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PNNL-29861

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U.S. DEPARTMENT OF ENERGY

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Summary

The fiscal year (FY) 2019 State of Technology (SOT) Assessment for a microalgae and woody biomass blend feedstock hydrothermal liquefaction (HTL) and biocrude upgrading system has been completed and reported here. This study is a preliminary economic analysis for this system. Inputs from the 2019 NREL open pond algae cultivation model provided microalgae seasonal flowrates and dewatered algae feedstock price. These inputs have been coupled with modeled experimental data from PNNL for algae/wood blends processed via HTL to assess the cost impacts, namely reduced capital and operating cost, as shown in the table below.

Change	Effect	Reason
Increase of the conversion throughput from 340 to about 598 U.S. tons/d ash free dry weight (AFDW)	Capital cost reduction through economies of scale	Higher Summer algal productivity than FY18 SOT based on NREL's inputs; lower productivity seasons (Winter, Fall and Spring) are brought up to Summer maximum rate with wood
Feedstock cost adjustment	Reduced feedstock cost by 34% at per ton AFDW basis	Lower algae feedstock cost; higher wood feedstock blend ratios from 24% in FY18 to 41% in FY19, which leads to lower blended feedstock cost
Hydrotreating guard bed liquid space hourly velocity (LHSV) improvement	15% reduction in cost of the HTL biocrude hydrotreating process (without including impacts of economies of scale and wood feedstock blend ratio)	HT guard bed LHSV increase leads to lower equipment and catalyst cost

These changes result in a 28% reduction in the conversion cost only from \$1.22/gge in 2018 to \$0.88/gge in 2019.

Acronyms and Abbreviations

AFDW	Ash free dry weight
ANL	Argonne National Laboratory
ASU	Arizona State University
FY	fiscal year
HT	hydrothermal
HTL	hydrothermal liquefaction
LCI	life-cycle inventory
MBSP	Minimum Biomass Selling Price
MFSP	minimum fuel selling price
MHTL	modular HTL
MHTLS	modular HTL system
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
SCSA	Supply Chain Sustainability Analysis
SOT	State of Technology
TEA	techno-economic analysis

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1.0 Background

Figure 1 shows the block flow diagram for algae/wood blend feedstock conversion via hydrothermal liquefaction (HTL) and biocrude upgrading system investigated in this study. Conversion comprises all processes inside of the dashed line boundary in Figure 1. In the modeled commercial-scale plant, algae blended with waste woody biomass slurry is pumped to the HTL reactor. Condensed phase liquefaction then takes place through the effects of time, heat and pressure. The resulting HTL products (oil, solid, aqueous, gas) are separated and the HTL biocrude is hydrotreated to form diesel and some naphtha range fuels. The HTL aqueous phase is recycled directly to the algae farm. For the balance of the modeled costs, process off gas is used to generate hydrogen, heat and power. A hydrogen plant is included for hydrotreating, which is assumed to be co-located with the algae ponds and HTL conversion. Nutrients recovered from HTL solids are recycled to the pond along with the HTL aqueous phase, hydrotreating aqueous effluent, and carbon dioxide containing flue gas to provide most of the required nutrients for algae growth.

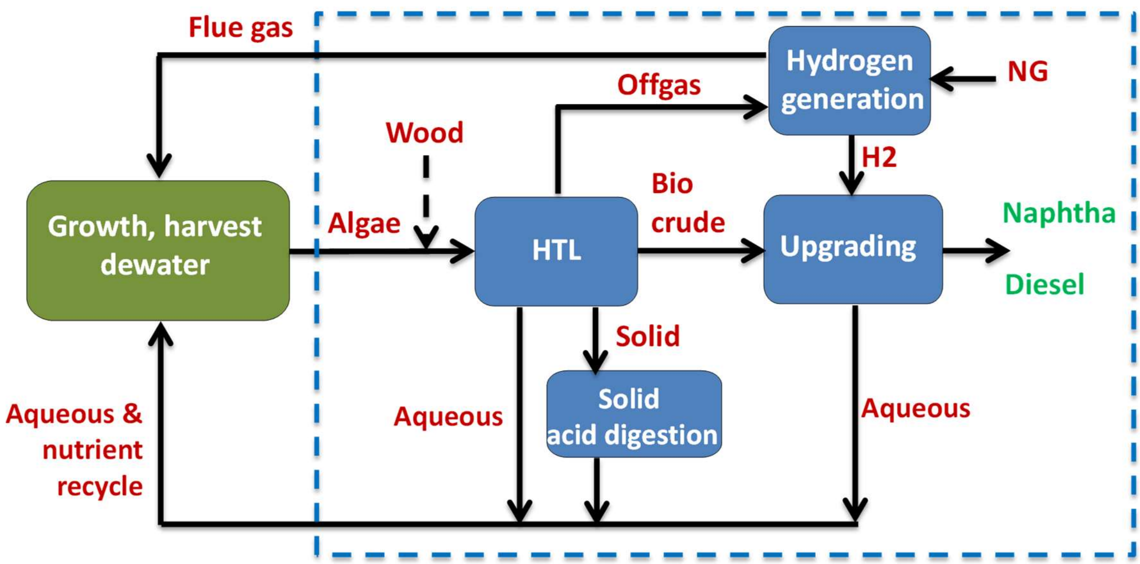

Figure 1. Algae/wood blend feedstock HTL and upgrading block diagram.

In the conversion model, the direct recycle of the HTL aqueous phase and the digestate from HTL solids digestion back to algae farm is assumed (Zhu et al. 2019). The algae ponds are assumed to behave like a bioreactor, where compounds in the recycle stream containing nutrient elements (e.g., N, P, and C) are biodegraded naturally and become available for algal growth. This reduces algae cultivation and HTL aqueous phase treatment costs. Recent studies focused on recycling the algae HTL aqueous phase for algae cultivation concluded that this offers a promising route to reducing nutrient demand (Alba et al. 2013; Bagnoud-Velásquez et al. 2015; Biller et al. 2012; Du et al. 2012). Pacific Northwest National Laboratory (PNNL) researchers have conducted lab-scale semi-continuous cultivation testing by using the recycled HTL aqueous from HTL testing (Edmundson et al. 2017). The test results demonstrated that algae productivity in a medium with the HTL recycled stream was not statistically different than that in a control medium. Therefore, the bioavailability of the recycled N and P from algae HTL has been verified. Verification of the viability of recycling nutrients for blended feeds still needs to be done. For now, it is assumed to be feasible. Nutrient credits were also assumed for carbon dioxide from flue gases and recycled wastewater from hydrotreating. In future years, feasibility of recycling wastewater from hydrotreating needs to be verified.

2.0 Research-Derived Improvements in Fiscal Year 2019

The fiscal year (FY) 19 research efforts for HTL and hydrotreating are described in this section.

2.1 HTL

The major improvement for HTL testing work in FY19 is using a modular HTL system (MHTLS) for engineering-scale algae/wood blended feedstock HTL conversion. Comparing to the bench-scale system used in previous experimental work, the MHTL system features larger flow rates and thus allows testing with line velocities more closed to pilot- and commercial-scale plants. The MHTLS consists of the following major operational areas: feed preparation and delivery, HTL conversion, products separation and storage (Lowry and Wagner 2015). Table 1 listed the major testing results of FY19 and FY18 MHTLS and selected pervious bench-scale testing results with algae only and algae/wood blended feedstock. As shown in the table, the MHTLS has higher feed flow rate, 12 L/h, than the preciously used 2 to 4 L/h bench-scale systems. It is also operated for longer periods of time, 16 to 85 hours, compared to 0.7 and 4 hours for the bench-scale testing. For algae/wood blended feedstock, the MHTLS-08 in FY19 has lower biocrude yield than the blend-scale testing AGChlr-03 in FY17. The reason is believed to be a result of poor biocrude/aqueous phase separation and solid filter issues experienced in the MHTLS operation. The efforts of improving biocrude recovery from HTL products stream in the MHTLS is still ongoing. Comparing to FY18 MHTLS testing using 100% algae as the feedstock, the MHTLS testing work in FY19 demonstrated and verified that an engineering-scale HTL system can effectively convert algae/wood blended feedstock to biocrude in a continuous mode. The blended feedstock biocrude is expected to have a high viscosity and shear strength than that from algae alone. Also, the resulting product biocrude will be denser than water and have a viscosity significantly higher than biocrude generated from 100% algae.

The engineering scale HTL testing allows higher feed flow rates, which is more representative for pilot or commercial scale, compared to previous bench-scale testing. In addition, this test provides an opportunity to adjust and improve both the feeding step, pressure letdown and the products separation steps. Therefore, the MHTLS testing provided reliable design and operating basis for a commercial-scale algae HTL plant design and techno-economic analysis (TEA).

Table 1. Experimental data of MHTL system and bench-scale HTL conversion.

Time Period		2018 - 2019	2017 - 2018		2016 - 2017	
Run ID	Units	MHTLS-08	MHTLS-03	MHTLS-06	AGChlr-02	AGChlr-03
Testing scale		Engineering	Engineering	Engineering	Bench	Bench
Volume of feed Slurry processed	L	193	360	970	8	1.3
Reactor type		PFR[1]	PFR	PFR	PFR	PFR
HOS	hour	16	30	85	4.0	0.7
Reactor Temperature	°C	345	347	341	340	345
Pressure	psig	2800	2833	2820	2953	2980
Volume at temp	L	3	3	3	0.5	0.5
Feed rate	L/h	12	12	12	2	2
LHSV [2]	L/L/h	4	4	4	4	4
Feedstock		50%/50% *Chlorella*/ wood	100% *Chlorella*	100% *Chlorella*	100% *Chlorella*	50%/50% *Chlorella* / wood
Density of feed	g/ml @20°C	1.09	1.05	1.07	1.06	1.06
Mass of wet feed	kg	211	378	1043	8.5	1.4
Total solids in feed	wt%	16.3%	18.3%	22.8%	22.1%	16.3%
Ash in dry feed	wt%	6.84%	14.3%	14.5%	14.1%	9.6%
Solids in slurry feed	wt%, AFDW [3]	15.3%	16%	19.5%	19.0%	14.7%
Mass yields (AFDW, normalized)						
Biocrude	g_{oil}/g_{feed}	32%	38%	37%	43%	46%
Aqueous	$g_{aqueous}/g_{feeed}$	43%	46%	n/a	36%	41%
Gas	g_{gas}/g_{feed}	22%	12%	n/a	17%	12%
Solid	g_{solid}/g_{feed}	2.9%	4.5%	n/a	4%	2.3%
Carbon yields (AFDW, normalized)						
C-Oil yield	%	59%	56%	53%	60%	66%
C-Water yield	%	22%	32%	29%	25%	24%
C-Gas yield	%	14%	5.9%	7.2%	8.1%	5.9%
C-Solid yield	%	5.4%	5.8%	11%	6.9%	3.6%
Biocrude compositions, dry basis						
Carbon	wt%	80%	79%	78%	79%	80%
Hydrogen	wt%	8.5%	10%	10%	11%	9.4%
Oxygen	wt%	7.5%	5.7%	5.9%	3.7%	5.8%
Nitrogen	wt%	3.2%	5.2%	5.3%	5.5%	3.8%
Sulfur	wt%	0.24%	0.68%	0.59%	0.61%	0.24%
Biocrude properties						
H:C	mol ratio, dry	1.3	1.5	1.5	1.6	1.4
Higher heating value	MJ/kg	34	36	36	40	39
TAN	Mg KOH/g oil	57	60	49	53	56

Time Period		2018 - 2019		2017 - 2018	2016 - 2017	
Density [4]	g/ml@40°C	1.04	0.98	0.97	0.96	1.05
Viscosity [4]	cSt@40°C	9,950	921	180	295	3,241
Moisture	wt%	4.8%	4.9%	6.8%	12.0%	6.3%
Ash	wt%	0.19%	0.48%	0.30%	0.47%	0.25%
Filterable solids	wt%, wet	0.36%	0.66%	0.07%	0.36%	0.26%
Note: [1] PFR = plug flow reactor; [2] LHSV = liquid hourly space velocity; [3] AFDW = ash free dry weight; [4] Density and viscosity for MHTLS-03 and 08 measured at 20°C.						

Another important HTL testing work in FY19 is two-stage sequential HTL conversion of algae and high through-put screening tests for algae/wood blended and wood only feedstock. The purpose of the testing is to investigate a potential way to achieve lower algae HTL and upgrading system cost via high value byproduct generation from the aqueous phase. A simplified block diagram for the sequential two-stage HTL experimental work is shown in Figure 2. The algae slurry containing 10 wt% algae feedstock (dry ash free) was pumped and preheated and then sent to the first stage HTL reactor. In this reaction step, algae were partially converted to solid and aqueous phase. The product stream was filtered, and the filtered wet solid has about 25 wt% dry ash free mass. The first stage aqueous phase is available for byproduct generation by converting carbohydrates in the stream to high value byproducts. The filtered wet solid is further pumped to high pressure and heated. The heated wet solid flow is then sent to the second stage HTL reactor. In this step, the solid from the first stage is converted to biocrude, aqueous, gas and solid products. In FY19, testing with different combinations of experimental conditions, including first stage temperature, space velocity and feedstock types, were conducted.

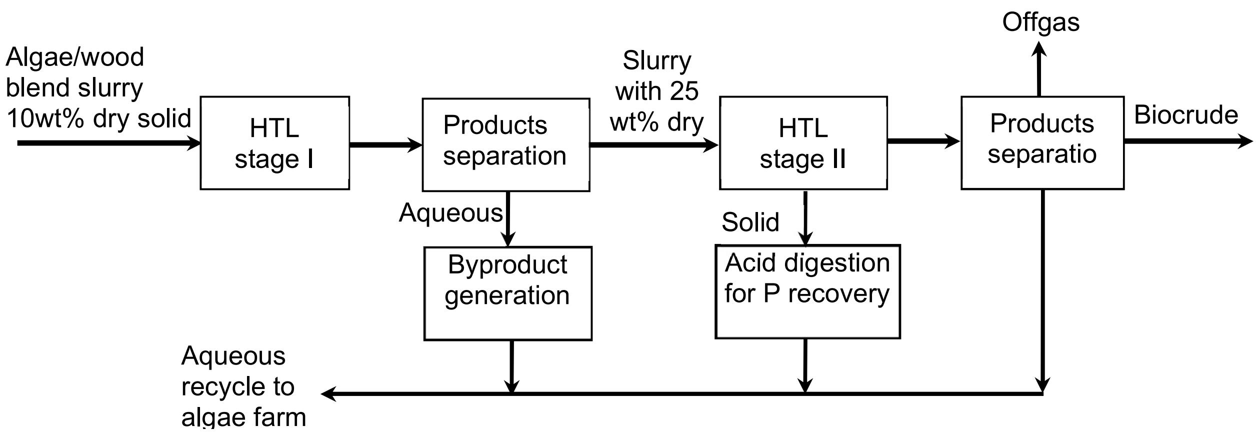

Figure 2. Simplified block diagram of two-stage sequential HTL process.

2.2 Hydrotreating

The FY19 HTLS biocrude hydrotreating testing (MHTLS-08) data are listed in Table 2. Compared to algae only HTL biocrude which needs pretreatment to remove aqueous salts and water from the biocrude (MHTLS-03), no similar pretreatment for the biocrude from the algae/wood blended feedstock is needed. This was verified by both MHTL-08 and AGCHLR-03 biocrude hydrothermal (HT) testing for blended feedstock. In the pretreatment process, biocrude is dried at 150 °C to remove moisture and then passed through a 1 or 5 μm filter to remove particles. The purpose of the pretreatment is to prevent premature deactivation of the hydrotreating catalyst caused by salts in biocrude water and facilitate the use of higher activity catalysts. Compared to the algae-derived HTL biocrude, the algae/wood (50%/50%) blended feedstock derived HTL biocrude has much lower sodium, magnesium, iron and sulfur content, based on HTL experimental results. The reason is the woody biomass has much lower inorganic content than algae. The FY19 hydrotreating testing for MHTLS-08 explored the possibility of no pretreatment for biocrude upgrading. However, considering commercial applications with high requirements for operating reliability and 100% algae being used in the summer season, pretreatment is recommended for a commercial algae HTL plant. Therefore, the cost of pretreatment is still included in the FY19 TEA.

In the HT testing, the pretreated or unpretreated biocrude is processed through a guard bed to remove iron and thus prevent plugging in the downstream hydrotreater. 100% algae-based HTL biocrude typically has approximately 1,000 ppm iron and the 50%/50% algae/wood biocrude has roughly half that amount. With using a guard bed, the biocrude iron content can be decreased to approximately 10 ppm with over 99% iron removed.

In 2017 testing, $CoMo/Al_2O_3$ sulfided catalyst was used for both the guard bed and the hydrotreater bed. In 2018, the hydrotreater bed catalyst was changed to sulfided $NiMo/Al_2O_3$. In 2019, catalysts are the same as that in 2018 HT testing. The guard bed catalyst space velocity was increased from 0.25 in FY18 to 0.50 h^{-1} in FY19. The HT testing results demonstrated that the increase in guard bed space velocity does not significantly affect the HT oil yield. Therefore, this improvement in the HT process was employed in the FY19 State of Technology (SOT) case TEA study.

As show in Table 2, the HT oil from the blended feedstock biocrude (MHTLS-08 and AGCHLR-03) has higher density than that from 100% algae HTL biocrude, for both engineering scale HTL (MHTL-08) and bench-scale AGCHLR-03. Higher HT oil density is caused by using woody biomass, which leads to more heavy compounds in HTL biocrude. For MHTLS-03 100% algae biocrude, the HT oil mass yields are calculated based on pretreated biocrude, while the other HT testing results are based on unpretreated biocrude. Therefore, the HT mass yields differences between MHTLS-08 and MHTLS-03 mainly result from the calculation basis difference. The distillation curves (ASTM D2887) are shown in Figure 3. The HT oil from the MHTLS-08 has similar percentage of gasoline boiling point range products, but more heavy products than the MHTLS-03 pretreated biocrude. However, another blended feedstock HT oil (AGCHLR-03) has fewer heavy products than MHTLS-08 HT oil. These differences can come from difference feedstock, HTL processing scales, HTL biocrude compounds, with or without HT pretreatment. As the current testing for blended feedstock is still very limited, more experimental work is needed to answer these questions.

Table 2. Experimental hydrotreating data from MHTL and bench-scale HTL biocrude from algae only or algae/wood blended feedstock.

Time Period	Units	2018 - 2019	2017 - 2018	2016 - 2017
Biocrude feed		MHTLS-08 biocrude	MHTLS-03 pretreated biocrude	AGCHLR-03 biocrude
Feedstock to HTL		50%/50% *Chlorella* and wood	100% *Chlorella*	50%/50% *Chlorella* and wood
Biocrude properties				
Density	g/mL@20ºC	1.05	0.896	1.05
Viscosity	cSt@20ºC	9,950	294	3,241
Moisture	wt%	5.4	1.9	6.3
HT process conditions				
Pretreatment		No pretreatment	Acid washed, dehydrated and filtered	No pretreatment
Pressure	psia	1500	1500	1500
Temperature	ºC	400 (Main bed) 325 (Guard bed)	400 (Main bed) 325 (Guard bed)	400 (Main bed) 400 (Guard bed)
Guard bed catalyst		$CoMo/Al_2O_3$ sulfided	$CoMo/Al_2O_3$ sulfided	$CoMo/Al_2O_3$ sulfided
Guard bed LHSV	h^{-1}	0.50	0.25	0.25
Main bed catalyst		$NiMo/Al_2O_3$ sulfided	$NiMo/Al_2O_3$ sulfided	$CoMo/Al_2O_3$ sulfided
Main bed LHSV	h^{-1}	0.35 (0.25 to 0.75 tested)	0.35 (0.2 to 0.75 tested)	0.25
Total time-on-stream for run	h	288	262	169
Reason for run termination		Consumed all feed	Consumed all feed	Consumed all feed
HT oil product		MHTL-08 HT oil (LHSV = 0.35)	MHTL-03 HT oil (LHSV = 0.35)	AGCHLR-03 HT oil
Density	g/mL@20ºC	0.85	0.79	0.83
Viscosity	cSt@20ºC	4.36	3.05	2.31
Water	wt% (via KF)	0.02	<0.01	<0.4
TAN	mg KOH/g oil	Not determined	Not determined	Not determined
HT mass yields [1]				
Yield to organic	g/g dry biocrude	0.88	0.90	0.83
Yield to aqueous	g/g dry biocrude	0.16	0.07	0.20
Yield to gas	g/g dry biocrude	0.06	0.07	0.08
H_2 consumption	g H_2/g dry biocrude	0.06	0.06	0.05
HT oil composition, dry basis				
Carbon	wt%	86	84	87
Hydrogen	wt%	13	14	13
Oxygen	wt%	0.5	1.1	2.3
Nitrogen	wt%	0.8	0.5	0.1
Sulfur	wt%	0.04	NA	NA

Note: [1] HT mass yields are not normalized. Results for MHTLS-03 are based on pretreated dry biocrude and the aqueous phase yield does not include water removed in the pretreatment process.

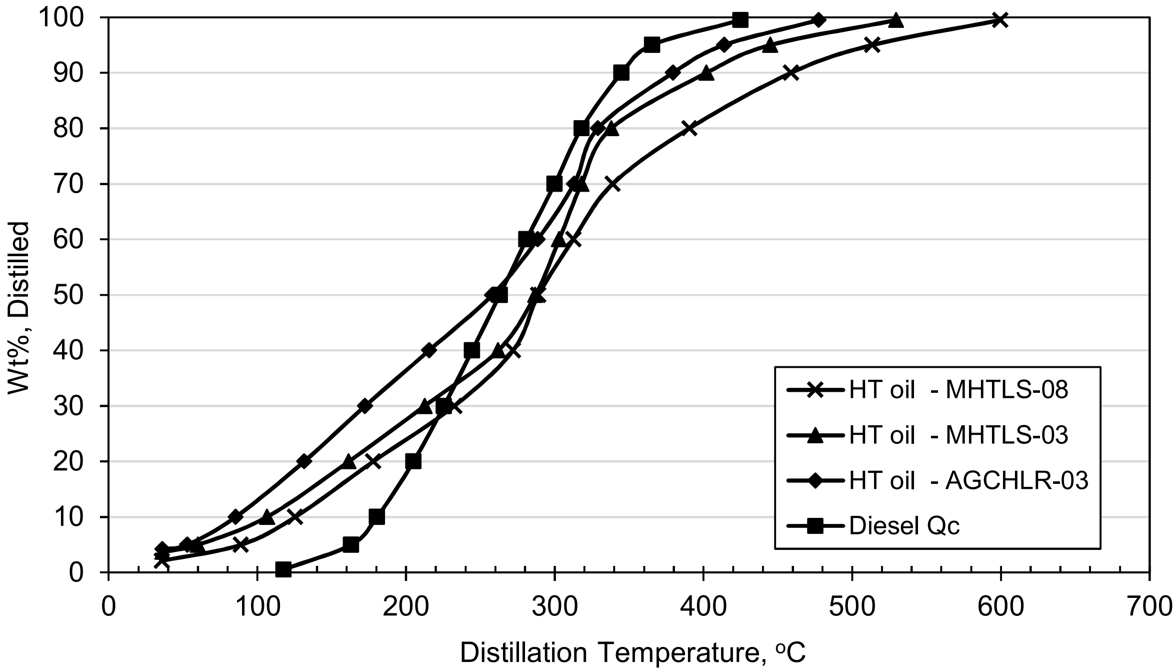

Figure 3. Distillation curves for hydrotreated oil from MHTL pretreated biocrude and bench scale unpretreated biocrude.

3.0 Process Simulation Inputs and Assumptions

3.1 Feedstock

FY19 seasonal flows to conversion for dewatered algae (20wt% solid, AFDW basis) and the associated Minimum Biomass Selling Price (MBSP) costs from National Renewable Energy Laboratory (NREL) are shown in Table 3. These flows are based on the low ash, high-carbohydrate *Scenedesmus* algae strain assumed in the NREL farm design and their CAP conversion model. The assumed NREL farm results are adapted for use with the algae composition actually processed during HTL research. Four cases are presented:

- Case 1: Unlined ponds at Arizona State University (ASU),
- Case 2: Lined ponds at ASU,
- Case 3: Unlined ponds at ASU with Florida algae evaporation, and
- Case 4: Lined ponds at ASU with Florida algae evaporation.

All four cases have the same algal productivities, while Cases 3 and 4 have slightly less algal biomass loss during dewatering. Therefore, Cases 1 and 2 result in the same flowrate of algae to conversion. The algae biomass production in FY19 has a higher annual average productivity, 16 $g/m^2/d$, than that for the FY18 SOT, which was 12 $g/m^2/d$. The FY19 SOT also has about 20% lower algae feedstock cost than that for FY18. The woody biomass feedstock cost is assumed to be $70.35/ton for dry forest residue feedstock based on inputs from Idaho National Laboratory, which is the same assumption used in the FY18 SOT. The blended feedstock cost is calculated linearly based on the blend mass ratios of algae and wood, and their individual feedstock cost.

Table 3. NREL FY19 SOT algal biomass seasonal productivity and MBSP encompassing growth, harvest and dewatering.

Cases	Summer	Fall	Winter	Spring	Annual Average	MBSP ($/ton AFDW, 2016$)
	Algae biomass to the conversion facility (AFDW) (kg/hr)					
Case 1	22,546	9,477	5,329	15,451	13,201	764
Case 2	22,546	9,477	5,329	15,451	13,201	961
Case 3	22,620	9,516	5,337	15,511	13,246	670
Case 4	22,620	9,516	5,337	15,511	13,246	866

Based on previous experimental results for algae/wood blend HTL, freshwater algae (*Chlorella*) results in the highest biocrude yield, is assumed to be the algae feedstock in the blend feedstock. Table 4 shows the elemental compositions for the algae and woody biomass used experimentally and in the process models. The feedstock assumptions are consistent with the FY18 assumption, i.e., waste wood being co-processed with algae during seasons of low algal productivity.

Table 4. Elemental composition for algal and woody feedstocks.

Elements, wt% ash free dry weight (AFDW)	Algae (*Chlorella*)	Woody biomass (forest residue) [1]
Carbon	53.8	50.0
Hydrogen	7.5	6.2
Oxygen	30.8	43.6
Nitrogen	7.2	0.2
Sulfur	0.6	0
Total	100	100
Ash, wt% dry basis	13.9	1.0
Phosphorus (in ash)	0.3	0

Note: [1] Woody biomass compositions at dry ash free basis were converted from dry basis data from PNNL HTL testing. Ash content is assumed to be 1% based on 2016 MYPP (U.S. DOE 2016).

There are some differences between the NREL farm model and the HTL SOT Cases and 2022 Target in terms of algae characteristics (Table 5). To maintain a consistent basis, the 2014 to 2016 HTL SOT conversion costs are based on experimental HTL and upgrading data from processing *Tetraselmis*. The 2017 to 2019 SOT is based on the best available experimental results for the freshwater algae (*Chlorella sp.*)/woody biomass blended feedstock HTL and biocrude upgrading.

Table 5. Algal elemental and biochemical compositions assumed in the SOT and target cases.

Elemental (AFDW wt%)	Algae assumed in NREL farm model	Actual strains used in HTL research		
SOT Time Period	2015-2022	2016	2017 to 2019	2025 and 2030 Projected
Carbon	54	49.5	53.8	59.4
Hydrogen	8.2	6.8	7.5	8.6
Oxygen	35.5	35.3	30.8	25.1
Nitrogen	1.8	6.4	7.2	5.5
Sulfur	0.2	2.1	0.6	0.7
Total	100	100	100	100
Component (dry wt%):				
Ash	2.4	22.0	13.9	13.0
Phosphorus (in ash)	0.22	0.5	0.3	0.7
Fermentable carbohydrates[1]	47.8	28.1	23.7	19.1
Other carbohydrates [2]	5	6.7	--	14.5
Protein	13.2	28.1	38.6	31.3
Lipids (fuel-relevant lipids as FAME)	27.4	5.0	--	17.4
Non-fuel polar lipid impurities [3]	2.7	6.8	23.7	3.4
Cell mass	1.6			
Total	100	97	100	99

Note: [1] For 2016 to 2018 HTL these are listed as "carbohydrates"; [2] For 2016 HTL these are listed as "other" and may include cell mass; for 2017 and 2018 HTL, total carbohydrates only were provided and listed under "Fermentable carbohydrates" in the table; [3] For 2017 and 2018 HTL, total lipid content only was provided and listed under "Non-fuel polar lipid impurities".

3.2 Process Simulation Assumptions

The major process inputs and assumptions for the blended algae/woody biomass HTL and upgrading system for FY19 SOT are listed in Table 6. For an algae/woody biomass HTL and upgrading model, the plant scale is sized to match the summer season algae flow rate, which is 596 ton/d (or 22,546 kg/h) for Cases 1 and 2 and 598 ton/d (or 22,620 kg/h) for Case 3 and 4, which is about 76% higher than the 340 ton/d of FY18 SOT. The algae feed rate differences between summer and the other seasons are made up by adding woody biomass. For each season, the blend ratio of algae-to-wood is varied based on the seasonal algae flow rate and the added woody biomass amount. The annual average blend ratio for algae-to-wood is 59/41 for FY19 SOT. Compared to FY18 with an algae/wood blend ratio at 76/24, the wood blend ratio of FY19 is higher and thus it leads to lower blended feedstock cost. The reason for higher wood blend ratio of FY19 results from the bigger seasonal algae production rates differences than that of FY18. Based on different seasonal blend ratios, the HTL biocrude yield, HT hydrocarbon yield, hydrogen consumption and other related parameters are specified based on best available experimental results for blended feedstock with different blend ratios. As seen in Table 6, because of the lower algae blend ratio (or higher wood blend ratio) for FY19, the HTL biocrude yield at an annual average basis is 0.41, which is lower than the 0.45 for FY18 with higher algae blend ratio. In addition, with more wood used in the blended feedstock, the hydrogen consumption per unit of biocrude for hydrotreated of FY19 SOT is also lower than the FY18 SOT with higher wood blend ratio.

Table 6. Key parameters assumptions for performance analysis.

Algae/woody biomass blends	Annual average	Summer	Fall	Winter	Spring
Feedstock, lb/h AFDW					
Cases 1 and 2					
Algae	29,103	49,706	20,894	11,748	34,063
Woody biomass	20,603	-	28,812	37,958	15,643
Total	49,706	49,706	49,706	49,706	49,706
Cases 3 and 4					
Algae	29,202	49,869	20,979	11,765	34,196
Woody biomass	20,667	0	28,890	38,104	15,673
Total	49,869	49,869	49,869	49,869	49,869
Blend wt% AFDW (all cases)					
Algae	59%	100%	42%	24%	67%
Woody biomass	41%	0	58%	76%	31%
HTL					
Biocrude yield, g/g AFDW feed	0.41	0.43	0.42	0.33	0.45
Hydrotreating					
Organic yield, g/g dry biocrude	0.85	0.87	0.84	0.82	0.86
H_2 consumption, g/g dry biocrude	0.048	0.046	0.052	0.038	0.057

4.0 FY19 SOT Modeled Costs

In this section, the major cost results are described and discussed.

4.1 Cost Results

The cost comparison between the FY17-19 SOTs and the 2025 target is shown in Table 7. To simplify the table, only the cases with algae feedstock from unlined ponds and Florida algae evaporation rates are shown. The detailed processing area cost contributions and key technical parameters for all cases are listed in Appendix A.

With lower algae feedstock cost and higher wood blend ratio, the 2019 SOT has a 27% lower blended feedstock cost than the 2018 SOT. The HTL biocrude production and balance of plant costs are also lower resulting from larger plant scale for the 2019 SOT. The conversion process improvement of 2019 SOT is the higher space velocity of the HT guard bed, which leads to $0.09/GGE decrease in the HT process cost. In addition, the higher wood blend ratio leads to higher HT guard bed catalyst life because iron in biocrude mainly comes from algae feedstock and so higher wood blend ratio leads to lower iron contents in biocrude. When combining other benefits from larger plant scale and higher wood blend ratio, the HT process cost of 2019 SOT is 29% lower than that of the 2018 SOT.

Table 7. Algae HTL SOT costs compared to target projection.

Production cost breakdown, $/gge ($2016)	2017 SOT	2018 SOT	2019 SOT	2025 Projected	2030 Projected
Feedstock	$6.66	$5.61	$4.10	$3.87	$3.14
Algae drying (summer & spring only)	$0.00	$0.00	$0.00	$0.11	$0.12
HTL biocrude production	$0.95	$0.84	$0.75	$0.47	$0.43
HTL biocrude hydrotreating to finished Fuels	$0.69	$0.59	$0.42	$0.23	$0.22
HTL aqueous phase treatment	$0.00	$0.00	$0.00	$0.66	$0.61
Balance of plant	$0.61	$0.57	$0.49	$0.28	$0.25
Nutrient recycle credits	-$0.86	-$0.78	-$0.78	-$0.32	-$0.32
Total	$8.05	$6.83	$4.98	$5.30	$4.45

Figure 4 graphically shows the total cost breakouts for each case shown in Table 7. The minimum fuel selling price (MFSP) for the FY19 SOT is approximately 27% lower than that of the FY18 SOT resulting from larger plant scale, lower feedstock cost, and improvement in HT process. Figure 5 shows the conversion cost only for each SOT case. The conversion cost only for FY19 SOT is 28% lower than that of FY18 SOT; the biggest contribution coming from the decrease in the HTL biocrude hydrotreating cost.

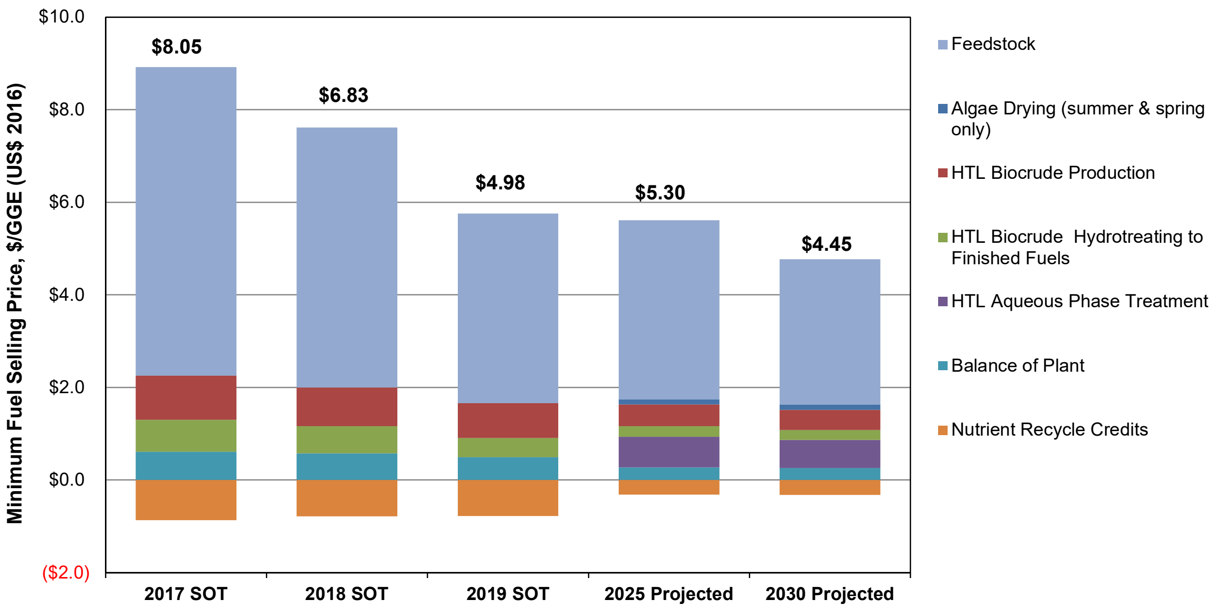

Figure 4. Algae/wood blend feedstock HTL and biocrude upgrading cost allocations.

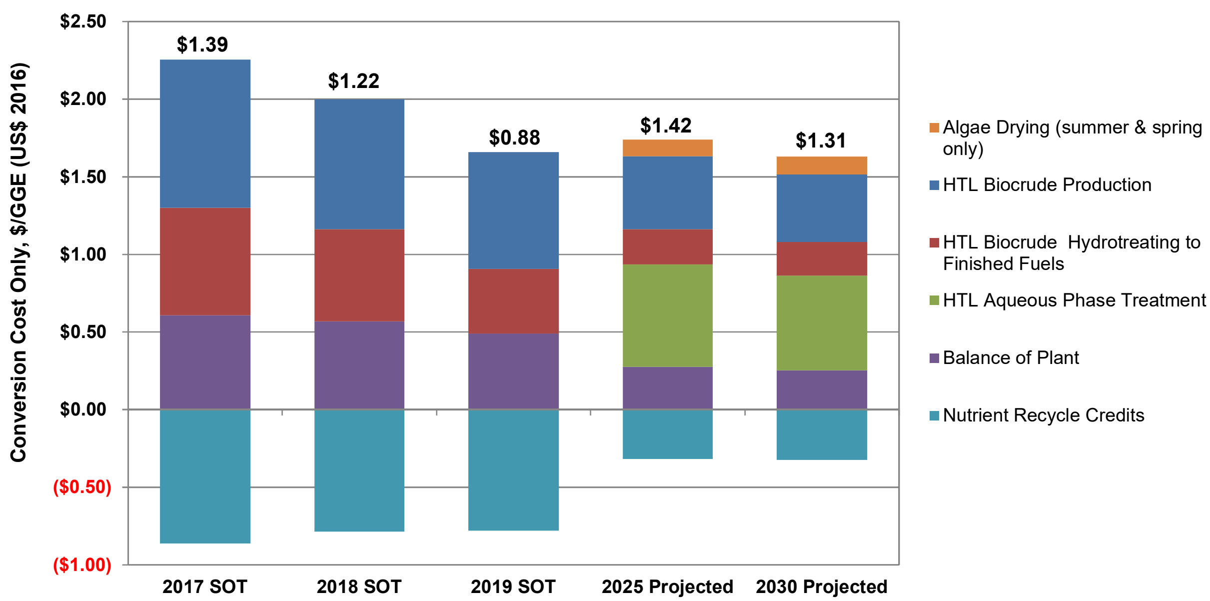

Figure 5. Algae HTL and biocrude upgrading conversion cost only allocations.

4.2 Sustainability Metrics

Table 8 listed the conversion sustainability metrics for FY17 to FY19 SOT cases. Because of the larger plant scale, FY19 SOT has a higher annual natural gas consumption for hydrogen production than that of FY18. However, the natural gas usage per U.S. ton feedstock is slightly lower resulting from lower biocrude yield per ton feedstock and lower hydrogen consumption per unit biocrude. Because of the lower final fuel yield, the electricity consumption per gge of final fuel product for the FY19 SOT is slightly higher than the FY18 SOT.

Table 8. Conversion sustainability metrics.

Input	FY 17 SOT	FY 18 SOT	FY 19 SOT
Fuel yield, gge fuel/ton AFDW biomass	104	115	106
Natural gas, mmscf/y			
To algae dryers	0	0	0
To hydrogen plant	419	475	822
Total natural gas usage	419	475	822
SCF natural gas/U.S. ton feedstock	4,078	4,228	4,160
SCF natural gas/gge final fuel	39.2	36.9	39.4
Electricity, kwh/gge final fuel	0.76	0.70	0.73

Conversion plant sustainability metrics are not useful by themselves and need to be coupled to the farm life-cycle inventory (LCI), to account for aqueous recycle from the conversion plant back to the farm. An LCI for the conversion plant will be delivered to ANL, who can then complete a full well-to-wheels life-cycle analysis using the farm inputs from NREL.

5.0 Conclusions and Future Work

As demonstrated by the current experimental work and TEA studies, the potential improvement for the single-stage HTL and biocrude upgrading system to achieve BETO (Bioenergy Technologies Office) goal of < $3/GGE is limited given the significant cost to produce dewatered algae. Initial testing for two-stage sequential HTL conversion process has demonstrated the potential to produce feedstock for high value byproducts which can be used to offset fuel production costs to achieve a lower MFSP. Therefore, research objectives that will address the improvements needed to meet the 2030 target costs include:

- Conduct additional engineering scale sequential multi-stage HTL testing for algae/non-algae blended feedstock to provide improved inputs for case studies and thus lead to a revised design basis reflecting research to date
- Investigate and assess alternative processes allowing byproducts generation from low temperature stage aqueous phase and optimize fuel generation from the high temperature stage
- Improve productivity of algae grown on recycled nutrients and improved nitrogen tracking
- Toxicity testing of recycled water from sequential multi-stage HTL process
- Optimization of hydrotreating pretreatment and reactor design.

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