HAB Biomass Recovery and Conversion

While the previous section focused on a single-point sensitivity analysis of the conversion process, reflecting parameters applicable to both HAB and EXT biomass sources, this segment evaluates further sensitivities for the HAB case alone to understand how HAB biomass collection parameters upstream may impact overall system economics through the conversion unit (either with CAP or AD biorefineries) given the more integrated nature for how the TEA analysis was conducted for the HAB case. Table 9 presents the full list and range of parameters involved in this analysis dedicated to HAB biomass, evaluating resultant responses required to maintain economic profitability via water treatment credits and associated HAB biomass transfer price (MBSP = MBPP) cascading to the conversion facility.

Table 9. Parameters Varied in the Single-Point Sensitivity Analysis for the Biomass Recovery Facility (HAB Case)

Assumption	Unfavorable	Baseline	Favorable
Biomass Recovery Facility			
Bloom duration (days)	90	180	270
Microalgae concentration in bloom (mg/L)	25	50	100
Facility nameplate capacity (MGD)	50	100	150
Total capital investment (TCI)	+25%	-	−25%
Labor costs	+50%	-	−50%
CAP Only			
Coagulant dosage – aluminum chlorohydrate (mg/L)	40	30	20
Coagulant price – aluminum chlorohydrate ($/kg)	1.30	0.90	0.50
AD Only			
Coagulant dosage – chitosan (mg/L)	20	10	5
Coagulant price – chitosan ($/kg)	26	18	10

CAP Conversion

Figure 15 highlights the large influence of parameters related particularly to the biomass collection module over the economic performance of the integrated system through CAP conversion. Bloom duration, the need for an ozonation unit, and both the capacity and TCI of the biomass recovery facility appear as the top variables determining the economic viability of the overall process, while all other parameters are constrained to a smaller impact. These results highlight that the biomass recovery facility (and therefore HAB conditions) strongly dictates the economic prospects for collecting HAB-derived biomass for further processing into fuels and coproducts. In contrast, parameters that only affect performance or economics of the conversion process alone (bottom portion of Figure 15, repeated from the same sensitivity parameters presented previously) may still translate to non-trivial differences in MBPP, but in turn may be satisfied by much smaller variances in required HAB collection water credits when nothing is otherwise changing in the upstream HAB biomass collection system.

It is noteworthy that varying specific parameters such as the coagulant price, need for ozonation, and both the TCI and labor costs of the biomass collection facility does not incur any changes to the MBPP determined in the conversion unit, as the flowrates of microalgae and coagulant remain unchanged in these cases (keeping in mind that MBPP is set from the conversion side; see Figure 5 for a detailed explanation of the iterative process). Rather, such parameters only affect the economic performance of the biomass recovery facility, thus impacting the water credits required to achieve the *same* MBPP to enable economic viability of the overall integrated system.

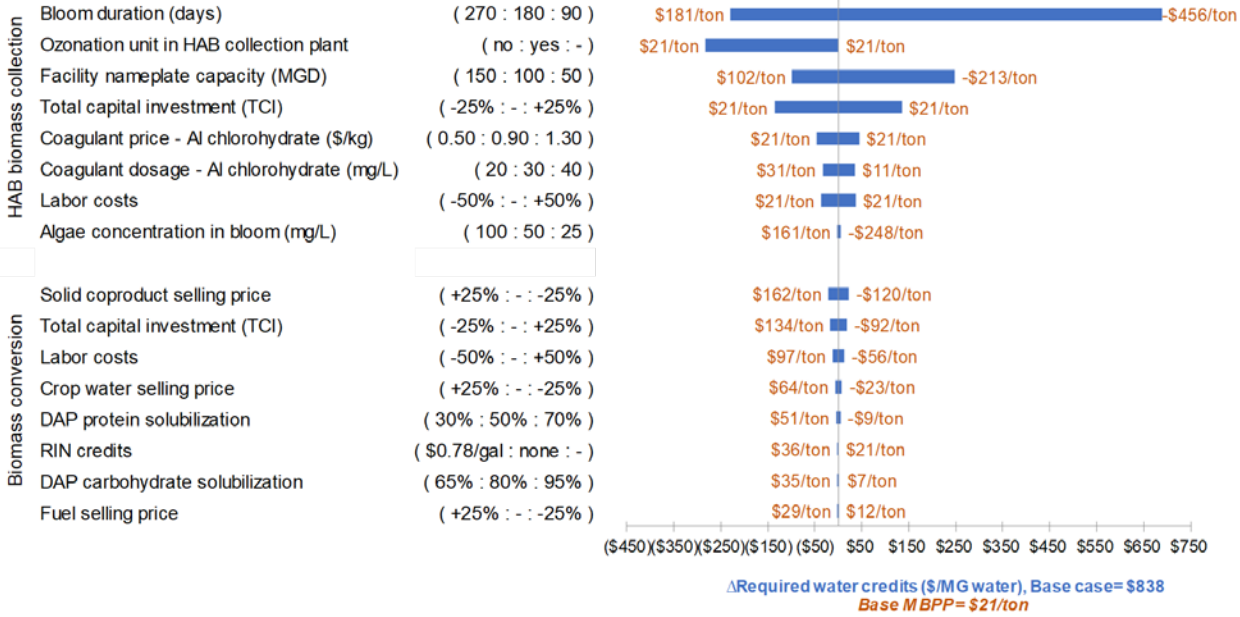


Figure 15. Single-point sensitivity analysis over MBPP and required water treatment credits for key parameters of the HAB biomass collection facility (top portion) versus downstream CAP conversion (bottom portion), considering economic impacts on the overall integrated system. Variations in required water credits are shown in blue bars, while the corresponding MBPPs are shown in orange text.

AD Conversion

Figure 16 presents the same results for the integrated system sensitivity analysis dedicated to the HAB-AD pathway. In this case, the same parameters as those for the HAB-CAP arrangement are again shown to be key drivers determining the economic viability of the integrated process, while also now including both dosage and price of the coagulant (chitosan in this case) as a more significant influence on overall economics. MBPP numbers for chitosan dosage appear to be counterintuitive, but can be explained by the conversion of chitosan into biogas: despite its high price, a reduction in its usage in the biomass recovery facility leads to a lower biogas yield in the biorefinery through AD. While this leads to better conversion economics (lower MBPP), it also leads to higher HAB biomass collection costs and thus required water treatment credits to achieve the associated MBPP at higher chitosan loading. These results also point to the need for optimizing chitosan dosage for the recovery of HAB biomass in the event it is used as the coagulant in similar recovery plants, as this compound often fetches high market prices and would then account for a large portion of the operational expenses of recovery facilities. A search for alternative, lower-cost coagulants is also warranted based on the results presented in this study.

Additionally, an analysis was carried out to determine the impact of not including the degradation of chitosan in AD reactors: if chitosan were to be processed through AD conversion without being digested, biogas output would be smaller than the baseline case, but the coagulant instead builds up in the residual solids that are sold as a fertilizer. The conversion plant would benefit from this setup, as the solid coproduct has a comparatively higher price than biogas. However, the advantages of the presence of chitosan in this fertilizer remain to be verified in order to justify this alternative approach. Finally, the assessment identified a reduction of roughly $280 per million gallons of water treatment credit required if the HAB biomass collection plants can operate without the ozonation unit.

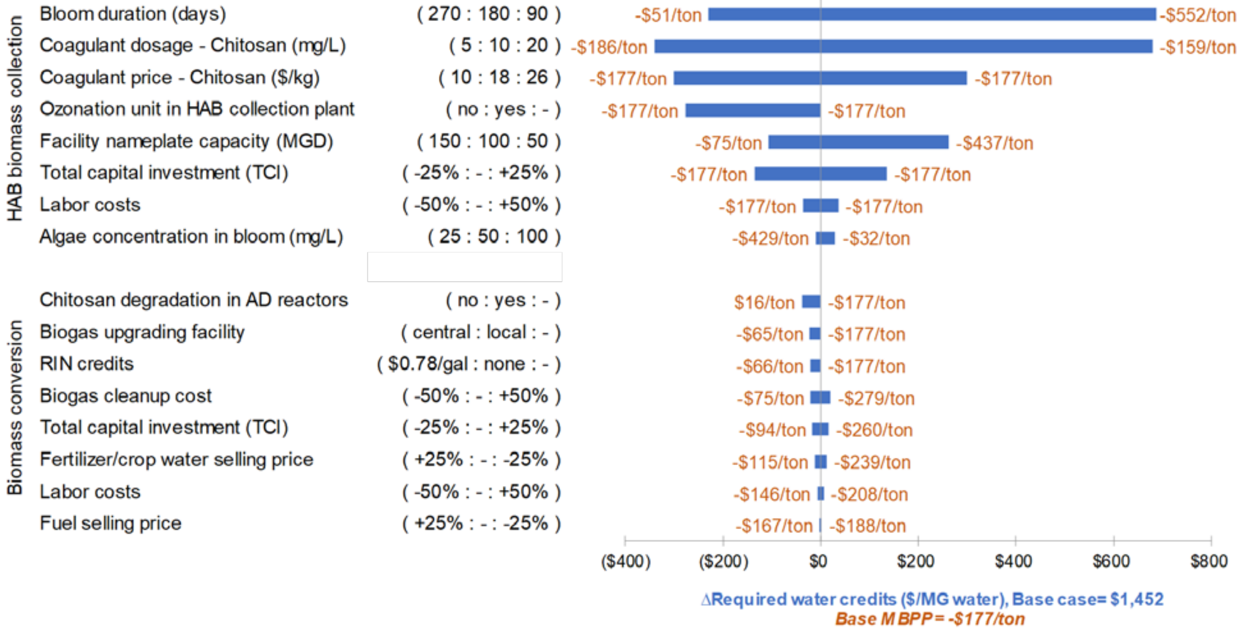


Figure 16. Single-point sensitivity analysis over MBPP and required water treatment credits for key parameters of the HAB biomass collection facility (top portion) versus downstream AD conversion process (bottom portion), considering economic impacts on the overall integrated system. Variations in required water credits are shown in blue bars, while the corresponding MBPPs are shown in orange text.

Discussion of Alternative HAB Treatment Options

While collecting algae from HAB events is the focus for the HAB scenario in this study, treatment is an alternative approach to addressing HAB events. Treatment usually consists of applying biocide or pesticide to disrupt algal blooms. The primary advantage of the treatment strategy is low capital cost. Virtually no capital equipment is required for treatment. Additionally, operating costs may be comparable or lower than collection and conversion strategies. Treatment methods are also mobile and can be applied as needed. However, treatment methods also have several disadvantages. The treatment chemical may kill non-targeted species, travel to other parts of the lake, or build up over time in one location. Decomposition of the algae consumes oxygen, which creates anoxic conditions. Additionally, decomposition releases nutrients back into the water, providing nutrients for future algal blooms [10].

Overall, the cost and efficacy of collection and conversion must be compared to that of treatment. It is understandable for states and municipalities to view the treatment option favorably, as it requires very low upfront costs and can be employed as needed, whereas collection and conversion requires allocating significant resources upfront and potentially maintaining capital equipment year-round. However, given the drawbacks for treatment noted above, this may be viewed as more of a temporary “band-aid” approach to HAB mitigation and misses the opportunity to tap a “free” source of biomass for added benefits of producing energy and other valuable products, potentially with near-term economic viability. Alternatively, of course, the most direct approach to mitigate HAB events is to prevent their underlying cause in the first place from agricultural runoff, presenting a further opportunity for algae in capturing and treating animal manure and fertilizer nutrient runoff through algae cultivation at the source, before it becomes an issue downstream in local water bodies.

Concluding Remarks

Again, as in Part 1 of this report, the analyses conducted here provide valuable insights on the opportunities and challenges for the production and use of algal biomass as may be collected from algal bloom events or sourced from current industry operations. Not only may these resources be procured at reasonable costs in the near term, but technologies for their conversion to renewable fuels and products may also be deployed in the near future at smaller community scale, leveraging relatively established and low-risk conversion processes. While such algae resources may be limited in their scalability (i.e., will not alone contribute billions of gallons to the national fuel infrastructure as commercial algae farms may one day be able to support), the significantly lower cost of algal biomass envisioned through these pathways could support important early expansion of the industry to begin "getting off the ground" and develop learning curves for producing, harvesting, and processing algal biomass as could be applied to commercial algae farming and more complex algal biorefineries further into the future. Namely, the TEA modeling conducted here highlights example pathways for conversion of HAB- and EXT-derived algal biomass via processing through simple CAP or AD conversion operations—with good potential for economical production of infrastructure-compatible fuels (ethanol, lipids for hydroprocessing to diesel or sustainable aviation fuels [SAF], and RNG for use as an energy source and/or subsequent upgrading for renewable hydrogen generation) and large-market coproducts (feed for bioplastics, crop fertilizers, and captured CO_2), particularly for CAP conversion. When policy incentives such as RIN credits are also considered, the economic potential of these approaches is considerably increased, particularly for AD conversion; however, the qualification for these credits must be certified by comprehensive life cycle assessment (LCA), which is outside of the scope of this analysis. Future work should expand on the results presented herein to also include LCA for purposes of better understanding the decarbonization potential for these strategies, in light of favorable economic potential demonstrated here.

Comparing between conversion technologies, the CAP pathway produces liquid fuels as well as a more valuable solid residual coproduct that may be utilized for thermoplastics, but at higher capital/operating expenses. Conversely, the AD pathway requires a lower capital investment (74%–78% of the CAP facility depending on biomass source) and annual operating costs (52%–78% of CAP facility non-feedstock operating costs) but produces a less valuable RNG product and AD effluent/digestate fertilizer materials—though opportunities may exist for higher-value RNG outlets in the near term through policy incentives, as well as potential implications on subsequent carbon capture options from RNG that would not apply for vehicle fuel use. Overall, the trade-offs between processing costs and product/coproduct revenues translate to more favorable economics for CAP conversion across both biomass sources, and generally unfavorable economics for AD conversion under base case assumptions (compared to landfill disposal of the biomass)—with favorable economics indicated by a higher allowable biomass purchase price that the conversion facility would be willing to pay.

For the HAB scenario, given a more intermittent scale of biomass availability, economical conversion through the CAP pathway can be achieved at approximately \$21/ton biomass as a "transfer" price from HAB collection to downstream conversion, while this value increases to \$139/ton for the EXT scenario coupled with CAP conversion, with the latter representing a purchase price of residual biomass following lipid extraction operations performed by industry for nutraceutical production of algal lipid constituents. The AD conversion process would require algae biomass to be purchased at negative values (−$177/ton for HAB or −$83/ton for EXT)—i.e., providing credits to the conversion facility for handling either biomass source, similar to a "tipping fee"—with base case economics less favorable than simply disposing of the biomass to a landfill at an assumed tipping fee of −$35/ton. Considerable room exists for further improvement in system economics through inclusion of policy credit incentives, which particularly may benefit the AD pathways by raising the allowable biomass transfer price by $100/ton or more to achieve more competitive economics with CAP conversion. For the HAB cases, current TEA modeling indicates the requisite biomass costs may be achieved by applying a water "treatment" credit of roughly $800–$1,400 per million gallons treated depending on the conversion pathway, as would be supported by local governments or jurisdictions to remove HABs from local water bodies (though this value strongly depends on HAB collection scale, duration of the year, and harvest concentration).

Moving forward, further opportunities exist to expand on the feasibility analyses conducted here, both to continue exploring the most promising findings and to address knowledge gaps identified during this work. These are summarized as follows:

- *HAB:* Partner with companies and/or research institutes directly involved with the collection of HAB biomass to fine-tune parameters and assumptions, namely coagulant type/dosage and microalgae concentration in HABs.
- *HAB:* Identify the full collective potential for HAB biomass recovery in the United States as a bioresource for the production of fuels and coproducts.
- *HAB:* Assess the scalability and economic viability of alternative systems such as mobile units for HAB biomass collection or marine/ocean HAB collection offshore, while also exploring the possibility of recovering other biomass resources such as macroalgae.
- *EXT:* Interface with companies extracting algal lipids to further understand the fate of residual biomass and viability of other options as pursued or considered now (beyond simple landfilling disposal).
- *EXT:* Incorporate experimental data regarding biomass compositions from lipid-extracted biomass, as well as data on conversion of biomass (pretreatment/fermentation/AD performance), to confirm details assumed here.
- Perform detailed LCA on each process to identify the key drivers of carbon intensity, opportunities for decarbonization, and the associated implications on policy incentives such as RIN and LCFS credits.

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