Pacific Northwest NATIONAL LABORATORY

PNNL-35507

2023 Business Case Study: Hydrothermal Liquefaction of Algal Bloom Biomass

December 2024

Yiling Xu
Scott Edmundson
Yunhua Zhu
Todd Hart
Dylan Cronin
Sam Fox
Andy Schmidt
Peter Valdez

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from
the Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062
www.osti.gov
ph: (865) 576-8401
fox: (865) 576-5728
email: reports@osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
or (703) 605-6000
email: info@ntis.gov
Online ordering: http://www.ntis.gov

PNNL-35507

2023 Business Case Study: Hydrothermal Liquefaction of Algal Bloom Biomass

December 2024

Yiling Xu
Scott Edmundson
Yunhua Zhu
Todd Hart
Dylan Cronin
Sam Fox
Andy Schmidt
Peter Valdez

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99354

Summary

A business case study was developed for the fiscal year (FY) 2023 to explore the technical and economic feasibility of converting lake-harvested algal bloom biomass (ABB) into biofuel via hydrothermal liquefaction (HTL). The case study includes reporting on the experimental demonstration of converting the algal feedstock to HTL biocrude. Using the experimental data, a preliminary techno-economic assessment (TEA) of a commercial-scale facility was completed to determine the economic feasibility of the process.

PNNL has published several key updates to the proposed design of the commercial-scale HTL system (Li et al., 2024). The process model for HTL used in this study was updated to match advancements in the newly proposed HTL design.

Table 1. Key changes of the 2023 business case study report compared to the 2022 SOT report.

Topic	This report	2022 SOT	Justification
Feedstock	Algal bloom biomass (ABB) harvested from lakes as the primary feedstock. Scenarios are included investigating ABB as a supplemental feedstock in an algal biorefinery	*Picochlorum celeri*	ABB is examined in the presented analysis as a primary and supplementary feedstock. ABB was selected as a zero-cost feedstock. The availability of ABB can be limited, and the ash content is high (>33 wt %)
Cost year basis	2020	2016	This year's report was updated to reflect a more recent cost basis.
Equipment design for HTL	Heat recovery system using steam flashing	Heat recovery system using heat exchangers	An update to the design of the HTL system was completed incorporating new unit operations that are proposed to improve process reliability.
Biocrude Yield	0.20 g/g feedstock ash-free dry weight (AFDW)	0.33 g/g feedstock AFDW	The reduced yield matches the experimental results for the HTL of ABB.
Processing Scale	30 – 980 tons/day AFDW	662 tons/day AFDW	Multiple scenarios were considered to determine an optimal processing scale to balance cost and availability of ABB.
Co-product(s)	Recovered nutrients for algae cultivation or cement additives	Recovered nutrients for algae cultivation	The aqueous and solids products are fed back to the algae farm, but some scenarios also include the sale of the HTL solids as a cement additive

Table 1 summarizes key differences between the current study and the 2022 state-of-technology (SOT) report (Zhu et al., 2023) published previously. In addition to changes to the HTL process model, updates from experimental results were incorporated into this year's study. Another key change is an update of the cost-year basis from 2016 to 2020.

Lake-harvested ABB was provided to PNNL from AECOM for HTL processing. The unoptimized yield of HTL biocrude from ABB was relatively lower than previous algal feedstocks at 20 wt % on an ash-free, dry weight basis (AFDW). Although the yield was less than typical, ABB is a cost-advantaged feedstock that could be provided at zero cost, or as an environmental benefit, if available. A zero-cost of the algae is assumed because the harvested ABB currently has no specific use and is landfilled after being collected. The goal of harvesting ABB is to remove excess nutrients and/or toxin-producing microalgae from affected water bodies. If removal of ABB from polluted lakes becomes more commonplace, then HTL can become a potential process to recover carbon and create value from a feedstock that would otherwise be landfilled. A preliminary assessment of the resource availability of ABB shows some potential as a non-trivial amount of biomass could be collected as a feedstock for processing via HTL.

Several scenarios were examined to find an optimal arrangement of feedstocks to enable an economically viable use of ABB. Inclusion of ABB with a typical HTL facility supported by an algae farm resulted in the best scenario when compared to a scaled-down facility using only ABB as the sole feedstock. The ABB and other biomass are better to supplement the supply of feedstocks to the HTL facility, especially at times of reduced seasonal availability. In this work, woody biomass is proposed to supplement the feedstock supply. The optimal scenario, combining farm-cultivated algae blended with ABB, resulted in a minimum fuel selling price (MFSP) of $6.26 per gasoline gallon equivalent (GGE) of distillate fuel products. The average feedstock cost was reduced by 8% by assuming a zero-cost for the ABB feedstock. The impact of using ABB was diluted because the annual contribution of the ABB as a feedstock is only 4% of total biomass consumption. The cost of HTL conversion increased 63% due to the proposed redesign of the HTL system (Li et al., 2024). The total potential fuel yield is 81 GGE/ton feedstock which is similar to the 83 GGE/ton yield reported in 2022 (Zhu et al., 2023).

Acknowledgments

We gratefully acknowledge AECOM Technical Services Inc. for supporting this work by providing algae samples used for laboratory experiments.

Acronyms and Abbreviations

ABB	algal bloom biomass
AFDW	ash free dry weight
EBS	engineered bioslurry
FY	fiscal year
GGE	gasoline gallon equivalent
HAB	harmful algal bloom
HHV	higher heating value
HTL	hydrothermal liquefaction
LHSV	liquid hourly space velocity
MFSP	minimum fuel selling price
MGD	million gallons per day
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
SOT	state of technology
SAF	sustainable aviation fuel
TEA	techno-economic analysis

Contents

Summary ii
Acknowledgments iv
Acronyms and Abbreviations v
Figures and Tables vii
1.0 Introduction 1
2.0 Experimental Work 3
2.1 Feedstocks 3
2.2 Hydrothermal Liquefaction 4
3.0 Techno-economic Assessment 8
3.1 Algal Blooms as Feedstock 8
3.2 Updates to the HTL Process Model 10
3.3 System Arrangement and Process Scenarios 12
3.4 Feedstock Properties 14
3.5 Process Assumptions 14
4.0 Results and Discussion 16
4.1 Cost Results 16
4.2 Sustainable Fuel Credits 21
4.3 Sustainability Metrics 22
5.0 Conclusions and Future Work 23
6.0 References 24
Appendix A – Details for the Process and Economic Models A.1

Figures and Tables

Figure 1. Photo of algal bloom material, as received, from a) Lake Jesup in Florida and b) Harsha Lake in Ohio. 3
Figure 2. Mass distribution of the HTL products (% dry, ash-free basis)....5
Figure 3. Carbon distribution of the HTL products (% dry, ash-free basis)....5
Figure 4. Simulated distillation curve for ABB & Wood and ABB & EBS samples. 6
Figure 5. Selected lakes within a 50-mile radius of Orlando that are susceptible to algal blooms, note: a map key identifying each lake is included in Table 6 [map data from Google]. 9
Figure 6. a) Previous and b) updated design for the HTL system....11
Figure 7. Flowsheet for the process model for scenarios 1 and 2. 13
Figure 8. Flowsheet for the process model for scenarios 3 – 8. 13
Figure 9. MFSP of biocrude for low- and high-availability scenarios for ABB. 16
Figure 10. Results for the MFSP of fuel (Scenario 7 is the representative case for 2023) 18
Figure 11. Sensitivity analysis for parameters related to the feedstock and the HTL process (scenario 7) 19
Figure 12. Sensitivity analysis for parameters related to the feedstock and the HTL process for ABB only (scenario 1). 20
Figure 13. Value of credits applied to the MFSP for scenario 7. 21

Table 1. Key changes of the 2023 business case study report compared to the 2022 SOT report. ii
Table 2. Composition of the Algal Bloom Biomass....4
Table 3. Composition of the HTL feedstock using ABB from Lake Jesup (ash-free, dry weight basis)....4
Table 4. Biocrude Composition and Properties. 6
Table 5. Trace metal composition (parts per million) of the HTL products 7
Table 6. Estimation of the biomass availability from top lakes with measurable algal blooms....9
Table 7. Summary of parameters investigated for alternative scenarios. 12
Table 8. Elemental and biochemical compositions of feedstocks used in the process model. 14
Table 9. Parameter assumptions for the process design for HTL and biocrude upgrading. 15
Table 10. Annual consumption of feedstocks and daily capacity of the HTL facility (AFDW basis). 16
Table 11. Sustainability metrics for the conversion of algal feedstocks to fuel and co-products. 22

1.0 Introduction

The strategic goals of the Bioenergy Technologies Office (BETO) of the U.S. Department of Energy (DOE) are summarized in the 2023 Multi-Year Program Plan (DOE, 2023a). BETO's goals emphasize the decarbonization of the transportation sector through the production of renewable, low-carbon fuels and the manufacture of sustainable chemicals and materials. Decarbonization of the transportation and industry sectors can occur through the use of renewable carbon resources, such as purpose-grown biomass or waste resources, that can be upgraded to replace the fuels or products that are used every day. The purpose of this document is to report the current state of technology to produce biofuels and other sustainable products via the hydrothermal liquefaction (HTL) of algal feedstocks, a renewable resource. The document summarizes current research related to the development of HTL technology and products. Techno-economic analysis (TEA) is also reported to measure the current technology developments against previous benchmarks for related technologies and products. Technical details for commercial design and an assessment of the availability of renewable algal resources is also included. PNNL has issued annual state-of-technology reports since 2017 and results of the present study will be compared against the previous results.

Recently, the use of low-cost algal feedstocks has been considered to increase the economic viability of algae-derived biofuels. In the 2021 State of Technology (SOT) report, PNNL summarized the use of wastewater-grown algae as a feedstock for HTL (Zhu et al., 2022). Assuming a zero-cost feedstock and the production and sale of a fertilizer co-product of struvite led to an estimated minimum fuel selling price (MFSP) of the resulting fuel products at $2.61 (2016$) per gasoline gallon equivalent (GGE). The reported MFSP was a significant decrease compared to the reported MFSP of $4.48/GGE as published in the 2020 SOT report. Overall, the change in MFSP was wholly influenced by the assumption that the feedstock could be provided at zero cost. Low- and zero-cost feedstocks could potentially enable cost-competitive fuels via HTL. Wastewater-grown algae are a potential low-cost resource because the value of the algae is derived from the removal of nutrients (nitrogen and phosphorus) during the wastewater treatment process. The resulting biomass can then be landfilled or possibly land-applied to maximize the nutrient benefits. The National Renewable Energy Laboratory (NREL) has also assessed the value of using algae cultivation as a processing step within wastewater treatment facilities (Wiatrowski et al., 2022). There are specific trade-offs for utilizing low-cost algae feedstocks. In particular, the algal feedstocks tend to accumulate more inorganic materials compared to farm-cultivated algae, creating challenges that can impair reliable operations of processing equipment. The amount of inorganic content creates processing challenges but there is greater opportunity to recover valuable non-fuel products, such as fertilizers, from the HTL process (Zhu et al., 2022).

Another potential source of low-cost algae are algal blooms that can occur in nutrient-saturated water bodies. Eutrophication poses a serious environmental challenge with far-reaching ecological and social implications. In general, environmental management agencies at all levels of government track and monitor water bodies for the presence of algal blooms (CAWQMC, 2023; NOAA, 2023; OEPA, 2023; FDEP, 2023a; EPA, 2023b). Of particular concern are harmful algal blooms (HAB) that are toxic to humans and wildlife. People can be exposed to toxins by ingestion of contaminated water or the exposure to aerosolized toxins, causing both acute and chronic illnesses (Heil and Muni-Morgan, 2021). There can also be negative economic consequences in the communities where the HABs occur, mainly impacting industries related to recreation, tourism, and fishery (Heil and Muni-Morgan, 2021).

While every state in the U.S. faces the challenge to manage algal blooms, Florida is especially susceptible due to its unique geography, climate, and abundance of aquatic ecosystems. Florida has over 7,000 lakes larger than 1 acre, with 35% of the state's lakes located in just 4 counties (Lake, Orange, Osceola, Polk) in central Florida (Schiffer, 1998). Nutrient pollution into the aquatic systems creates the opportunity for prolific algal growth, particularly during the summer months (FDEP, 2023b). A review of news reports conducted from 2010 to 2022 revealed that 115 of Florida's lakes have experienced at least one algal bloom (EWG, 2023). In 2023 alone, 58 algal blooms have been recorded in Florida, the largest bloom occurred in Lake Okeechobee, the nation's fourth-largest lake with a surface area of 700 square miles. Within the last year, the area of the lake encompassed by the bloom measured 440 square miles (NASA, 2023a). For this report, an area in Florida will be studied as an example.

The harvesting and disposal of algal blooms is a proposed solution to reduce the environmental and economic impacts. The Army Corp of Engineers and AECOM have recently reported success in removal of blooms from affected lakes. The general method to harvest the bloom is by pumping the affected water through a dissolved air flotation unit (Page et al., 2020; TetraTech, 2022). Shore-positioned or floating systems are deployed to harvest the algal bloom. Dosing of flocculants and coagulants enable separation of the biomass and nutrients from the water. High-quality, algae-free effluent is then returned to the water-body source to remediate water quality over time.

Although algal bloom materials are a potential resource for low-cost feedstocks, the general availability and scale of the materials requires additional investigation. NREL has completed a preliminary assessment, highlighting that current tools are insufficient to accurately estimate the potential amount of biomass available for harvesting and processing (Wiatrowski et al., 2022). Recent studies have estimated bloom quantity and frequency by measuring chlorophyll intensity per lake area (Mishra et al., 2019) and duration (Myer et al., 2020). Although mapping tools that are available online may report some detail about the frequency of blooms and the concentrations of toxins or algae present, assessment of the available biomass should be considered in future studies. Current studies, including the information presented herein, include assumptions to estimate the total mass of an algal bloom. An assumptive estimate of biomass potential is reported in section 3.1 of this report.

The goal of this report is to provide an assessment of the utilization of ABB as an HTL feedstock, enabling the recovery of nutrients and carbon, rather than disposing of it as a waste material. Experimental results of the HTL of ABB will be reported. A TEA of the ABB-to-fuel process will also be reported.

2.0 Experimental Work

In this section, the experimental work that was completed in the 2023 FY is summarized. The data from the experiments were used to support the process and economic models discussed in this report.

2.1 Feedstocks

ABB was provided to the PNNL experimental team by AECOM Technical Services Inc. (AECOM). AECOM is an engineering company that is investigating technologies for harvesting algal blooms. Photos of the as-received materials are shown in Figure 1. Both samples were harvested using AECOM's Hydronucleation Flotation Technology (TetraTech, 2022).

The first sample (Figure 1a) was harvested in March 2022 from Lake Jesup in Seminole County, Florida (AECOM, 2022). The second sample (Figure 1b) was harvested in September 2023 from William H. Harsha (Harsha) Lake in Clermont County, Ohio (AECOM, 2023). During the harvesting process, part-per-million quantities of inorganic flocculant and polymer coagulant were added to the lake influent. After harvesting, the algal slurry was further concentrated using dewatering equipment such as a rotary screw press. For the sample from Harsha Lake, a wood powder was added to the dilute slurry to facilitate the dewatering process, concentrating the algal slurry to 15 wt % solids. The content of wood with respect to algae was approximately 25% by mass.

(a) (b)

Figure 1. Photo of algal bloom material, as received, from a) Lake Jesup in Florida and b) Harsha Lake in Ohio.

The proximate composition of each slurry was measured and is reported on an AFDW basis in Table 2. In both samples, the dried algal slurry is equally composed of both ash and carbohydrates. On an ash-free basis the ABB from Lake Jesup is equal parts of carbohydrates (45%) and proteins (44%), whereas the ABB from Harsha Lake is mostly carbohydrates (80%). Lipids were present in each sample but comprised less than 3% of the ABB. The high concentration of ash (>33% dry basis) in the slurry may have negative impacts on hydrothermal processing. The ash material may accumulate in the flow system, increasing the frequency in which solids are removed from the equipment, impacting process reliability, as well as the recovery of the energy-dense HTL biocrude.

Table 2. Composition of the Algal Bloom Biomass

	Lake Jesup Sample		Harsha Lake Sample	
Component	Dry basis (%)	Ash-free, dry weight basis (%)	Dry basis (%)	Ash-free, dry weight basis (%)
Ash	33	-	44	-
Carbohydrate	33	49	45	80
Protein	32	48	10	18
Lipid	2	3	1	2

To facilitate processing, the ABB from Lake Jesup was blended with engineered bioslurry (EBS). EBS is a blended food waste provided by Waste Management. EBS was selected because it is a proven feedstock for HTL and because it is a low-ash feed (9 wt %) (Snowden-Swan et al., 2022). The EBS was added to dilute the ash of the ABB and improve its flow characteristics. The ABB and EBS slurry was mixed at a 4:1 mass ratio. The resulting mixture had an ash content of 27 wt %. A slurry of 15.6 wt % solids was prepared as the maximum concentration that was considered pumpable. Additional investigation will be needed to understand how viscosity of the slurry is impacted by the polymers used to flocculate the ABB. A high concentration of diatoms in the ABB may also impact the fluid characteristics of the biomass slurry. Proximate analysis of the EBS and ABB and EBS mixture are reported in Table 3.

Table 3. Composition of the HTL feedstock using ABB from Lake Jesup (ash-free, dry weight basis)

Component	EBS Composition (%)	ABB & EBS Composition (%)
Ash	9	27
Carbohydrate	40	35
Protein	23	31
Lipid	28	7

2.2 Hydrothermal Liquefaction

HTL for both ABB samples from AECOM and the experimental results are presented herein. The HTL feedstocks were processed in the bench-scale continuous-flow HTL reactor at PNNL (Elliott et al., 2013).

At the onset of processing the ABB and EBS blend, a slipstream of 1 Lph of water was added to the feed stream to reduce viscosity and maintain consistent flow. The combined flow rate was 5 Lph and the added water reduced the solids concentration in the slurry to 12%. The liquid hourly space velocity (LHSV) was 10 L/h/L and the reaction temperature was 325 °C. The pressure in the HTL reactor was maintained at 2,800 psig.

The algae and wood powder sample from Harsha Lake was blended with a 1 wt % Na_2CO_3 solution as a precaution to avoid plugging that can occur with feedstocks that contain high concentrations of ash or lignocellulosic biomass. The carbonate solution was added because of the known content of ash and wood powder. The feed rate was 2.4 Lph (4.3 L/h/L) at a reactor temperature of 326 °C. The pressure in the HTL reactor was maintained at 2,800 psig.

The HTL results from both samples are presented together to provide points of comparison between the two. Figure 2 shows the mass distribution of the HTL products which includes the biocrude, aqueous phase products, solids, and gas. The yield of biocrude is low compared to the HTL processing of other cultivated algal feedstocks that are typically in the range of 30 – 40% AFDW. The lipid content of the EBS likely contributes to the increased yield of biocrude for the ABB and EBS feedstock when compared to the yield of biocrude for the ABB and wood feedstock. The ABB and wood blend also has a higher yield of solid and gas products.

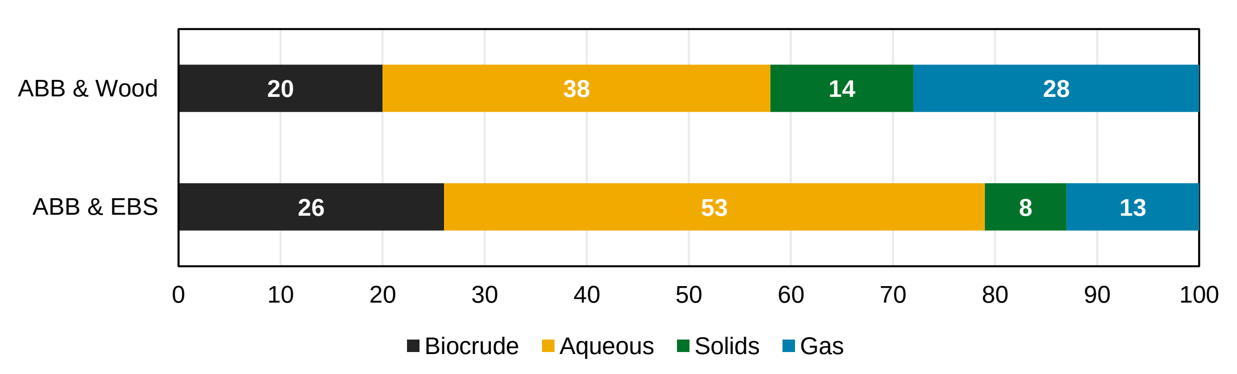

Figure 2. Mass distribution of the HTL products (% dry, ash-free basis)

Figure 3 shows the distribution of carbon in the HTL products. Large amounts of ash in the feed (44%) may retain some of the biocrude, which can contribute to the large amount of carbon in the solid products for the ABB and wood sample.

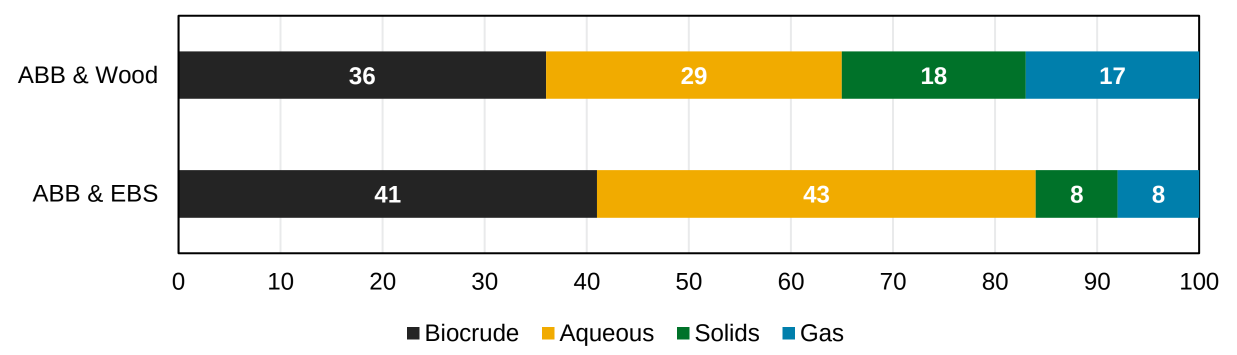

Figure 3. Carbon distribution of the HTL products (% dry, ash-free basis)

Table 4 shows the measured composition and properties of the biocrude from each feedstock. The composition is consistent with most HTL biocrudes from other algal feedstocks, but the H:C ratio is lower than expected for the ABB and wood feedstock, which is typically >1.1. Crystals were visually observed in the biocrude from the ABB and wood sample. The wood powder that was added to the biomass to aid in dewatering the slurry may have increased the presence of lignin, resulting in the crystalline particulate as well as the reduced hydrogen content. Lignin consists of mostly aromatic structures with a low H:C ratio. More preferred values for H:C ratio, HHV (>35 MJ/kg), and density (<1 g/mL) were observed in the biocrude from the ABB and EBS feedstock. The lipid content from the EBS fraction likely contributes to the favorable composition and physical properties of the biocrude.

Table 4. Biocrude Composition and Properties.

Property	Units	ABB & Wood	ABB & EBS
C content	wt %	80	76
H content	wt %	6.0	10
O content	wt %	8.4	7.9
N content	wt %	4.2	4.8
S content	wt %	0.82	0.90
H:C	mol ratio	0.89	1.56
HHV	MJ/kg	34.3	37.5
TAN	mg_{KOH}/g_{oil}	75	90
Density	g/mL	1.02	0.99
Moisture	wt %	16.2	4.4
Ash	wt %	0.11	0.25

The biocrude samples were analyzed via simulated distillation (Figure 4), using a gas chromatography method described previously (McCurry, 2018). The distillation profile is mostly consistent with other HTL biocrudes. About 50% of the crude fraction boils within the middle-distillate range (150 – 340 °C) which includes jet fuel and diesel fuel fractions. The simulated distillation excludes any materials with a high boiling point (>550 °C) and the non-boiling fraction is not quantifiable in this analysis method.

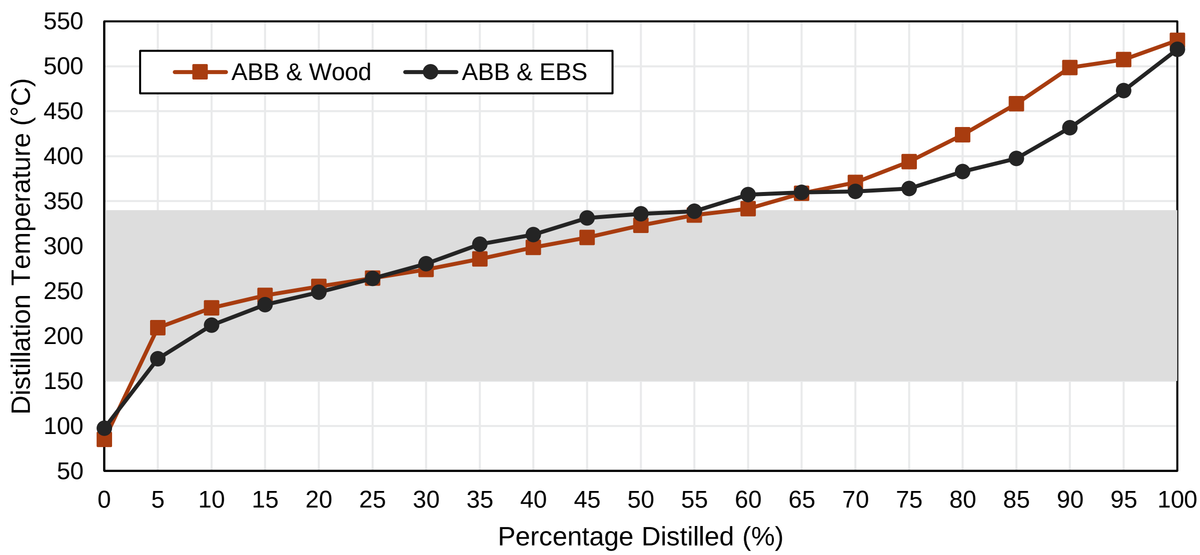

Figure 4. Simulated distillation curve for ABB & Wood and ABB & EBS samples.

Table 5 shows the metal composition of the feedstocks and HTL products. Metals of concern include Al, Si, and Fe. In general, the inorganic content is not desired because it does not favorably impact the yield of biocrude or improve HTL processing. Si is suspected from diatoms present in the biomass from wild or non-farmed ABB sources. Previous samples with high diatom concentrations have been non-pumpable in the laboratory-scale equipment for HTL. Al may be sourced from soils or coagulants and is not desirable for processing. Fe may poison catalysts during biocrude upgrading. As is typically observed in HTL experiments, many of the metals are concentrated in the solids. Dissolved metals such as K and Na partition to the biocrude and aqueous products.

Table 5. Trace metal composition (parts per million) of the HTL products

	ABB & Wood				ABB & EBS			
Element	Feed	Biocrude	HTL Solids	Aqueous Phase	Feed	Biocrude	HTL Solids	Aqueous Phase
Al	100,000	1,100	87,000	1	38,000	47	91,000	< 1
Ba	81	< 30	130	< 1	180	< 15	500	< 1
Ca	9,500	150	14,000	3	5,700	54	20,000	< 1
Cr	430	< 30	670	< 1	97	< 15	210	< 1
Cu	35	< 30	51	< 1	32	17	67	< 1
Fe	9,300	300	11,000	< 1	22,000	500	61,000	< 1
K	3,900	92	6,300	52	3,600	130	5,200	220
Mg	1,300	45	2,500	< 1	2,000	20	4,900	1
Mn	500	< 30	930	< 1	440	< 15	1,800	< 1
Na	26,000	900	27,000	2,500	5,800	340	4,700	710
Ni	< 30	< 30	60	< 1	43	< 15	120	< 1
P	3,400	< 30	5,400	< 1	6,400	< 15	22,000	15
Sr	31	< 30	50	< 1	140	< 15	400	< 1
Zn	35	< 30	67	< 1	78	< 15	180	< 1
Si	47,000	1,300	79,000	51	54,000	1,100	160,000	58
Ti	1,000	< 30	1,800	< 1	1,100	< 15	3,700	< 1
S	3,100	7,100	1,000	130	6,400	6300	3,000	520
Zr	< 30	< 30	33	< 1	41	< 15	93	< 1

3.0 Techno-economic Assessment

In this section, the design inputs and assumptions for the HTL and biocrude upgrading system are described. An availability assessment of ABB is presented. Changes in the overall design of the HTL processing system are also introduced.

3.1 Algal Blooms as Feedstock

Satellite imaging is used to track algal blooms. Chlorophyll-a is a distinct signature of photosynthetic biomass and can be detected with increasing precision from earth observation satellite platforms such as the Moderate Resolution Imaging Spectroradiometer on NASA's Aqua satellite (NASA, 2023b). Although directly correlated with photosynthetic biomass (both terrestrial and algal), chlorophyll makes up a small and highly variable fraction of the total carbon within the biomass. Assumptions for the concentration of chlorophyll-a in biomass can range from <0.01 to >0.1 g/g (Arteaga et al., 2016). Furthermore, depending on the satellite spectral data processing methodology, the chlorophyll-a index can be truncated to look specifically at the cyanobacterial concentration by examining the spectral shape of the signature and removing signatures without phycocyanin responses. Phycocyanin is a pigment predominantly associated with cyanobacteria, the group of algae primarily responsible for freshwater harmful algal blooms. Reducing the available biomass to only include cyanobacterial biomass may significantly reduce the total available planktonic biomass available from bloom mitigation operations.

Converting satellite detected chlorophyll-a signatures to available biomass introduces several major assumptions. One pathway is to convert the satellite data to cell counts, which is used in harmful algal bloom monitoring networks, such EPA's CyAN Web App (EPA, 2023c). The monitoring networks and tools provide reasonable and actionable data for lake management to prevent loss of life due to potentially toxic blooms of cyanobacteria. Converting image-derived cell counts to mass values has some potential issues. One such issue is the variability of cell counts for colonial cyanobacteria such as *Microcystis,* which forms gelatinous masses filled with relatively small cells (2 – 5 µm cell diameter), complicating methods for cells counts (Joung et al., 2006). Compounding the error in the conversion from cell count to mass is the estimation of a biomass per cell, which is also variable depending on the environment in which the cell is growing. The estimate of mass per unit cell can range from 20 to 15,000 pg/cell (Holm-Hansen, 1969; Hu, 2014). Intermediate values for the per cell weight of cyanobacteria bacteria are reported to be on the order of hundreds of picograms per cell (Zhang et al., 2018; Wiatrowski et al., 2022). Values for common green microalgae are 3,000 pg AFDW/cell (Chioccioli et al., 2014; Dahlin et al., 2019).

In this report, the availability of ABB is estimated from cell counts recorded in the EPA's CyAN Web App (EPA, 2023c). Values for average cell weight of cyanobacteria of 20 and 100 pg/cell were used to estimate the total potential biomass in each lake. Using the assumed values for cell weight resulted in bloom concentrations that are comparable to observed values that can vary in magnitude up to hundreds of mg/L (Page et al., 2020). A conservative estimate is used because of the assumptions and uncertainties associated with the estimation method.

The ABB is assumed to be harvested from 15 lakes in Florida that are regularly affected by algal blooms. The lakes near Orlando with the highest average of algae concentration for June through November of 2023 were selected. The weekly average data includes summer and fall seasons when the highest concentration of blooms will occur. The locations of these lakes are shown on a map in Figure 5, each situated within a 50-mile radius near Orlando.

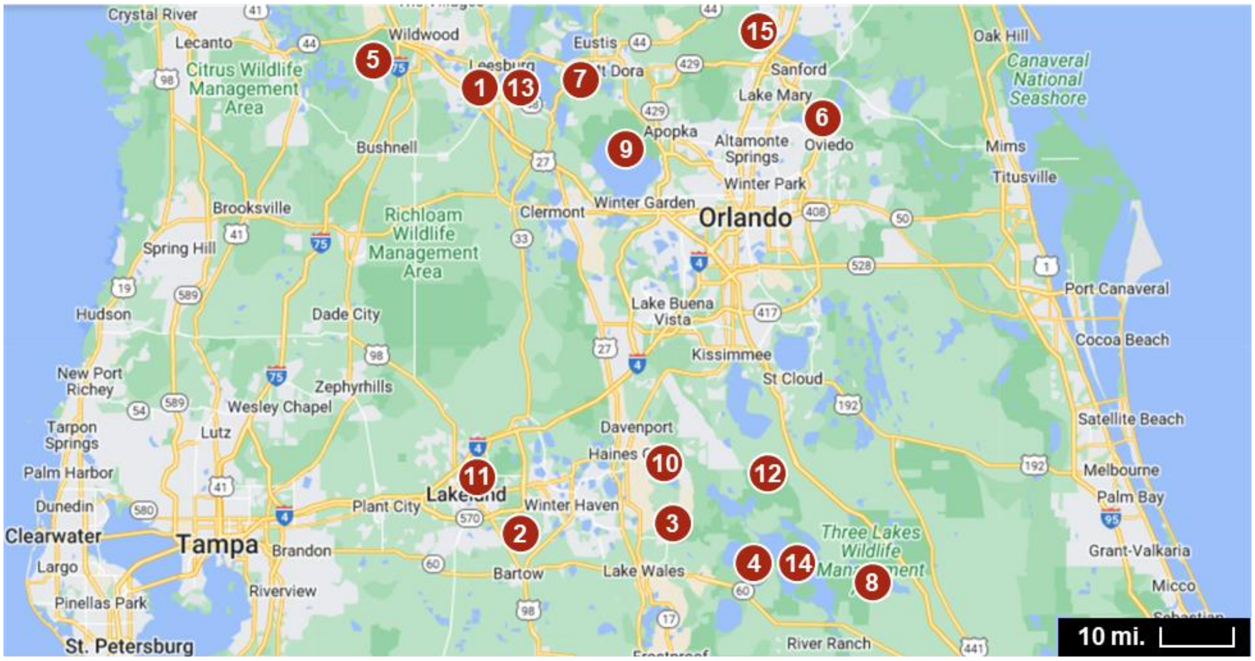

Figure 5. Selected lakes within a 50-mile radius of Orlando that are susceptible to algal blooms, note: a map key identifying each lake is included in Table 6 [map data from Google].

Table 6. Estimation of the biomass availability from top lakes with measurable algal blooms

Map Key	Lake	Bloom concentration, weekly average for June to November, 2023 (cells/mL)	Biomass potential, low availability		Biomass potential, high availability	
			mg/L	ton/d	mg/L	ton/d
1	Denham	2,400,00	48	20	240	100
2	Hancock	1,300,000	27	11	130	56
3	Pierce	1,200,000	24	9.9	120	50
4	Tiger	1,100,000	23	9.5	110	47
5	Panasoffkee	960,000	19	8.1	97	40
6	Jesup	920,000	18	8.0	92	38
7	Dora	900,000	18	7.4	89	37
8	Marian	820,000	16	7.0	82	34
9	Apopka	780,000	16	6.5	78	33
10	Marion	760,000	15	6.0	76	32
11	Parker	700,000	14	5.9	70	30
12	Cypress	650,000	13	5.0	65	27
13	Harris	480,000	10	4.0	48	20
14	Kissimmee	380,000	8.0	3.0	38	16
15	Konomac	300,000	6.0	2.5	30	12
	Total	-	-	114	-	572

Table 6 summarizes the six-month weekly average of cyanobacteria cell concentrations for the selected lakes. It is assumed that a bloom harvesting system with a processing capacity of 100 million gallons per day (MGD) is located at each lake. The harvesting capacity is likely overestimated and will need to be adjusted to the size of the lake in future estimations. Current deployments of algae harvesting systems are currently limited to pilot-scale demonstrations, however a feasibility analysis for a 65 MGD harvesting facility at Lake Okeechobee in FL has been proposed (Page et al., 2020).

Multiplying the concentration of algae by the total treatment capacity yields the mass of ABB harvested from each lake. The total dry mass of ABB harvested is estimated to be 114 or 572 tons per day, based on a “low-availability” or “high-availability” basis, respectively. The per day harvesting rate occurs during the 6-month season, accumulating ABB from the selected region.

3.2 Updates to the HTL Process Model

In this section, an overview of the process model is described. In this FY, researchers at PNNL executed a detailed engineering exercise to thoroughly investigate available off-the-shelf systems and designs that could be incorporated into a commercial-scale HTL facility. One key outcome of the exercise was the selection of a steam flashing and recovery system to replace the low-temperature heat exchanger that provides heat to the feedstock stream by recovering heat from the HTL product stream. At the laboratory and pre-pilot scale, it was known that the heat exchanger was prone to fouling and clogging, especially during the initial heating stages. The known challenges would negatively impact the reliability of the HTL process at commercial scale. Therefore, a new system design was incorporated, which uses flash vessels to transfer heat from the products to the reactants and to prevent fouling and clogging.

Figure 6 shows a block diagram depicting the previous (a) and proposed (b) arrangement of equipment for the HTL process. In summary, in the proposed HTL process, the feedstock slurry is fed into a series of two low-pressure vessels. Each vessel includes a steam injection system, which uses recovered steam from the product stream to heat the contents of each flash vessel. The feedstock slurry is heated to an intermediate temperature (~170 °C). After steam heating, the feedstock is transferred to a high-pressure pump and then heated again, using a heat exchange system to achieve the trim heating required to reach the reaction temperature (>300 °C). After the reactor, the product stream passes through the heat exchanger for heat recovery. The product stream is then flashed, producing high-temperature steam mixed with volatiles and gas produced during HTL. The steam is injected into the low-pressure vessel to heat the feedstock stream. The resulting HTL product stream is still relatively rich in water content. The product stream passes through various decanting and filtration steps to separate the biocrude, aqueous, and solid phase products.

Full details of the changes to the overall design of the HTL system are published in a complementary PNNL report (Li et al., 2024). For the purposes of the analysis reported herein, the process model built in Aspen Plus, and the corresponding economic model have both been updated to incorporate the design changes.

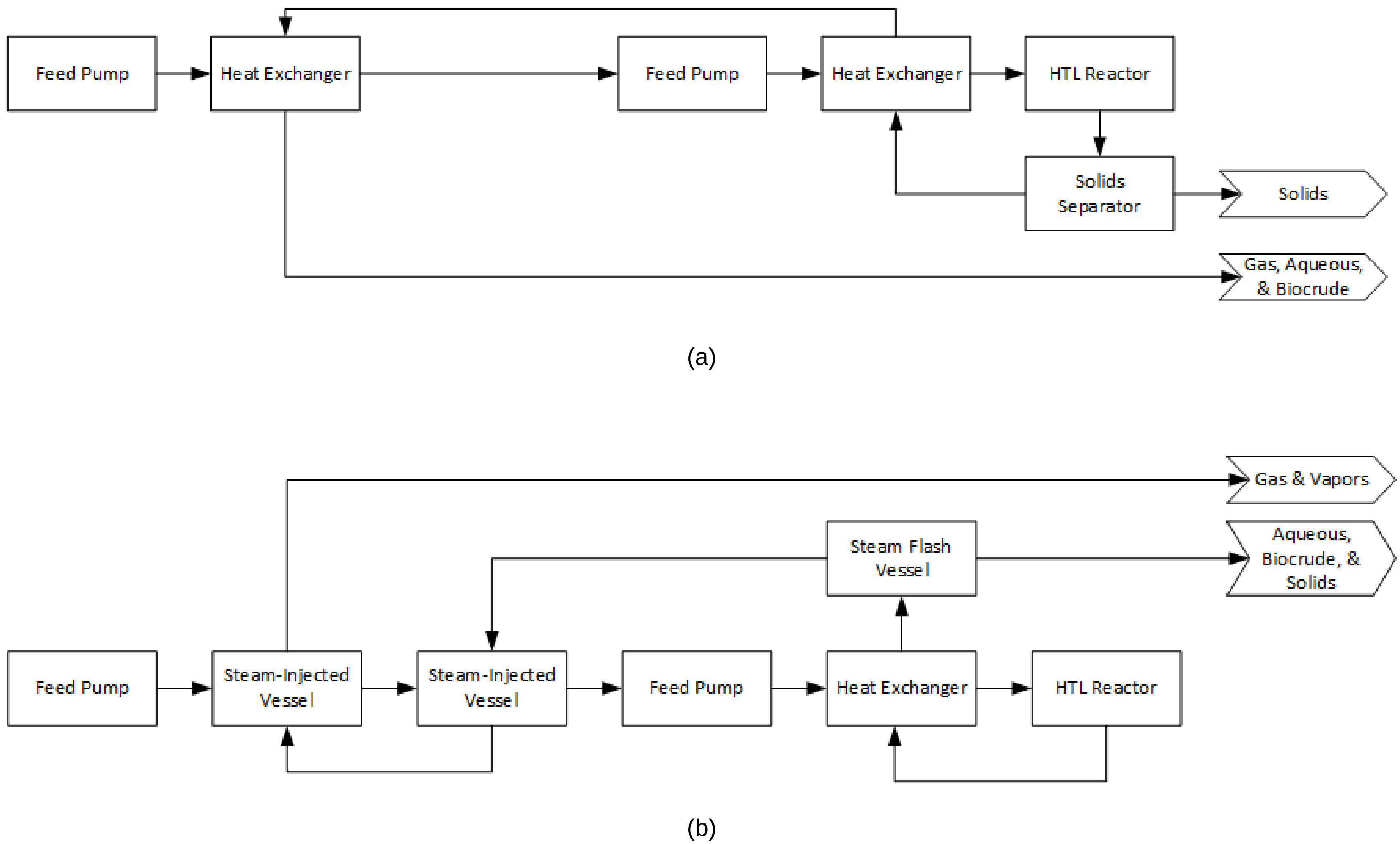

Figure 6. a) Previous and b) updated design for the HTL system

3.3 System Arrangement and Process Scenarios

Several process scenarios were investigated to find the best scenario to minimize cost and efficiently incorporate and process the ABB at a commercial-scale facility for HTL. Feedstock availability, co-location with an algae farm, inclusion of woody biomass, and storage strategy all had significant impacts on the plant capacity and overall system arrangement.

The following variables were investigated:

- Availability of ABB, 114 vs. 572 tons/day
- Inclusion or exclusion of farm-cultivated algae as a feedstock
- Inclusion or exclusion of woody biomass as a feedstock
- Storage of algal biomass to supplement feedstock supplies.

Table 7. Summary of parameters investigated for alternative scenarios.

Scenario	ABB (tons/day)	Inclusion of farm-cultivated algae	Inclusion of woody biomass	Stored feedstocks
1	114	No	N/A	ABB
2	572	No	N/A	ABB
3	114	Yes	Yes	ABB
4	572	Yes	Yes	ABB
5	114	Yes	No	ABB, farm-cultivated algae
6	572	Yes	No	ABB, farm-cultivated algae
7	114	Yes	Yes	None
8	572	Yes	Yes	None

Table 7 summarizes the setpoints for each variable for a given scenario. In the first two scenarios, only ABB is considered as the primary feedstock for the HTL facility. The availability of ABB is varied, examining low- and high-availability, respectively. Figure 7 presents a block flow diagram illustrating the key components of the process model. The scope of analysis is defined by the dashed-line boundary. As introduced in section 3.1, algal blooms are harvested at the source. The ABB is assumed to be concentrated to a thickened slurry (~20 wt %) so no additional processing is necessary. The ABB slurry is transported by truck to a centralized HTL facility, which would be located within 50 miles from the harvesting locations. The HTL processing facility is assumed to be situated adjacent to or on-site at a water resource recovery facility (WRRF). Co-location with the WRRF enables disposition of the HTL aqueous phase to the WRRF as high-strength wastewater. Wastewater sludge from the WRRF could also be co-processed with ABB to ensure feedstock availability for HTL processing. HTL of wastewater sludge is evaluated in a complementary report from PNNL (Li et al., 2024).

The resulting HTL products: biocrude (oil), solid, aqueous, and gas phases, are separated during production. The HTL biocrude is to be transferred offsite to be upgraded into fuels at the nearest refineries in the Gulf Coast region. The aqueous phase is discharged to the WRRF. The HTL solids will undergo additional water removal and drying for sale as blendstock in cement manufacturing. Cement manufacturing was considered because of the high ash content of the HTL solids with a composition rich in Ca, Fe, Al, and Si. Fly ash has commonly been used in cement processing and has a similar composition to the HTL solids (Thomas, 2007). The value of the HTL solids is assumed to be $100/ton when sold for cement processing, which can vary from $50/ton to $200/ton based on the quality of the feedstock as supplementary cementitious material (IHS, 2020; DOE, 2023b). The process off-gas, which includes combustible and non-combustible components will be used to partially offset natural gas used for process heating.

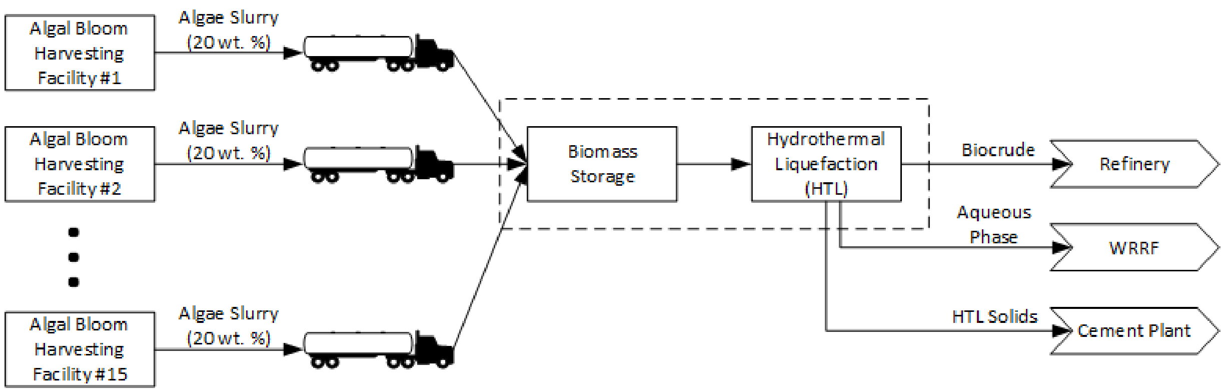

Figure 7. Flowsheet for the process model for scenarios 1 and 2.

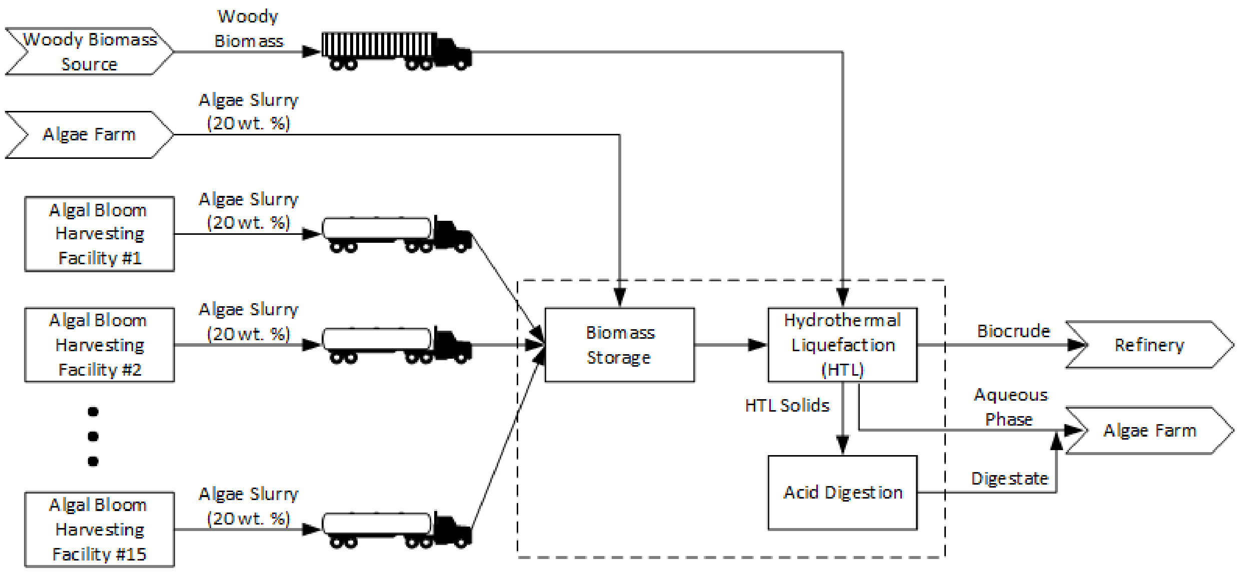

Figure 8. Flowsheet for the process model for scenarios 3 – 8.

In the subsequent scenarios 3 – 8, ABB is used to supplement a traditional arrangement for an algal biorefinery which includes an algae farm and co-located HTL facility. Previous reports describe in detail the design of the algal biorefinery (Zhu et al., 2023). The flowsheet for the process model is illustrated in Figure 9. For the algal biorefinery, the HTL process is primarily supplied by the algae farm. Woody biomass can be used to supplement algae supplies during seasons of reduced algal productivity. Storage of the ABB and farm-cultivated algae are also considered to maintain feedstock availability during low-productivity seasons.

3.4 Feedstock Properties

Physical property data for the ABB and wood blend are reported in Table 8. The properties for the farm-cultivated algae, *Picochlorum celeri*, and woody biomass are also reported from previous analyses (Zhu et al., 2023). and used directly in the model. The composition of ABB and wood was substituted directly for scenarios where only ABB is the feedstock or blendstock.

The cost of the ABB is assumed to be $0/ton, whereas the cost of the farmed *P. celeri* is $655/ton, adjusted for 2020 (Klein and Davis, 2023). The cost of woody biomass is $76/ton adjusted for 2020 (Hartley et al., 2020).

Table 8. Elemental and biochemical compositions of feedstocks used in the process model.

Elemental composition, wt % AFDW	*Picochlorum celeri*	Algal bloom biomass and wood	Woody biomass
Carbon	53.7	41.8	50
Hydrogen	7.2	6.2	6.2
Oxygen	26.5	48.4	43.6
Nitrogen	11.3	3.1	0.2
Sulfur	1.3	0.6	0
Total	100	100	100
Ash, wt % dry basis	15.9	44.5	1.0
Phosphorus (in ash), wt % of dry feed	1.6	0.3	0
Biochemical composition, wt % AFDW			
Lipid	7.0	1.6	NR
Protein	72.6	18.3	NR
Carbohydrates (balance)	20.4	80.1	NR
Total	100	100	

NR = Not reported

3.5 Process Assumptions

Table 9 summarizes the assumed parameter values used in the process model. The experimental results (section 2.2) inform the conditions for HTL processing, the yield distribution of the HTL products, and the composition of the HTL biocrude. The product yields are adjusted to close mass and elemental balances in the Aspen Plus-based process model while fitting experimental results as closely as possible. The composition of the HTL biocrude in the Aspen Plus model is adjusted to match mass and elemental yields, and the boiling point distribution.

In this year's report, hydrotreatment is excluded from the presented scenarios, therefore specific details related to the processing conditions for hydrotreatment are not included. It is instead assumed that produced biocrude from the HTL facility is processed at a nearby refinery, with the closest refineries in Alabama, Mississippi, and Louisiana. The calculated MFSP for the biocrude includes the cost associated with the transportation of the biocrude to a refinery and the adjustment in sale price to the purchaser for accepting the biocrude. The adjustment is included to offset any additional processing required for the biocrude. Excluding hydrotreatment reduces the capital intensity by removing the equipment needed for hydrogen generation and the hydrotreatment. Additionally, in most of the studied scenarios, the capacity of the standalone algal processing is insufficient to be matched with a cost-effective scale for hydrotreatment. To estimate the costs of preliminary hydroprocessing of the HTL biocrude by an external provider, the costs relevant to the installation and operation of a catalyst guardbed and a pre-treatment catalyst for hydrotreatment were annualized and calculated as a per GGE fee.

Table 9. Parameter assumptions for the process design for HTL and biocrude upgrading.

Processes	Value
HTL	
Temperature, °C	350
Pressure, psia	3000
LHSV, L/h/L	4
Products yields, g/g feedstock, AFDW	
Biocrude	0.21
Aqueous	0.37
Solid	0.29
Gas	0.14
Elemental of biocrude, wt % dry basis	
Carbon	76%
Hydrogen	11%
Oxygen	3.9%
Nitrogen	7.8%
Sulfur	0.63%
Ash	0.90%
Moisture, wt %	16%
Offsite Biocrude Upgrading	
Transportation cost, $/barrel	10
Hydrogen demand, $/GGE biocrude	0.20
Catalyst replacement, $/GGE biocrude	0.14

Another significant change in this year's report is the update of the cost year from 2016 to 2020 for the economic model. Indices for labor, materials, and equipment were updated to reflect the 2020 cost year.

4.0 Results and Discussion

The results from the economic model are discussed in this section. A sensitivity analysis is also reported to facilitate identification of processing scenarios that will have the most significant impact to the MFSP. Detailed results of the cost analysis are reported in Appendix A.

4.1 Cost Results

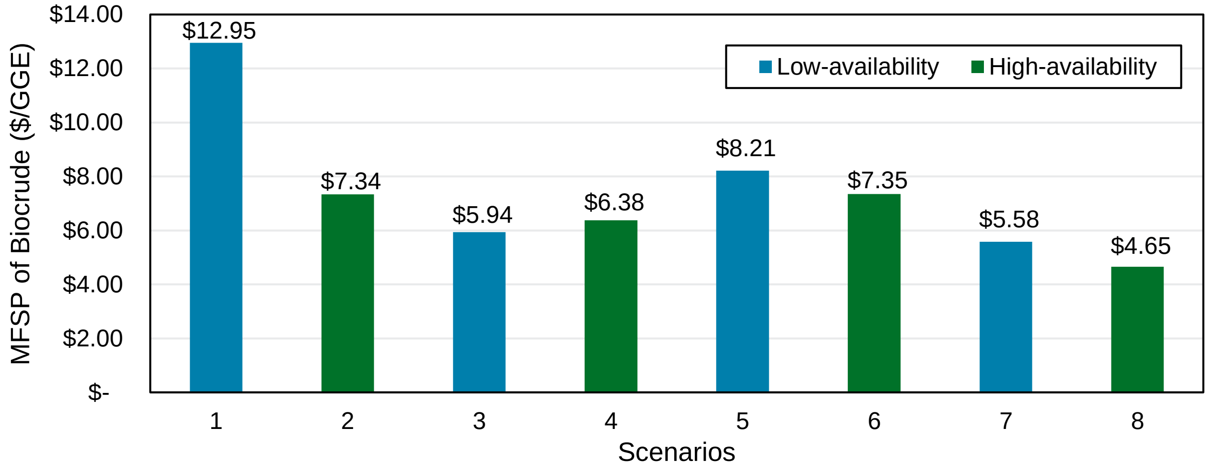

Figure 9. MFSP of biocrude for low- and high-availability scenarios for ABB.

Table 10. Annual consumption of feedstocks and daily capacity of the HTL facility (AFDW basis).

Scenario	1	2	3	4	5	6	7	8
Annual consumption of ABB (tons/year)	10,000	52,000	10,000	52,000	10,000	52,000	10,000	52,000
Annual consumption of farm-cultivated algae (tons/year)	0	0	140,000	140,000	140,000	140,000	140,000	140,000
Annual consumption of woody biomass (tons/year)	0	0	70,000	31,000	0	0	90,000	130,000
Total biomass consumption (tons/year)	10,000	52,000	220,000	223,000	150,000	192,000	240,000	322,000
Plant capacity (tons/day)	30	148	662	662	443	561	726	980
Modeled yield of biocrude (wt. % AFDW)	21	21	32	30	32	30	32	31

Figure 9 shows the MFSP of biocrude for the scenarios listed in Table 7. For each presented scenario, low- and high-availability of the ABB is evaluated, corresponding to biomass availabilities of 114 and 572 tons/day, respectively. Table 10 shows annual consumption of biomass and the capacity of the HTL facility for each scenario. The table also includes the yield of biocrude used in the process model. In the first scenarios 1 and 2, the cost of the feedstock is assumed to be zero. The inclusion of greater volumes of no-cost ABB (scenario 2) reduces the MFSP from $12.95/GGE to $7.34/GGE. The greater availability of ABB increases the plant capacity, resulting in favorable costs due to scale-up. For all scenarios, the plant scale is adjusted to match the maximum availability of ABB and farm-cultivated algae during months of peak productivity. The limited potential of ABB significantly impacts the processing scale and smaller scale plants are not as economically effective as the larger capacity plants that are modeled in the other scenarios, which incorporate additional biomass supplies. Scenarios 1 – 6 include the storage of algal biomass to maintain consistent, year-long production rates, while minimizing the utilization of woody biomass. Whereas in scenarios 7 and 8, no feedstocks are stored, and the supply is supplemented with woody biomass to match the plant capacity. The no-storage scenarios result in the greatest plant capacities, which result in the lowest estimated values for MFSP. From the investigated scenarios, scenario 7 results in the lowest MFSP of biocrude at the more conservative estimate for ABB availability.

In scenario 4, it is observed that the inclusion of more ABB does not reduce MFSP as might be expected when compared to scenario 3. In scenarios 3 and 4, the maximum processing capacity of the HTL facility is defined by the maximum summer productivity of the algae farm. During the seasons of reduced supply from the algae farm, the feedstock supply is supplemented with ABB or woody biomass. Despite the greater utilization of ABB in scenario 4, the biocrude yield from ABB is less than the biocrude yield from woody biomass. Although yield synergies have not been directly explored in this research, additive models for predicting biocrude are reasonably accurate (Jiang et al., 2019). The greater yield of biocrude in scenario 3 over scenario 4 is the primary factor for the reduced MFSP. Although feedstock cost is expected to influence significant changes in MFSP between the scenarios, the actual difference in feedstock costs between the two scenarios is 3%. For scenarios 3 and 4, the aggregate feedstock costs are $443 and $429 per ton, respectively.

In scenarios 5 and 6, the algal biorefinery operates using only algal feedstocks and supply from the algae farm and the ABB is stored to enable consistent supply throughout the year. The exclusion of woody biomass is the primary reason for the cost increase. The zero-cost assumption for the ABB helps to reduce feedstock costs but the reduced yield of biocrude from ABB negates the cost benefits. For scenarios 5 and 6, the aggregate feedstock costs are $635 and $501 per ton, respectively.

In scenarios 7 and 8, an optimized arrangement, similar to previous biorefinery designs (Zhu et al., 2023) omits the storage of algal biomass, but instead supplements the algal feedstock with woody biomass. During the summer and fall seasons, the algal supply is boosted by the availability of ABB. The optimized arrangement results in the lowest MFSP for biocrude for both low- and high-availability estimates of ABB. For scenarios 7 and 8, the aggregate feedstock costs are $410 and $314 per ton, respectively.

Figure 10 shows the calculated MFSP for fuels produced via HTL of algal feedstocks. The figure includes results from this year’s and previous years’ studies published by PNNL. The credits from the sale of co-products and recycled nutrients are also included. The reported costs from previous reports have been updated to the 2020 cost basis. The calculated MFSP for this report represents the finished fuel products produced from scenario 7, which is $6.26/GGE. Scenario 7 includes the processing of farm-cultivated algae, supplemented with woody biomass. To calculate the MFSP of fuel, assumptions from the 2022 report are incorporated into the analysis, which include the relevant costs of upgrading the HTL biocrude at a hydroprocessing facility that matches the scale of the HTL biorefinery (Zhu et al., 2023). The case study and MFSP results presented in the 2022 report are relatively similar with several key design elements and assumptions carried over from the 2022 study to the 2023 study. For example, in the 2022 report, the HTL facility is supplied by a 5,000-acre algae farm and incorporates the use of woody biomass. Examination of the individual cost categories between the 2022 and 2023 results shows a modest increase in the contribution for HTL production from $1.04 to $1.69/GGE. The cost increase for HTL production can be largely attributed to the increase in capital expenses to accommodate the redesign. Between 2022 and 2023, there is a slight decrease in the cost of the feedstock, resulting in contribution of $5.97 versus $5.19/GGE, respectively, to the total MFSP. Tabulated values from Figure 10 are included in Appendix A.

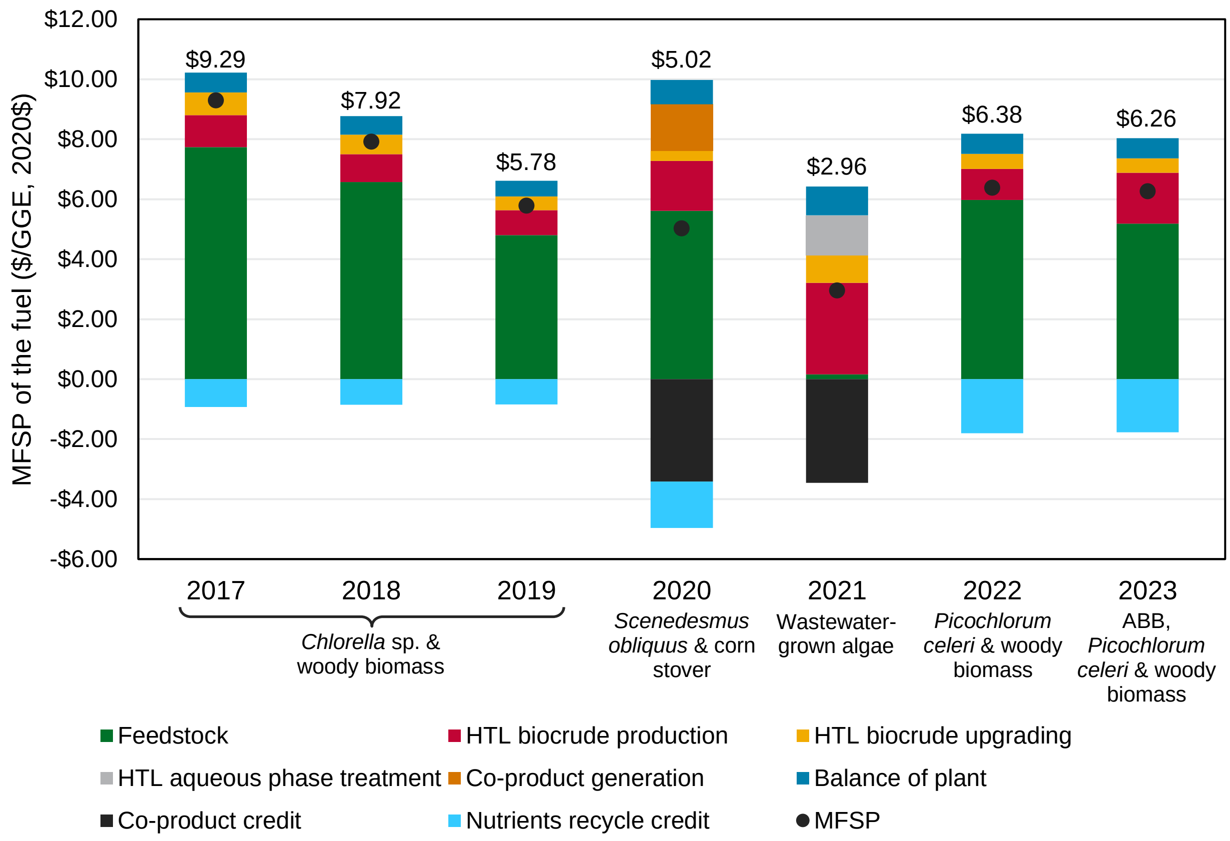

Figure 10. Results for the MFSP of fuel (Scenario 7 is the representative case for 2023)

A sensitivity analysis was completed to evaluate how certain parameters affected the MFSP of finished fuels for scenario 7, which represents the lowest MFSP using low-availability ABB. The results of the analysis are shown in Figure 11. The baseline MFSP is $6.26/GGE. Adjustments to the cost of feedstock price can have the highest impact to the MFSP. The cost of feedstock can also be reduced by utilizing a greater portion of ABB as a feedstock. The impacts associated with changes to the cost, composition, or yield outcomes from ABB are minimal because the ABB only represents a small portion of the feedstock used.

As discussed previously, a greater availability of ABB can reduce the MFSP. The cost of feedstock from the algae farm has a significant impact on the MFSP. However, the cost and composition of ABB feedstock does not appear to influence the MFSP, but the impact is lessened by the limited portion of ABB that is used in the process. The HTL process is most sensitive to fluctuations in the yield of biocrude produced from the farm-cultivated algae mainly because it is the majority feedstock. Increasing the yield of biocrude from the ABB does not show significant impact on the MFSP, but it is mainly because it contributes a small portion of the total feedstock supply. The impact of capital cost changes is typically a significant driver for MFSP. Ash content may not appear to have substantial sensitivity but may have a greater impact in scenarios where more ABB is utilized.

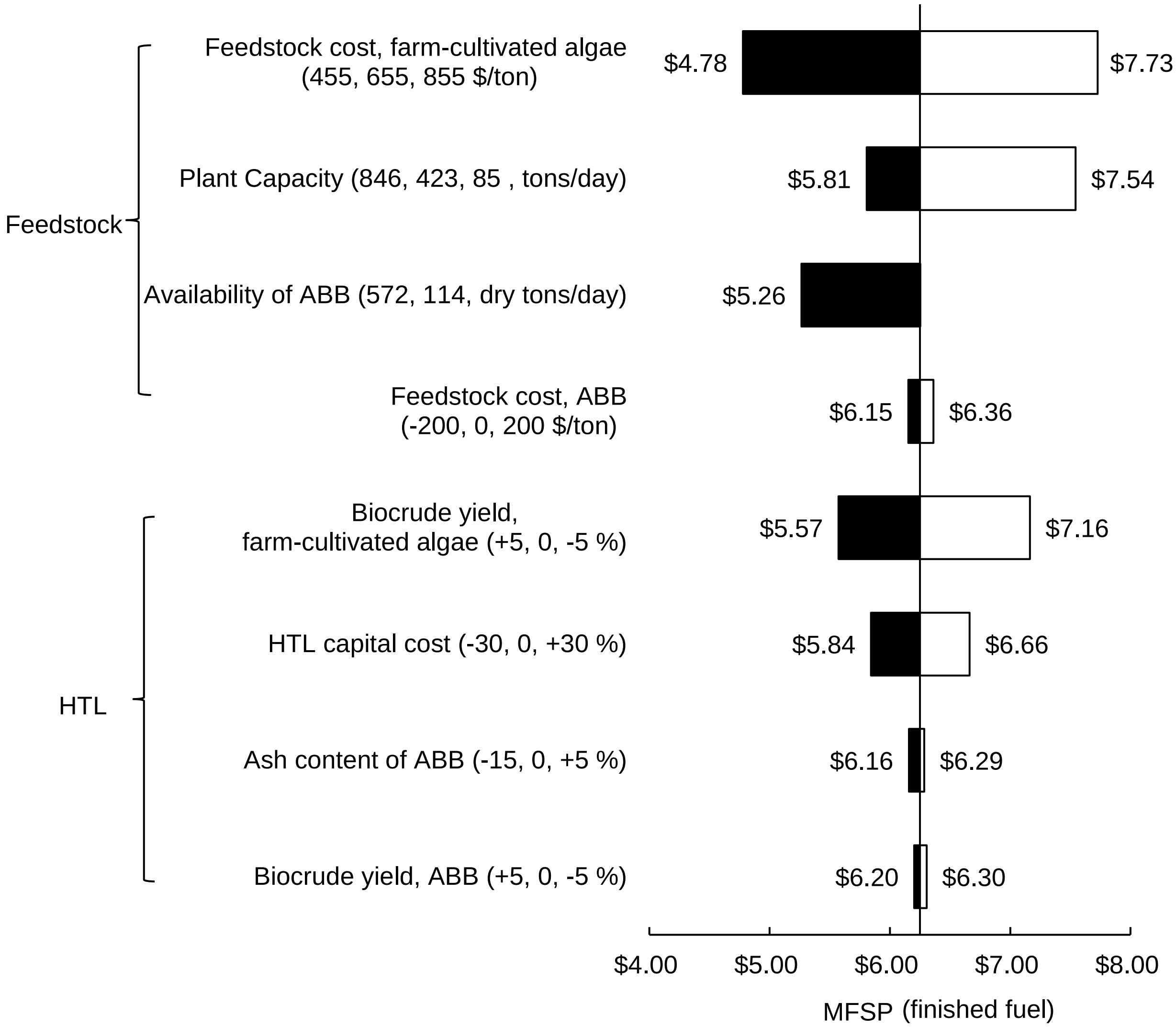

Figure 11. Sensitivity analysis for parameters related to the feedstock and the HTL process (scenario 7)

Another sensitivity analysis has been investigated for scenario 1, as shown in Figure 12, to examine how certain parameters affected the MFSP with ABB as the only feedstock. Although this design is not economically viable based on current data, the variance of some parameters may inform improvements for the process. The MFSP of HTL biocrude is greatly influenced by the size of the production plant and the availability of ABB feedstock. The upper limit of plant scale is assumed to be 1000 dry ton/d, which is roughly double the current highest availability of ABB. At this scale, the cost to produce biocrude could be as low as the costs for scenario 7. However, the availability of such a large quantity of ABB is uncertain. Similarly, longer algal bloom period (from 6 months to 9 months) also increased the ABB feedstock availability and reduced the MFSP.

Aside from the availability of ABB, the feedstock price is also a key factor. Although the base assumption is a zero-cost feedstock, it is possible that a tipping fee could be charged to the operators of the harvesting system. Alternatively, the operators may charge a price for the feedstock. ABB is typically landfilled, with tipping fees ranging $50 – $200 per ton.

Other factors such as the ash content, resulting biocrude yield, and HTL capital cost are also impactful to the MFSP. Lower ash and higher biocrude yield are ideal for fuel production. The sale price of the potential cement co-product has little influence on the MFSP. However, if the ash in the algae could be removed prior to HTL, it could reduce the size of HTL facility, saving both the capital expense for oversized equipment and energy consumption costs. Taken together, all the proposed improvements related to harvesting amounts, availability, and composition could increase the feasibility of a standalone facility for processing the biomass from algal blooms.

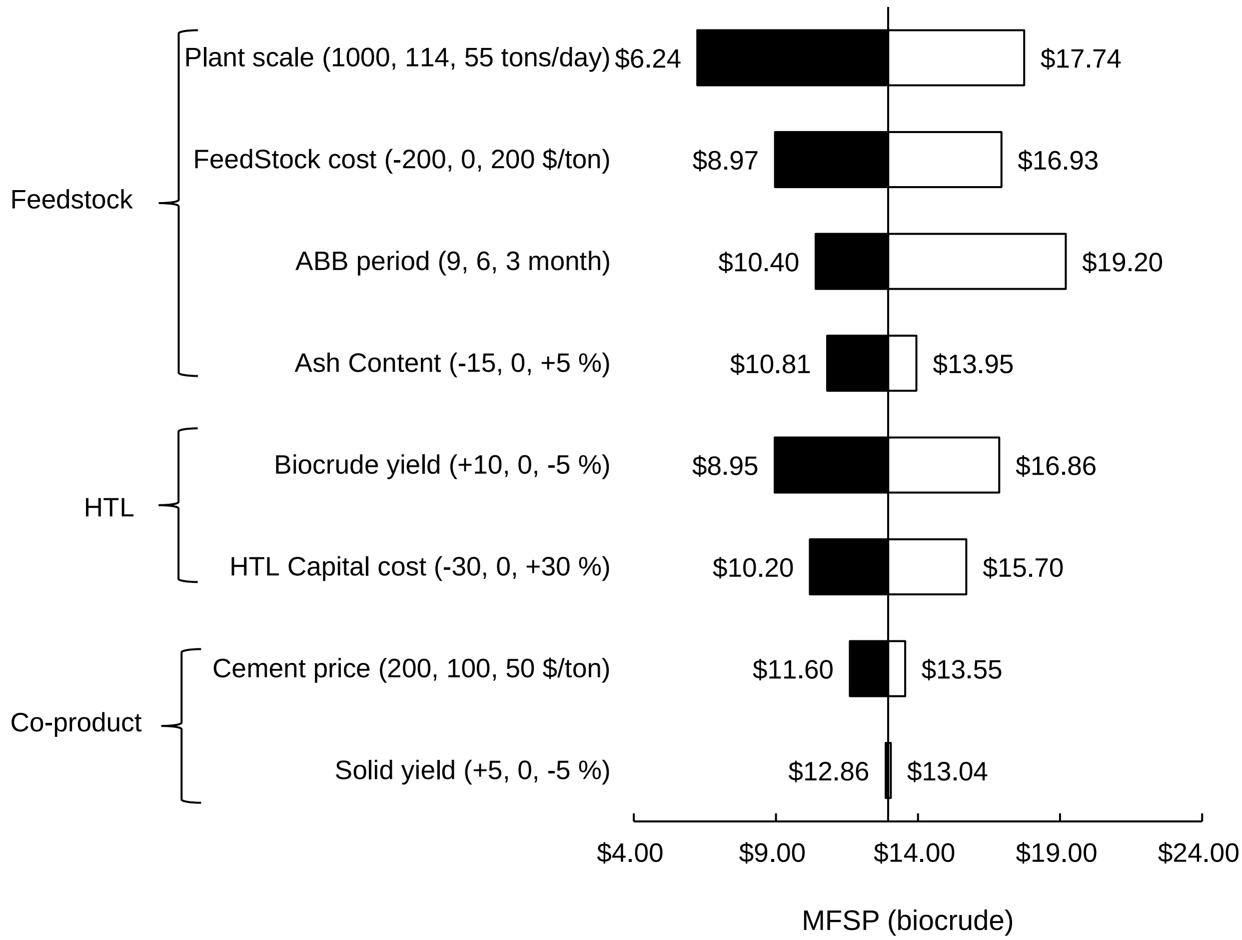

Figure 12. Sensitivity analysis for parameters related to the feedstock and the HTL process for ABB only (scenario 1).

4.2 Sustainable Fuel Credits

The U.S. government has implemented various programs to support the production and use of biofuels, recognizing their potential to reduce greenhouse gas emissions and promote energy independence. Financial incentives such as tax rebates, grants, loan guarantees, and research funding are essential to overcome the initial economic barriers faced by biofuel producers. Three potential incentives are considered to further reduce the MFSP of the fuels produced via HTL. The reduction in carbon intensity for the fuel was assumed from a previous analysis of HTL-produced, algae-derived fuels (Cai et al., 2023).

1. The Renewable Fuel Standard program has provided Renewable Identification Numbers (RINs) as credits for producers of renewable fuel products. Advanced biofuels produced from a non-corn, renewable biomass, with a 50% reduction of lifecycle GHG emissions can be assigned a D5 RIN code. The D5 RIN price is estimated from the 2020 annual average (EPA, 2023a) and amounts to a reduction in MFSP of $1.60/GGE.

2. The Biodiesel Production and Blending Tax Credit (BTC) provides producers of renewable diesel with a credit of $1.00 per gallon of diesel produced or used in blending (DOE, 2023c). A recent upgrade in the policy includes credits for the producers of sustainable aviation fuel (SAF) (NBAA, 2023). The adjusted value of the BTC is a reduction in MFSP of $0.91/GGE.

3. The low-carbon fuel standard (LCFS) in California provides incentives for fuels that achieve a reduction in carbon intensity in the lifecycle of the fuel. The carbon intensity of a fuel is measured in grams of carbon dioxide equivalent per megajoule of energy (gCO_2e/MJ). The credits are calculated based on the amount of equivalent emissions avoided per unit of energy compared to traditional fossil fuels (gasoline/diesel). The LCFS credit price was calculated from annual average price in 2020 (Neste, 2023). The reduction in carbon intensity for HTL-produced diesel was calculated in the 2022 Supply Chain Sustainability Analysis as 51% from the diesel baseline (Cai et al., 2023). The value of the LCFS credit was a reduction of $1.19/GGE from the MFSP.

The D5 RIN and LCFS credits are regarded as taxable income in the overall calculation. Taken altogether, the total MFSP could be reduced from $6.26/GGE to $2.56/GGE as Figure 13 shows, making it economically competitive against traditional fossil fuels.

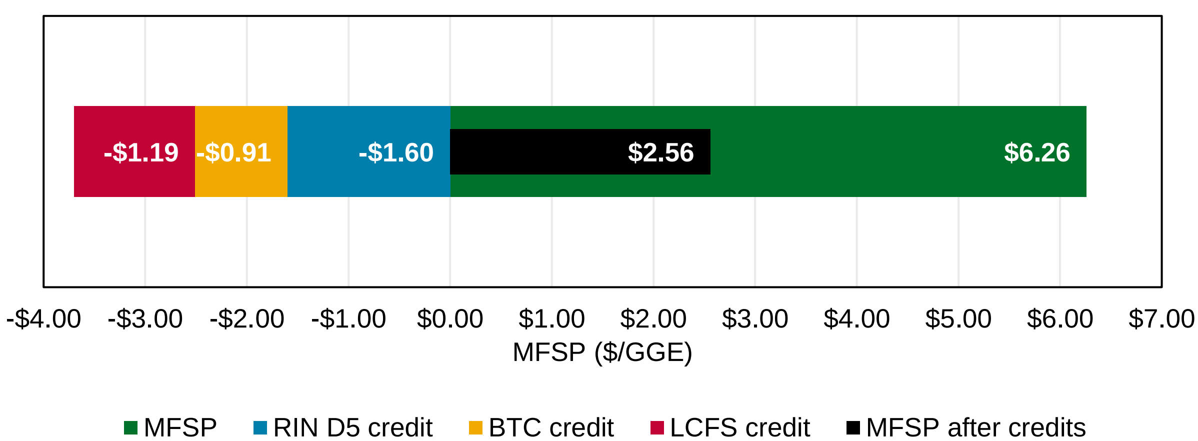

Figure 13. Value of credits applied to the MFSP for scenario 7.

4.3 Sustainability Metrics

Table 11 summarizes the sustainability metrics related to the conversion of biomass to fuels and co-products. The table includes the reported metrics from previous years for comparison. The sustainability metrics for scenario 7 are presented in the table. Based on the selected set of metrics for scenario 7, when compared against the results from 2022, there are no specific advantages for using ABB to supplement an algae farm. However, the results presented herein will be incorporated into a full life-cycle analysis to understand and quantify the potential sustainability benefits of using the ABB and presented in a future version of the Supply Chain Sustainability Analysis report (Cai et al., 2023). ABB has limited specific uses (e.g., land application as fertilizer) after harvesting, therefore the analysis presented herein provides an argument for value-added processing with the potential to offset fuels and other products.

Table 11. Sustainability metrics for the conversion of algal feedstocks to fuel and co-products.

Input	Units	2017	2018	2019	2020	2021	2022	2023
Feedstock flow rate								
Algae	ton/d AFDW	228	258	350	405	139	423	455
Non-algae biomass	ton/d AFDW	83	82	248	293	0	240	271
Total	ton/d AFDW	311	340	598	698	139	662	726
Fuel yield	GGE fuel/ton feedstock AFDW	104	115	106	78.7	73.4	83.2	81.3
Co-product yield	lb/ton feedstock AFDW	0	0	0	238	771	0	0
Nutrients recycle credits	lb/ GGE fuel	19.5	16.7	19.5	40.5	0	31.0	32.2
Natural gas consumption								
For fuel production	MMscf/y	419	475	822	1,069	72	923	1,100
For co-product generation	MMscf/y	0	0	0	631	0	0	
Total	MMscf/y	419	475	822	1,701	72	923	1,100
	scf/ton feedstock AFDW	4,078	4,228	4,160	7,387	1,574	4,343	4,724
	scf/GGE fuel	39.2	36.9	39.4	93.8	21.5	52.2	58.1
Makeup water	kg/GGE fuel	5.16	4.7	5.23	2.99	28.6	10.2	10.8
Electricity	kwh/GGE fuel	0.76	0.7	0.73	3.44	1.71	0.83	1.14
Carbon efficiency								
Fuel C/feedstock C	%	54	58	53	41	38	42	41
Fuel + co-product C/feedstock C	%	--	--	--	50	38	--	--
Overall carbon efficiency	%	48	51	47	32	36	37	36
Energy efficiency								
Fuel products/feedstock only	% HHV basis	65	70	64	55	46	50	52
Overall energy efficiency	% HHV basis	54	57	52	44	42	41	41

5.0 Conclusions and Future Work

For the 2023 business case study, the feasibility of using harvested ABB as an HTL feedstock was investigated. As a standalone feedstock, there is insufficient supply to support an economically feasible and standalone HTL facility. However, the feedstock should not be ignored as algal blooms have economic and environmental impacts on communities. The study herein shows that ABB can be best utilized as a supplemental feedstock for HTL processing. Co-processing via HTL at wastewater treatment facilities could also be economically viable. The ABB is processable via HTL but additional improvements are needed to boost biocrude yield and reduce the impacts of the excessive ash content. Harvesting of algal blooms is a recently introduced approach to managing blooms, so the availability of the of the feedstock is limited at present. However, if the harvesting approach is successful, HTL offers a valuable alternative to landfilling the ABB.

Future work for the advancement of HTL technology and the utilization of cost-advantaged algal feedstocks should include:

- Improving the estimate of biomass availability and understanding the near-term potential of ABB as a feedstock for HTL processing.

- Investigating the synergies impacting processing and economic outcomes when blending algal feedstocks with wastewater sludges for HTL processing via lab experiments and analysis.

- Coupling downstream processing models for ABB with upstream models and analyses for the removal and harvesting of ABB.

- Defining the impact of toxins and their fate during hydrothermal processing. Preliminary reports show the potential for toxin destruction, but more detail is needed (Gunderson, 2021).

- Demonstrating the application of HTL co-products, mainly aqueous and solids, as they are assumed to be used in the process models. That is, demonstrate the recycling of the aqueous and solids as cultivation nutrients or demonstrate the use of the solids as a cement additive.

6.0 References

AECOM (2022) "Intact Celluar Algae Harvesting with Simultaneous Nutrient Export in Lake Jesup to Mitigate Harmful Algal Blooms (HAB) and Reduce Nutrients. Technical Report prepared for St. Johns River Water Management District of Florida." AECOM Technical Services Inc.

AECOM (2023) "Deployment of Algae Harvesting to Improve Water Quality in Ohio. Technical Report prepared for the Ohio Department of Natural Resources." AECOM Technical Services Inc.

Arteaga, L., M. Pahlow and A. Oschlies (2016). "Modeled Chl:C ratio and derived estimates of phytoplankton carbon biomass and its contribution to total particulate organic carbon in the global surface ocean." *Global Biogeochemical Cycles* 30(12): 1791-1810. https://doi.org/10.1002/2016GB005458.

Cai, H., L. Ou, M. Wang, R. Davis, M. Wiatrowski, A. Bartling, B. Klein, D. Hartley, P. Burli, Y. Lin, M. Roni, D. N. Thompson, L. Snowden-Swan, Y. Zhu, S. Li, Y. Xu and P. Valdez (2023) "Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2022 State-of-Technology Cases." https://doi.org/10.2172/1963599.

CAWQMC, California Water Quality Monitoring Council (2023), "HAB Reports Map." https://mywaterquality.ca.gov/habs/where/freshwater_events.html. Accessed September 2023.

Chioccioli, M., B. Hankamer and I. L. Ross (2014). "Flow Cytometry Pulse Width Data Enables Rapid and Sensitive Estimation of Biomass Dry Weight in the Microalgae Chlamydomonas reinhardtii and Chlorella vulgaris." *PLOS ONE* 9(5): e97269. https://doi.org/10.1371/journal.pone.0097269.

Dahlin, L. R., A. T. Gerritsen, C. A. Henard, S. Van Wychen, J. G. Linger, Y. Kunde, B. T. Hovde, S. R. Starkenburg, M. C. Posewitz and M. T. Guarnieri (2019). "Development of a high-productivity, halophilic, thermotolerant microalga Picochlorum renovo." *Communications Biology* 2(1): 388. https://doi.org/10.1038/s42003-019-0620-2.

DOE, Department of Energy (2023a), "Bioenergy Technologies Office Multi-Year Program Plan 2023." https://www.energy.gov/sites/default/files/2023-03/beto-mypp-fy23.pdf. Accessed October 2023.

DOE, Department of Energy (2023b), "Pathways to Commercial Liftoff: Low-Carbon Cement." https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf. Accessed January 2024.

DOE, Department of Energy (2023c), "Biodiesel Production and Blending Tax Credit." https://afdc.energy.gov/laws/5831. Accessed October 2023.

Elliott, D. C., T. R. Hart, A. J. Schmidt, G. G. Neuenschwander, L. J. Rotness, M. V. Olarte, A. H. Zacher, K. O. Albrecht, R. T. Hallen and J. E. Holladay (2013). "Process development for hydrothermal liquefaction of algae feedstocks in a continuous-flow reactor." *Algal Research* 2(4): 445-454. https://doi.org/10.1016/j.algal.2013.08.005.

EPA, Environmental Protection Agency (2023a), "RIN Trade and Price Information." https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information. Accessed October 2023.

EPA, Environmental Protection Agency (2023b), "Cyanobacteria Assessment Network Application (CyAN app)." https://www.epa.gov/water-research/cyanobacteria-assessment-network-application-cyan-app. Accessed September 2023.

EPA, Envrionmental Protection Agency (2023c), "Cyanobacteria Assessment Network (CyAN)." https://qed.epa.gov/cyanweb/. Accessed September 2023.

EWG, Environmental Working Group (2023), "News Reports of Algae Blooms, 2010 to Present." https://www.ewg.org/interactive-maps/algal_blooms/map/. Accessed October 2023.

FDEP, Florida Department of Environmental Protection (2023a), "Algal Bloom Sampling Status." https://floridadep.gov/AlgalBloom. Accessed September 2023.

FDEP, Florida Department of Environmental Protection (2023b), "Freshwater Algal Blooms Frequently Asked Questions." https://floridadep.gov/sites/default/files/freshwater-algal-bloom-faqs_2019.pdf. Accessed September 2023.

Gunderson, K. (2021). "Effects of Hydrothermal Liquefaction on Algal Toxins from Harmful Algal Bloom". Master's Thesis, University of Illinois Urbana-Champaign.

Hartley, D. S., D. N. Thompson and H. Cai (2020) "Woody Feedstocks 2020 State of Technology Report." INL/EXT-20-59976-Rev000. https://doi.org/10.2172/1782211.

Heil, C. A. and A. L. Muni-Morgan (2021). "Florida's Harmful Algal Bloom (HAB) Problem: Escalating Risks to Human, Environmental and Economic Health With Climate Change." *Frontiers in Ecology and Evolution* 9: 646080. https://doi.org/10.3389/fevo.2021.646080.

Holm-Hansen, O. (1969). "Algae: Amounts of DNA and Organic Carbon in Single Cells." *Science* 163(3862): 87-88. https://doi.org/10.1126/science.163.3862.87.

Hu, W. (2014). "Dry weight and cell density of individual algal and cyanobacterial cells for algae research and development". Master's Thesis, University of Missouri-Columbia.

IHS (2020) "IHS CHEMICAL PEP YEARBOOK INTERNATIONAL." IHS Markit.

Jiang, Y., S. B. Jones, Y. Zhu, L. Snowden-Swan, A. J. Schmidt, J. M. Billing and D. Anderson (2019). "Techno-economic uncertainty quantification of algal-derived biocrude via hydrothermal liquefaction." *Algal Research* 39: 101450. https://doi.org/10.1016/j.algal.2019.101450.

Joung, S. H., C. J. Kim, C. Y. Ahn, K. Y. Jang, S. M. Boo and H. M. Oh (2006). "Simple method for a cell count of the colonial Cyanobacterium, Microcystis sp." *J Microbiol* 44(5): 562-565.

Klein, B. and R. Davis (2023) "Algal Biomass Production via Open Pond Algae Farm Cultivation: 2022 State of Technology and Future Research." NREL/TP-5100-85661. https://doi.org/10.2172/1984451.

Li, S., Y. Jiang, T. Seiple, L. Snowden-Swan, L. Ou, H. Cai, M. Thorson, B. Spry, A. Schmidt, U. Kilgore, E. Diaz, M. Santosa, H. Wang, T. Hart, S. Fox, D. Cronin, X. Fonoll Almansa, J. Norton, R. Gibby and B. Gibby (2024) "Site-specific Design Case Study for Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels." PNNL-37046. https://doi.org/10.2172/2481290.

McCurry, J. D. (2018) "Simulated Distillation Analysis of Middle Distillates Using the Accelerated ASTM D2887 Method." Agilent Technologies. https://www.agilent.com/cs/library/applications/application-distillation-astm-d2887-8890-gc-5994-0548en-agilent.pdf.

Mishra, S., R. P. Stumpf, B. A. Schaeffer, P. J. Werdell, K. A. Loftin and A. Meredith (2019). "Measurement of Cyanobacterial Bloom Magnitude using Satellite Remote Sensing." *Scientific Reports* 9(1): 18310. https://doi.org/10.1038/s41598-019-54453-y.

Myer, M. H., E. Urquhart, B. A. Schaeffer and J. M. Johnston (2020). "Spatio-Temporal Modeling for Forecasting High-Risk Freshwater Cyanobacterial Harmful Algal Blooms in Florida." *Frontiers in Environmental Science* 8: 581091. https://doi.org/10.3389/fenvs.2020.581091.

NASA, National Aeronatics and Space Administration (2023a), "Algae Bloom in Lake Okeechobee." https://earthobservatory.nasa.gov/images/151581/algae-bloom-in-lake-okeechobee. Accessed September 2023.

NASA, National Aeronautics and Spaca Administration (2023b), "Chlorophyll." https://earthobservatory.nasa.gov/global-maps/MY1DMM_CHLORA. Accessed October 2023.

NBAA, National Business Aviation Association (2023), "What Will the SAF Blenders Credit Mean for Operators?" https://nbaa.org/news/business-aviation-insider/2023-01/will-saf-blenders-credit-mean-operators/. Accessed October 2023

Neste (2023), "California Low Carbon Fuel Standard Credit price." https://www.neste.com/investors/market-data/lcfs-credit-price#4194b959. Accessed October 2023.

NOAA, National Oceanic and Atmospheric Administration (2023), "Harmful Algal Bloom Monitoring System." https://coastalscience.noaa.gov/science-areas/habs/hab-monitoring-system/. Accessed September 2023.

OEPA, Ohio Environmental Protection Agency (2023), "Harmful Algal Bloom (HAB) Monitoring." https://epa.ohio.gov/monitor-pollution/maps-and-advisories/harmful-algal-bloom-monitoring. Accessed October 2023.

Page, M. A., B. A. MacAllister, A. Urban, C. Veinotte, I. E. Macallister, K. L. Pokrzywinski, J. P. Riley, E. Martínez-Guerra, C. G. White, C. R. Grasso, A. M. Kennedy, C. C. Thomas, J. M. Billing, A. J. Schmidt, D. Levy, B. Colona, D. Pinelli and C. V. John (2020) "Harmful Algal Bloom Interception, Treatment, and Transformation System, “HABITATS” : pilot research study phase I - summer 2019." ERDC TR-20-1. https://www.erdc.usace.army.mil/Portals/55/CERL/HABITATS/HABITATS%20Pilot%20Reaserch%20Study-%20ERDC%20TR-20-1.pdf?ver=2020-06-23.

Schiffer, D. M. (1998) "Hydrology of central Florida lakes : a primer." US Geological Surey Circular 1137. https://fl.water.usgs.gov/PDF_files/c1137_schiffer.pdf.

Snowden-Swan, L. J., S. Li, Y. Jiang, M. R. Thorson, A. J. Schmidt, T. E. Seiple, J. M. Billing, D. M. Santosa, T. R. Hart, S. P. Fox, D. Cronin, K. Kallupalayam Ramasamy, D. B. Anderson, R. T. Hallen, X. Fonoll-Almansa and J. Norton (2022) "Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2021 State of Technology." https://doi.org/10.2172/1863608.

TetraTech (2022) "Assessment of Nutrient Management Technology Submission, Algae Harvesting Hydronucleation Flotation Technology (HFT)." H2Ohio Technology Assessment Program (TAP). https://h2.ohio.gov/wp-content/uploads/2022/09/H2Ohio-Technology-Assessment-Final-Report-Algae-Harvesting-HFT-Jan-2022.pdf.

Thomas, M. (2007) "Optimizing the Use of Fly Ash in Concrete." https://www.cement.org/docs/default-source/fc_concrete_technology/is548-optimizing-the-use-of-fly-ash-concrete.pdf.

Wiatrowski, M. R., B. Klein, C. Kinchin, Z. Huang and R. Davis (2022) "Opportunities for Utilization of Low-Cost Algae Resources: Techno-Economic Analysis Screening for Near-Term Deployment." NREL/TP- 5100-81780. https://doi.org/10.2172/1891269.

Zhang, H., J. Jia, S. Chen, T. Huang, Y. Wang, Z. Zhao, J. Feng, H. Hao, S. Li and X. Ma (2018). "Dynamics of Bacterial and Fungal Communities during the Outbreak and Decline of an Algal Bloom in a Drinking Water Reservoir." *Int J Environ Res Public Health* 15(2). https://doi.org/10.3390/ijerph15020361.

Zhu, Y., A. J. Schmidt, P. J. Valdez, L. J. Snowden-Swan and S. J. Edmundson (2022) "Hydrothermal Liquefaction and Upgrading of Wastewater-Grown Microalgae: 2021 State of Technology." PNNL-32695. https://doi.org/10.2172/1855835.

Zhu, Y., Y. Xu, A. J. Schmidt, M. R. Thorson, D. J. Cronin, D. M. Santosa, S. J. Edmundson, S. Li, L. J. Snowden-Swan and P. J. Valdez (2023) "Microalgae Hydrothermal Liquefaction and Biocrude Upgrading: 2022 State of Technology." PNNL-34032. https://doi.org/10.2172/1962867.

Appendix A – Details for the Process and Economic Models

Table A1. Summary of production costs for algae HTL from 2017 to 2023.

Production cost breakdown, $/GGE ($2020)	2017	2018	2019	2020	2021	2022	2023
Feedstock	$7.74	$6.57	$4.80	$5.61	$0.16	$5.97	$5.19
HTL biocrude production	$1.06	$0.93	$0.83	$1.67	$3.05	$1.04	$1.69
HTL biocrude upgrading to finished fuels	$0.76	$0.65	$0.46	$0.33	$0.92	$0.50	$0.48
HTL aqueous phase treatment	$0.00	$0.00	$0.00	$0.00	$1.33	$0.00	$0.00
Co-product generation	$0.00	$0.00	$0.00	$1.56	$0.00	$0.00	$0.00
Balance of plant	$0.66	$0.62	$0.53	$0.81	$0.96	$0.67	$0.67
Co-product credit	$0.00	$0.00	$0.00	-$3.41	-$3.46	$0.00	$0.00
Nutrients recycle credit	-$0.93	-$0.85	-$0.84	-$1.55	$0.00	-$1.80	-$1.77
Minimum fuel selling price (MFSP)	$9.29	$7.92	$5.78	$5.02	$2.96	$6.38	$6.26

Table A2. Parameter assumptions for the economic model

Parameters	**Value**
Internal rate of return	10%
Plant financing debt/equity	60% / 40% of total capital investment
Term for debt financing	10 years
Interest rate for debt financing	8% annually
Plant life	30 years
Income tax rate	21%
Working capital cost	5% of fixed capital investment
Depreciation schedule	7 years
Construction period	3 years (8% 1st yr, 60% 2nd yr, 32% 3rd yr)
Startup time	6 months
On-stream factor	90%
Total indirect cost	55% of total direct cost
Cost year	2020 US$

Table A3. Detailed costs and process parameters

Processing Area Cost Contributions & Key Technical Parameters	Metric	2017	2018	2019	2020	2021	2022	2023
Cost Year	year	2020	2020	2020	2020	2020	2020	2020
Fuel Selling Price	$/GGE	$9.29	$7.92	$5.78	$5.02	$2.97	$6.38	$6.26
Conversion Contribution	$/GGE	$1.55	$1.35	$0.97	-$0.59	$2.97	$0.41	$1.08
Production Diesel	mm GGE/yr	7.1	8.9	13.7	12	2.4	9.3	9.9
Production Sustainable Aviation Fuel (SAF)	mm GGE/yr	0.0	0.0	0.0	0.0	0.0	5.0	5.3
Production Naphtha	mm GGE/yr	3.6	4.0	6.6	6.3	1.0	3.4	3.7
Diesel Yield (AFDW feedstock basis)	GGE/US ton feedstock	69	79	70	51	52	42	41
SAF Yield (AFDW feedstock basis)	GGE/US ton feedstock	0	0	0	0	0	25	25
Naphtha Yield (AFDW feedstock basis)	GGE/US ton feedstock	35	36	33	27	22	16	15
Diesel Yield (areal basis)	GGE/acre-yr	1,416	1,771	2,746	2,365	6,705	1,850	1,981
SAF Yield (areal basis)	GGE/acre-yr	0	0	0	0	0	997	1,068
Naphtha Yield (areal basis)	GGE/acre-yr	724	800	1,310	1,261	2,804	687	735
Co-product Yield (AFDW feedstock basis)	lb /lb feedstock	0	0	0	0.12	0.39	0.00	0.00
Natural Gas Usage-drying (AFDW feedstock basis)	scf/US ton feedstock	0	0	0	0	0	0	0
Natural Gas Usage-HTL, H2 gen, bioprocessing (AFDW feedstock basis)	scf/US ton feedstock	4,078	4,228	4,085	7,387	1,574	4,343	4,323
Carbon efficiency, C in fuels/C in feedstock	%	54%	58%	53%	41%	38%	42%	41%
Carbon efficiency, C in co-products/C in feedstock	%	0%	0%	0%	10%	0%	0%	0%
Feedstock								
Total Cost Contribution	$/GGE fuel	$7.74	$6.57	$4.80	$5.61	$0.00	$5.97	$5.19
Feedstock Type		*Algae with wood supplement*	*Algae with wood supplement*	*Algae with wood supplement*	*Algae with corn stover supplement*	*Algae grown in wastewater*	*Algae with wood supplement*	*Algae with ABB & wood supplement*
Feedstock Cost (AFDW basis)	$/US ton feedstock	$745	$695	$456	$408	$0	$446	$696
Algae storage								
Total Cost Contribution	$/GGE fuel	$0.00	$0.00	$0.00	$0.00	$0.16	$0.00	$0.00
Capital Cost Contribution	$/GGE fuel	$0.00	$0.00	$0.00	$0.00	$0.09	$0.00	$0.00
Operating Cost Contribution	$/GGE fuel	$0.00	$0.00	$0.00	$0.00	$0.07	$0.00	$0.00

Table A3. Detailed costs and process parameters (continued)

Processing Area Cost Contributions & Key Technical Parameters	Metric	2017	2018	2019	2020	2021	2022	2023
HTL Biocrude Production								
Total Cost Contribution	\$/GGE fuel	\$1.06	\$0.93	\$0.83	\$1.67	\$3.05	\$1.04	\$1.69
Capital Cost Contribution	\$/GGE fuel	\$0.62	\$0.55	\$0.52	\$0.62	\$1.54	\$0.65	\$1.10
Operating Cost Contribution	\$/GGE fuel	\$0.44	\$0.38	\$0.31	\$1.06	\$1.51	\$0.39	\$0.60
Liquid Hourly Space Velocity (LHSV)	h^{-1}	4.0	4.0	4.0	Stage I: 4; Stage II: 3.5	4.0	4.0	4.0
HTL Carbohydrate Extraction	%, extracted/ carbohydrate in feedstock	0%	0%	0%	58%	0%	0%	0%
HTL Biocrude Yield (AFDW)	lb /lb feedstock	0.41	0.45	0.41	0.30	0.29	0.33	0.32
HTL Biocrude Upgrading to Finished Fuels								
Total Cost Contribution	\$/GGE fuel	\$0.76	\$0.65	\$0.46	\$0.33	\$0.92	\$0.50	\$0.48
Capital Cost Contribution	\$/GGE fuel	\$0.33	\$0.30	\$0.25	\$0.19	\$0.43	\$0.28	\$0.27
Operating Cost Contribution	\$/GGE fuel	\$0.43	\$0.35	\$0.21	\$0.14	\$0.49	\$0.22	\$0.21
Mass Yield on dry HTL Biocrude	lb/lb biocrude	0.81	0.82	0.81	0.83	0.82	0.79	0.79
HTL Aqueous Phase Treatment								
Total Cost Contribution	\$/GGE fuel	\$0.00	\$0.00	\$0.00	\$0.00	\$1.33	\$0.00	\$0.00
Capital Cost Contribution	\$/GGE fuel	\$0.00	\$0.00	\$0.00	\$0.00	\$0.50	\$0.00	\$0.00
Operating Cost Contribution	\$/GGE fuel	\$0.00	0.00	0.00	0.00	\$0.83	\$0.00	\$0.00
Bioprocessing for Co-product Generation								
Total Cost Contribution	\$/GGE fuel	\$0.00	\$0.00	\$0.00	\$1.56	\$0.00	\$0.00	\$0.00
Capital Cost Contribution	\$/GGE fuel	\$0.00	\$0.00	\$0.00	\$0.71	\$0.00	\$0.00	\$0.00
Operating Cost Contribution	\$/GGE fuel	\$0.00	0.00	0.00	0.85	0.00	0.00	\$0.00
Fermentation Productivity	g/L-hr	0	0	0	0.46	0	0	0
Fermentation Process Yield	g product/ g extracted carbohydrates	0	0	0	0.37	0	0	0
Balance of Plant								
Total Cost Contribution	\$/GGE fuel	\$0.66	\$0.62	\$0.53	\$0.81	\$0.96	\$0.67	\$0.67
Capital Cost Contribution	\$/GGE fuel	\$0.32	\$0.31	\$0.26	\$0.45	\$0.54	\$0.34	\$0.33
Operating Cost Contribution	\$/GGE fuel	\$0.34	\$0.31	\$0.27	\$0.36	\$0.42	\$0.33	\$0.34
Co-product Credits	\$/GGE fuel	\$0.00	\$0.00	\$0.00	-\$3.41	-\$3.46	\$0.00	\$0.00
Nutrient Recycle Credits	\$/GGE fuel	-\$0.93	-\$0.85	-\$0.84	-\$1.55	\$0.00	-\$1.80	-\$1.77

Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354

1-888-375-PNNL (7665)

www.pnnl.gov