PNNL-33622

Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2022 State of Technology

November 2022

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;
ph: (865) 576-8401
fax: (865) 576-5728
email: mb-reports@osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <https://www.ntis.gov/about>
Online ordering: http://www.ntis.gov

PNNL-33622

Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2022 State of Technology

November 2022

Lesley Snowden-Swan
Shuyun Li
Michael Thorson
Andy Schmidt
Dylan Cronin
Yunhua Zhu
Todd Hart
Miki Santosa
Sam Fox
Teresa Lemmon
Marie Swita

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

Pacific Northwest National Laboratory
Richland, Washington 99354

Summary

Data from Pacific Northwest National Laboratory's (PNNL) conversion hydrothermal liquefaction (HTL) program for wet waste was used to update the pathway techno-economic analysis (TEA) for the fiscal year 2022 State of Technology (2022 SOT). Figure S.1 shows the modeled minimum fuel selling price (MFSP) for the 2022 SOT, along with the previous years' SOTs (Snowden-Swan et al. 2020, 2021, 2022). These costs are for a HTL plant scale of 110 dry ton/day sludge feed and a larger centralized upgrading plant scale of 38 million gallons/year biocrude feed, commensurate with the design case. All costs were updated to 2020 dollars. Corresponding cost breakdowns and technical parameters for each case are given in Appendix B. In previous years' analyses options with and without ammonia (NH_3) stripping treatment of the HTL aqueous phase recycle stream were included in the analysis to account for cases with direct recycle of untreated HTL aqueous phase back to the wastewater treatment plant. In the FY21 SOT assessment however, system boundaries for the analysis were adjusted to reflect separate ownership/operatorship for the HTL plant and with that, nutrient surcharge fees associated with disposal of the aqueous phase wastewater to a municipal sewer system were incorporated to provide an improved accounting of true disposal costs for a standalone plant. With these changes, there is no significant cost difference between the case including ammonia removal and the case excluding ammonia removal and therefore the "no NH3 removal" options will not be included in the 2022 and future SOTs.

The primary updates for this year's SOT are the incorporation of jet fuel testing results into the process and economic models to align with BETO's focus on sustainable aviation fuel (SAF). The experimental team fractionally distilled hydrotreated HTL biocrude derived from wet waste (sludge) to produce a jet fuel cut that was then characterized and screened for SAF feasibility via Tier α and Tier β testing by University of Dayton (Cronin et al. 2022). The screening results showed that nearly all critical properties tested for the jet fuel cut are within typical ranges for conventional petroleum jet and ASTM-approved SAF. However, nitrogen levels for the jet cut from hydrotreated HTL biocrude are significantly higher than conventional jet fuel. With this in mind, the team ran follow-on hydrotreating of the HTL jet cut to test the efficacy of deep dehydrogenation (HDN) as a final finishing step for production of SAF from this pathway. Initial testing of NiMo catalyst at similar conditions to those used for biocrude hydrotreating reduced nitrogen from 5,100 ppm to 53 ppm, a 99% reduction. Further research is needed to optimize HDN catalyst and reaction conditions and fully understand the potential impact that nitrogen has on engine performance.

The experimental results were used as a basis to modify the biocrude upgrading plant model to represent fractionation and deep HDN of a jet fuel cut for potential production of SAF (along with diesel and naphtha cuts). The resulting modeled MFSP for the 2022 SOT is estimated at $3.15 per gasoline-gallon equivalent (GGE). The MFSP is unchanged from the FY21 SOT case primarily due to equal shifts in capital between the hydrotreating and hydrocracking sections of the plant. Specifically, the fraction of hydrotreated biocrude product sent to hydrocracking was reduced to match the experimental fractional distillation data, resulting in lower capital associated with hydrocracking. On the other hand, additional equipment is needed for the HDN step, balancing the savings resulting from reduced hydrocracking capital.

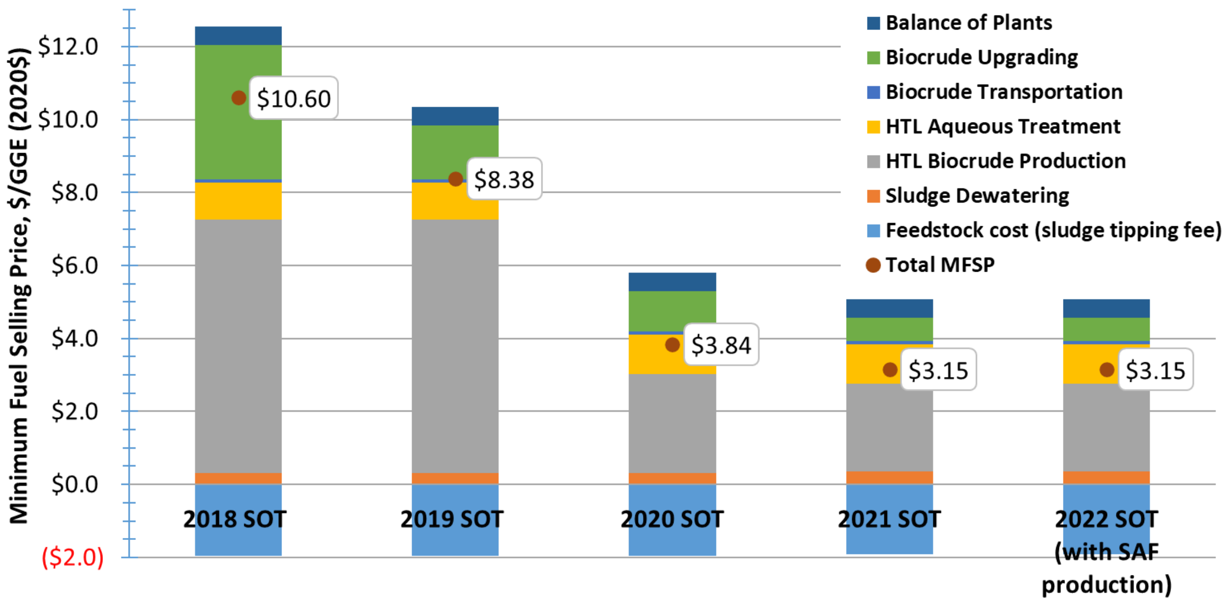


Figure S.1. Wet waste HTL and upgrading pathway cost allocations for 2022 SOT with SAF production.

Wet waste feedstocks tested in FY22 include the following:

- Blend of food waste engineered bioslurry (EBS®) from Waste Management for AD (tested in bench scale) and primary/secondary sludge (7.4:1 wt) from wastewater treatment at Great Lakes Water Authority (GLWA) in Detroit, MI (EBS:sludge 60:40 AFDW) (tested in bench scale system).
- Primary/secondary (43/57 dry basis) sludge from wastewater treatment at Great Lakes Water Authority (GLWA) in Detroit, MI (tested in bench scale system)
- Dissolved air flotation waste from yogurt manufacturing (tested in bench scale system)
- Food waste blend from Tri-Cities, Washington (fry crumbs, soy pulp, waste cheese curds, yogurt production waste) (tested in bench scale system)
- Food waste EBS® (tested in Modular Hydrothermal Liquefaction System, MHTLS)

Much progress has been made to advance the state of technology and reduce modeled costs through demonstration of continuous processing of numerous wet waste feedstocks, high solids pumping, extended biocrude hydrotreating catalyst life, and initial viability of SAF from the pathway. Additional work is needed to identify remaining "pain points" and further de-risk the process for piloting and commercialization. Results from the experimental and analysis work this year shows that the wet waste HTL pathway is potentially viable for production of SAF. Further work is needed to verify and optimize the performance of a SAF-centric HTL pathway and advance the readiness level of the HTL and upgrading technologies for scale-up and commercial adoption. Priority areas of R&D for the pathway moving forward are the following:

HTL:

- Further work and down-selection of the best technology for treatment and nutrient recovery from AP and HTL solids.

- Initial analysis on the PDU by a subject matter expert with refinery/petrochemical design experience indicates that the HTL solids removal process design blowdown and solids filter design will likely have issues at industrial scale. Work is needed to identify the most beneficial designs.

Biocrude Upgrading:

- Work to fully elucidate the potential impact of nitrogen and other heteroatom content on jet fuel properties and specifications for SAF application.
- Verify and optimize the performance of the final HDN step for enabling SAF production.
- Demonstrate in the lab hydrocracking of the heavy cut from hydrotreated biocrude and optimize the reactor conditions for maximized jet yield.

Acronyms and Abbreviations

AFDW	ash-free dry weight
BETO	Bioenergy Technologies Office
CCCSD	Central Contra Costa Sanitary District
CSTR	continuous stirred-tank reactor
DAF	dry, ash-free
EBS	engineered bioslurry
FOG	fats, oils, and grease
FY	fiscal year
GGE	gasoline-gallon equivalent
GHG	greenhouse gas
GLWA	Great Lakes Water Authority
HTL	hydrothermal liquefaction
JBLM	Joint Base Lewis McChord
MBSP	minimum biocrude selling price
MFSP	minimum fuel selling price
MHTLS	modular hydrothermal liquefaction system
PFR	plug-flow reactor
PNNL	Pacific Northwest National Laboratory
R&D	research & development
SAF	sustainable aviation fuel
SOT	state of technology
TEA	techno-economic analysis
WHSV	weight hourly space velocity
WRRF	wastewater treatment and water resource recovery facility

Contents

Figures

Tables

1.0 Introduction

Each year the U.S. Department of Energy Bioenergy Technologies Office (BETO) assesses progress in their research and development efforts toward sustainable production of renewable fuels (DOE 2016) through the annual state of technology (SOT) assessment. The SOT assessment evaluates the impact of the year's research progress on the modeled minimum fuel selling price (MFSP) for selected biofuel conversion pathways and measures the current state of the technology relative to defined goal case projections. Technical and cost targets for a projected goal case set for the year 2022 were previously established for the wet waste hydrothermal liquefaction (HTL) and biocrude upgrading pathway and summarized in a design report (Snowden-Swan et al. 2017). Process performance advancements made by the Pacific Northwest National Laboratory (PNNL) team for HTL and biocrude hydrotreating have resulted in yearly reductions in the modeled MFSP relative to the initial SOT (2018) (Snowden-Swan et al. 2020, 2021, 2022). This report summarizes the R&D progress and associated techno-economic analysis (TEA) for the pathway 2022 SOT. Methods and economic assumptions for the n^{th} plant analysis used for the TEA are consistent with the design report (Snowden-Swan et al. 2017), with the exception of updates in the modeled cost year (2020) and income tax rate (21%). Appendix D provides the full list of financial and economic assumptions used in the analysis. Life cycle inventory data for the conversion process is listed in Appendix C. This data is supplied to Argonne National Laboratory for their supply chain sustainability analysis to track and guide research toward improved greenhouse gas (GHG) emissions, energy usage, water usage and other environmental metrics for the pathway (Cai et al. 2022).

2.0 Conversion Model Overview

Figure 1 shows the block flow diagram for the overall process. The general process configuration remains the same as the 2021 SOT case where the HTL plant is located next to or nearby a water resource recovery facility (WRRF) but is separately owned and operated by a private company. As presented in the 2021 SOT report, with the assumption of separate HTL plant ownership (Figure 1), revenue from offtake of the WRRF's waste sludge (i.e., a negative feedstock cost) is included in the HTL plant economics based on national sludge disposal costs. Thickened sludge (3-6% solids) is assumed to be pumped from the WRRF to the nearby HTL plant where it is then dewatered to 25% solids in preparation for conversion into biocrude. The HTL plant pays for this dewatering, as well as for disposal of waste solids (HTL solids and lime sludge) and for discharge of the HTL aqueous phase (AP) to the municipal sewer system. The produced HTL biocrude is shipped via tractor trailer to a centralized biocrude upgrading plant that processes 10 times the amount of biocrude generated from one 110 dry ton/day HTL plant. The assumed cost of transporting biocrude 100 miles to a centralized upgrading plant at a cost of $0.092 per gasoline-gallon equivalent (GGE) biocrude remains the same as with the previous SOT assessments.

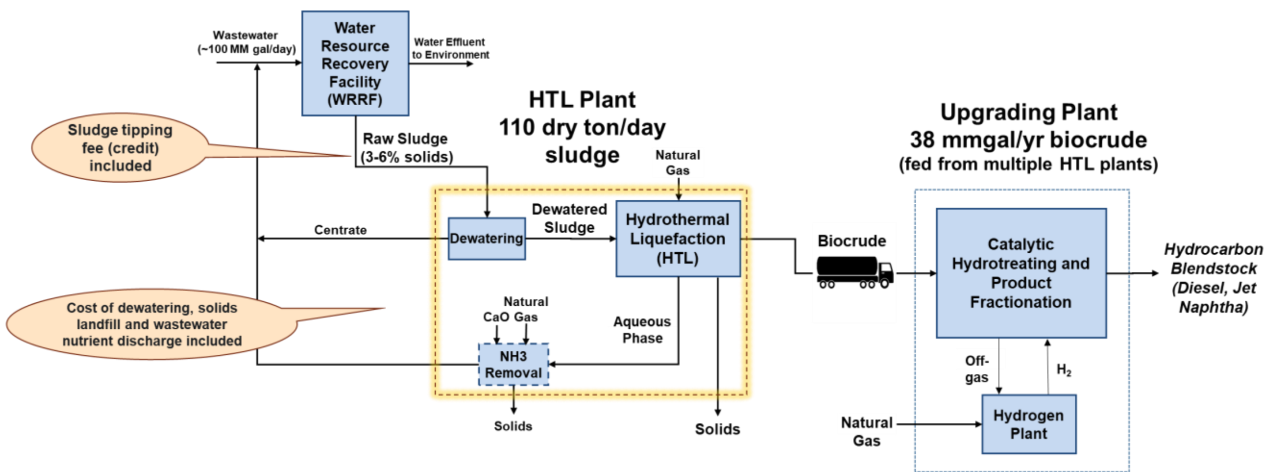


Figure 1. Process flowsheet for the wet waste HTL and upgrading 2022 SOT.

While the focus of R&D and the annual SOTs for the wet waste HTL pathway has been on the production of renewable diesel in the past, BETO has shifted their decarbonization goals to transportation modes that are difficult to electrify, with a particular emphasis on sustainable aviation fuel (SAF) applications. In light of this, PNNL has recently investigated the feasibility of the jet boiling-range cut from hydrotreated biocrude derived from sewage sludge, manure, and food waste, and found that it meets nearly all Tier α and Tier β fuel properties tested for initial SAF candidate screening (see Section 3.4). Based upon this new research, a TEA is presented for HTL-derived SAF for this year's SOT assessment. While the same general process configuration as the FY21 SOT (Figure 1) remains the basis of our modeling, modifications were made to the biocrude upgrading plant model to reflect the experimental data from jet cut testing and the corresponding changes to the process that would be needed to SAF alongside diesel and naphtha. The details of the upgrading plant flowsheet modifications for SAF production are presented in Section 4.0, along with the major assumptions and TEA results for the SAF case.

3.0 Experimental Results and Design Basis

This section presents the testing results and feedstock cost analysis that form the basis of the SOT assessment. Key experimental results from PNNL's FY22 R&D include 1) wet waste feedstock compositional analysis; 2) wet waste HTL processing; and 3) hydrotreating processing. The following sections present the experimental data and a discussion of how it was used in the analysis. Note that not all testing data was used directly in the modeled SOT, however this report serves to document much of the testing work that demonstrates broad applicability of the technology across a diverse set of feedstocks and effectively helps to advance the state of the pathway.

3.1 Wet Waste Feedstock Composition

Wet waste feedstocks tested in FY22 include the following:

- Blend of food waste engineered bioslurry (EBS®) prepared by Waste Management (tested in bench scale) and wastewater treatment primary/secondary sludge (7.4:1 dry wt) from Great Lakes Water Authority (GLWA) in Detroit, MI (EBS:sludge ratio of 48:52 dry wt) (tested in bench scale system)
- Primary/secondary (43:57 dry wt) sludge from wastewater treatment at Great Lakes Water Authority (GLWA) in Detroit, MI (tested in bench scale system)
- Dissolved air flotation waste from yogurt manufacturing (tested in bench scale system)
- Blend of food processing waste including yogurt manufacturing, cheese curds, okara (pulp) from soy, and fry crumbs at a 42:13:36:9 (dry wt) ratio (tested in bench scale system)
- Food waste EBS® (tested in Modular Hydrothermal Liquefaction System, MHTLS)

Table 1 gives the ultimate and proximate analysis for the feedstocks tested. Analysis for the GLWA mixed primary/secondary sludge (WW06) on which the design case (Snowden-Swan et al. 2017) and SOT are based is also listed for comparison. The first waste tested (WW24) was a mixture (dry basis) of 48% food waste EBS® from Waste Management and 52% primary/secondary (7.4:1 dry wt) sludge from GLWA. This blend was tested to emulate the approximate ratio of sludge and food waste that is generated in the Detroit area and many metropolitan areas nationwide. The EBS® technology is used to produce an engineered slurry that can be added to anaerobic digesters to enhance energy production (Waste Management 2018). The sludge feedstock was provided from the feed line to GLWA's incinerator. Next, a pure GLWA sludge feedstock (43:57 dry wt) was tested (WW25) to check the variability of waste composition and performance of sample collected from the same facility as the one assumed for the design case feedstock (WW06, see Appendix A). Waste generated from dissolved air flotation treatment of wastewater from a yogurt manufacturing facility located in Southern Idaho was also tested (WW26) in the bench scale system. Gibby Group, a company that handles hundreds of thousands of tons of agricultural/food processing byproducts and waste streams annually, provided this waste for testing. A blend of food processing wastes consisting of yogurt manufacturing waste, fry crumbs, soy pulp (okara), and waste cheese curds at a 42:13:36:9 (dry basis) ratio, respectively, was prepared and tested in the bench scale system (WW27). And finally, a pure food waste EBS® was run in the engineering scale system (MHTLS 16) to provide a comparison of performance to the bench-scale run conducted with the same waste sample in FY21 (WW23, see Appendix A). A comprehensive list of all wet waste feedstocks tested to date in support of the HTL pathway development is given in Appendix A. The modeled 2022 SOT feedstock composition remains unchanged to maintain consistency with the design case and to show the impact of the research progress on advancement of the technology.

Table 1. Ultimate and proximate analysis (wt%) of wet waste samples tested.

	WW24 EBS® Slurry Food Waste/ GLWA Sludge (Dry)	WW24 EBS® Slurry Food Waste/ GLWA Sludge (DAF)	WW25 43/57 Sludge GLWA (Dry)	WW25 43/57 Sludge GLWA (DAF)	WW26 Waste from Yogurt Production (Dry)	WW26 Waste from Yogurt Production (DAF)	WW27 Food Waste Blend (Dry)	WW27 Food Waste Blend (DAF)	MHTLS 16 EBS® Slurry Food Waste (Dry)	MHTLS 16 EBS® Slurry Food Waste (DAF)	2021 and 2022 SOT Models (Sludge) (Dry)	2021 and 2022 SOT Models (Sludge) (DAF)
C	40.2	48.5	33.4	46.9	57.8	59.3	54.7	57.0	54.3	57.2	46.8	52.1
H	5.7	6.9	5.5	6.7	8.6	8.9	7.8	8.1	8.4	8.9	6.5	7.2
O	33.4	40.3	31.8	38.8	23.9	24.5	29.6	30.9	29.1	30.7	29.7	33.1
N	3.0	3.7	5.5	6.7	6.8	7.0	3.6	3.8	2.9	3.0	5.7	6.3
S	0.6	0.7	0.8	0.9	0.3	0.3	0.2	0.2	0.2	0.2	1.2	1.3
Ash	29.5	n/a	30.1	n/a	6.7	n/a	7.3	n/a	7.7	n/a	15.0	n/a
P	0.8	n/a	2.4	n/a	1.0	n/a	0.5	n/a	0.4	n/a	1.9	n/a
Carb	27.5	39.8	20.1	29.1	8.1	8.8	31.2	34.1	41.4	44.7	Not modeled	
Fat	23.0	33.2	15.6	22.5	42.7	46.2	38.4	41.9	27.7	29.9	Not modeled	
Protein	18.6	27.0	33.5	48.4	41.6	45.0	22.0	24.0	22.8	24.6	Not modeled	
FAME	12.8	18.6	10.0	14.5	39.1	38.8	22.1	24.2	21.4	23.1	Not modeled	
Ash	31.0	n/a	30.8	n/a	7.3	n/a	8.4	n/a	7.3	n/a	Not modeled	

DAF = dry, ash-free

3.2 Wet Waste Hydrothermal Liquefaction Data

Testing of HTL at PNNL is performed in bench-scale and engineering-scale systems. The capacities of the bench-scale system's stirred vessel reactor and plug-flow reactor (PFR) are 600 mL and 550 mL, respectively, with a flow rate of 2-4 L/hour. Note that only the 550 mL PFR was used for run WW-24. The engineering scale system is a modular HTL system (MHTLS) and has a pure plug flow reactor configuration but with a capacity approximately five times that of the bench scale system (12-16 L/hour). Illustrations of each system can be found in the team's previous work (Snowden-Swan et al. 2020). Testing with the food/sludge, pure sludge, and waste from yogurt production (WW24-27) were run in the bench scale unit. Testing of the EBS® food waste (MHTLS 16) was run in a pure plug flow configuration in the engineering scale system. Experimental HTL testing conditions and results are given in Table 2, along with the parameters used for the modeled SOT cases. Product yields are given on a percent dry, ash-free (DAF) mass basis (lb DAF product/lb DAF feed multiplied by 100).

Table 2. Wet waste HTL testing results and model assumptions.

Operating Conditions and Results	WW24 EBS® Slurry Food Waste/ GLWA Sludge	WW25 43/57 Sludge GLWA SS-1	WW25 43/57 Sludge GLWA SS-2	WW26 Waste from Yogurt Production	WW27 Food Waste Blend	MHTLS 16 EBS® Slurry Food Waste	2021 and 2022 SOT Model (Sludge)
Temperature, °F (°C)	638 (337)	648 (342)	609 (321)	647 (342)	631 (333)	660 (349)	656 (347)
Pressure, psia (MPa)	2946 (20.3)	2950 (20.3)	2956 (20.4)	2953 (20.4)	2895 (20.0)	2790 (19.3)	2979 (20.5)
Feed solids, wt%							
Ash included	23.3%	16.0	16.0	20.0%	26.3%	17.1%	25%
Ash-free basis	16.4%	11.2	11.2	18.7%	24.3%	15.8%	21%
Liquid hourly space velocity, vol./h per vol. reactor	3.6	3.8	3.8	3.8	5.5	4.0	4.0
Equivalent residence time, min.	17	16	16	16	11	15	15
Product yields[(a)] (dry, ash-free sludge), wt%							
Oil (biocrude)	56%	35%	20%	64%	56%	52%	45%
Aqueous	16%	37%	47%	20%	26%	29%	28%
Gas	18%	15%	15%	12%	15%	18%	16%
Solids	11%	13%	19%	3%	3%	2%	12%
Carbon yields							
Oil (biocrude)	63%	47%	29%	70%	74%	69%	67%
Aqueous	19%	27%	35%	22%	15%	20%	23%
Gas	8%	8%	9%	5%	7%	9%	10%
Solids	11%	17%	27%	3%	3%	2%	1%
HTL dry biocrude analysis, wt%							
C	75.2%	77.6%	74.4%	74.9%	77.4%	75.6%	78.3%
H	10.5%	9.6%	10.2%	11.0%	10.5%	11.7%	10.8%
O	8.4%	5.4%	6.7%	8.5%	7.9%	8.2%	4.8%
N	4.9%	6.2%	7.5%	5.3%	4.0%	3.6%	4.9%
S	0.5%	1.0%	1.1%	0.3%	0.2%	0.2%	1.2%
P	0.0%	0.0%	0.0%	0.00%	0.00%	0.00%	Not modeled[(b)]
Ash	0.59%	0.08%	0.13%	0.04%	0.02%	0.68%	0.0%
HTL dry biocrude H:C ratio (mol)	1.7	1.5	1.6	1.8	1.6	1.9	1.6
HTL biocrude dry higher heating value[(c)], Btu/lb (MJ/kg)	16,200 (37.7)	16,300 (37.9)	16,000 (37.2)	16,400 (38.2)	16,557 (38.5)	16,870 (39.2)	17,100 (39.7)
HTL biocrude moisture, wt%	2.9%	4.3%	35.5%	7.6%	3.9%	8.1%	4.0%
HTL biocrude wet density @ 104°F (40°C) (g/ml)	0.95	0.98	1.00	0.92	0.96	0.94	0.98
AP chemical oxygen demand (mg/L)	78,930	58,233	58,567	95,900	89,963	69,700	94,022

(a) Recovered after separations.
(b) Phosphorus partitioning is not directly modeled in Aspen because of the small quantity, most of which reports to the solid phase.
(c) Calculated using Boie's equation (Boie 1953).

3.3 Testing of Jet Cut from Hydrotreated Biocrude

To support BETO's new volumetric goals toward SAF production, testing in FY22 was focused on generation and testing of jet boiling range cuts from hydrotreated HTL biocrudes. Whole hydrotreated biocrude products derived from sludge (MHTLS15) and food waste (WW23) were fractionally distilled to produce jet cuts in the boiling range of 150-250°C. The full details of this work can be found in the published article by Cronin et al. (2022). Tables A.1-4 and A.5-6 provide compositional analysis of the wet wastes and biocrudes corresponding to these samples. The jet cuts were then analyzed for elemental composition, heat of combustion, and simulated distillation. In addition, the samples were sent to the University of Dayton (UD) for physical property testing to provide an initial investigation of SAF compatibility. The UD team has developed a method for prescreening of critical physical properties for candidate SAF fuels referred to as Tier α and Tier β testing (Yang et al. 2022). The Tier α method utilizes two-dimensional gas-chromatography mass spectrometry to determine carbon number and hydrocarbon type distribution and allow for prediction of the distillation curve, derived cetane number and heat of combustion (HOC) of the candidate fuel. The Tier β method determines surface tension (σ), density (ρ), viscosity (ν), flash point, and freeze point of the fuel sample.

Figure 2 shows the results of Tier α and β testing (reprinted with permission from Cronin et al. 2022), for the jet cut from sewage sludge derived hydrotreated biocrude. Properties tested include carbon number and hydrocarbon type distribution (Figure 2a), critical jet fuel properties (Figure 2b), and distillation curve (Figure 2c). Ranges for conventional jet fuel (shown in green) are also given for comparison. These results show that nearly all critical properties examined for the jet cut from hydrotreated sludge-derived biocrude fall within the range of conventional jet, indicating that SAF derived from HTL of wet wastes is feasible and warrants further investigation.

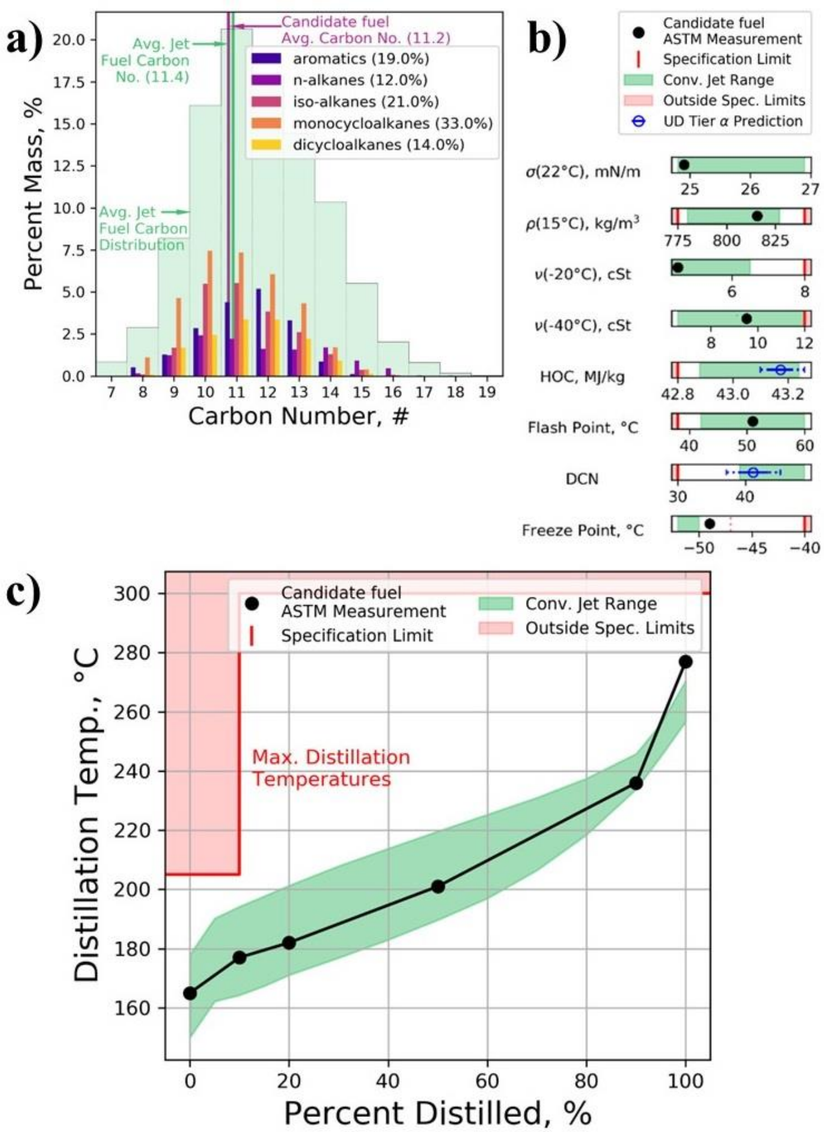


Figure 2. Results of SAF candidate testing for jet cut from hydrotreated sludge-derived HTL biocrude. (a) hydrocarbon type analysis results, with comparison to an average conventional jet fuel (green region); (b) critical jet fuel properties as predicted (Tier α) and measured (Tier β), with comparison to the specifications for Jet A-1; (c) distillation curve, with comparison to the collective analysis of 3 aviation

fuels (POSF 10325, 10264, and 01289) [Edwards, J.T., 2017). (Reprinted with permission from D. Cronin, 2022)

While the results from Tier α and β testing are promising, the heteroatom content of upgraded biocrude, including the jet cut, remains high relative to conventional fuel, in the range of 500-15,000 ppm (Cronin et al. 2022; Tables A.5 and A.6), stemming from the inherent nature of the basic macromolecules (carbohydrates, lipids, proteins) present in the original wet waste feedstock. Nitrogen is the most dominant heteroatom remaining in hydrotreated biocrude due to the presence of molecules such as pyrroles and pyrrolidines, which contain bonds particularly recalcitrant to hydrotreating. Therefore, the team proposed a deep hydrodenitrogenation (HDN) step for the fractionated jet cut to attempt to further reduce nitrogen content. Initial testing of deep HDN on the jet cut sample from sludge was conducted in a fixed-bed bench-scale system with conditions similar to the biocrude hydrotreating system previously described (Subramaniam et al. 2021; Snowden-Swan et al. 2020). Table 3 lists the catalyst, reactor conditions, and nitrogen content before and after HDN of the wet-waste derived jet fuel sample. These results show a 99% reduction in nitrogen down to 53 ppm in the jet sample. Oxygen levels in the feed material to the HDN reactor were below detection limits and are therefore not reported. Note that this was the initial test to establish a baseline performance and effectively no optimization of conditions was performed. Performance improvements for the HDN step are entirely plausible and will be targeted in work going forward.

Table 3. Initial HDN experimental testing conditions and results.

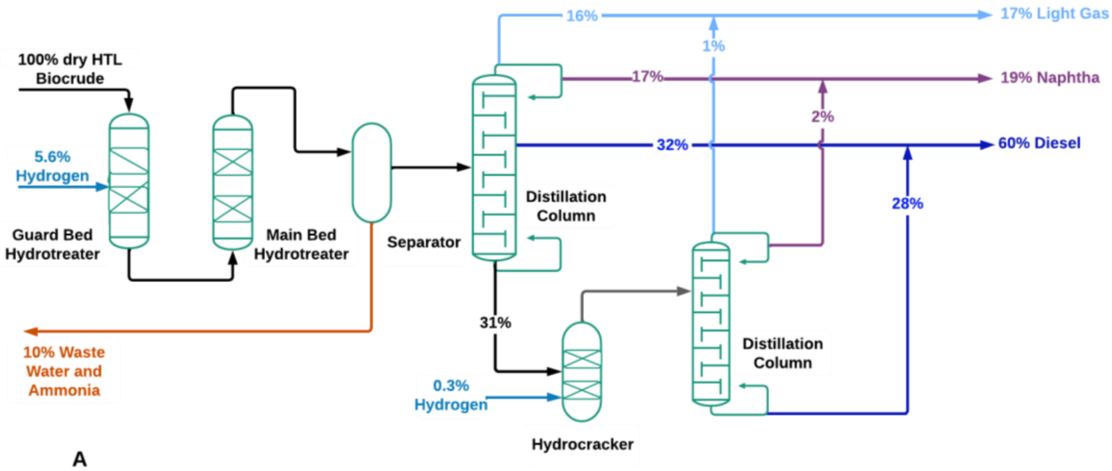
	Value
Catalyst	NiMo/Al2O3
WHSV, hr^{-1}	0.5
HDN temperature, °C (°F)	400 (752)
HDN pressure, MPa (psi)	10.8 (1,566)
Nitrogen before HDN, ppm	5100
Nitrogen after HDN, ppm	53

4.0 2022 SOT Modeled Performance and Costs

This section presents the economic and performance results for the SOT. All costs have been updated to 2020 dollars. The focus of the analysis this year is to estimate the jet fraction and potential cost impact of producing SAF from this feedstock/conversion pathway. To estimate the potential economic impact of shifting the pathway toward SAF, a preliminary TEA was performed to estimate the baseline jet fuel fraction produced and the associated MFSP. The analysis is based on the experimental data presented in the previous section.

Figure 3 shows a simplified, high-level flowsheet and mass balance for the biocrude upgrading plant process model for the 2021 SOT with production of diesel and naphtha (Figure 3A) and for the 2022 SOT configuration to include jet production (Figure 3B). Note that the balance of the mass flowing out of the system is produced wastewater from the hydrotreating reactions, not shown on the figure. Similar to previous SOTs, the heavy residual fuel from the hydrotreated biocrude product is assumed to be further treated in the hydrocracker to improve the jet- and diesel-range fuel yields. The fraction of heavy residual sent to the hydrocracker was reduced from 31% for the previous SOT to 11% for the current case, to align with the FY22 fractional distillation results (13% gasoline-range, 17% jet-range, 38% diesel-range, 11% heavy residual, and 16% light gases). As modeled, the hydrocracked heavy product contributes an additional 8% and 2% to the jet and diesel range fuel yields, respectively. The finished fuel includes 15% naphtha, 25% jet and 40% diesel. Further research is needed to optimize the jet fraction by tuning the cracker catalyst and/or conditions to convert more of the diesel and heavy residue into jet range product.

While Tier α and β testing of the hydrotreated jet fraction are in ranges amenable with SAF standards (Section 3.3), the nitrogen content is significantly higher than that of petroleum jet. Conventional jet A fuel is reported to contain 9-15 ppm nitrogen while the upgraded HTL biocrude's nitrogen content is in the range of 300-10000 ppm (Cronin et al. 2022). Therefore, a final, deep HDN step, as illustrated in Figure 3, may be required to reduce nitrogen to acceptable levels. The key economic assumptions for the HDN step listed in Table 4 along with the HDN performance data (Table 5) were used as the basis of the process and economic model updates for this year's SOT. The capital cost of the HDN reactor is estimated by Aspen Capital Cost Estimator, ACCE v10.0. The reactor diameter can be calculated using the inlet volumetric flow rate and superficial velocity in Table 4. The required catalyst volume and bed height can be obtained with the assumed WHSV of 0.5 hr^{-1} and then vessel length is determined assuming a 50% overall vessel void fraction to place the intercooler coils and other internals.



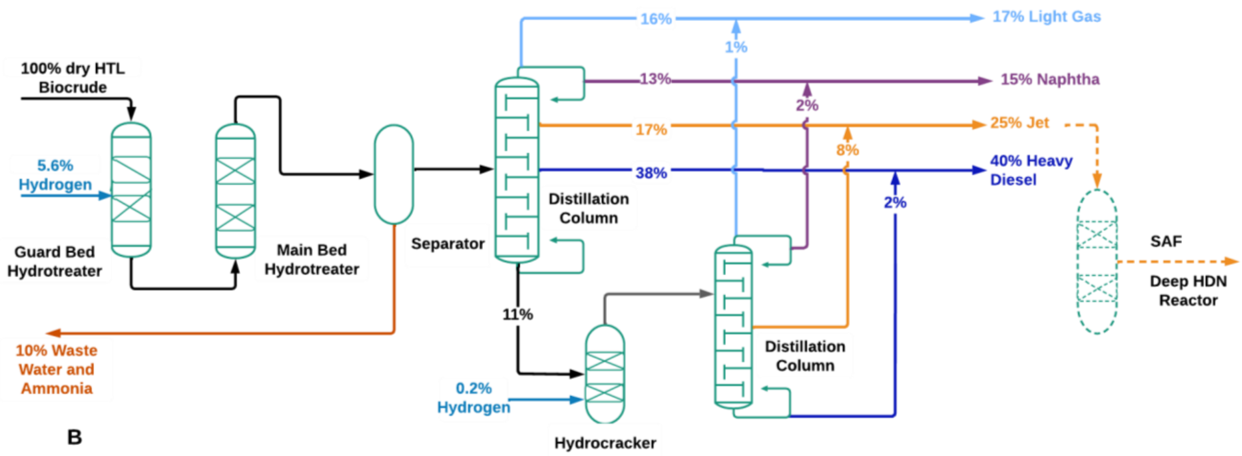


Figure 3. Upgrading design and mass flows for diesel production for previous SOTs (A) and for the preliminary analysis of SAF production for the 2022 SOT (B).

Table 4. Key modeling and economic assumption for deep hydrodenitrogenation step.

	Value
Catalyst price (2020$) ($/lb)[1]	11.3
Catalyst life (year)	2
WHSV (hr^{-1})	0.5
HDN design temperature (°C)	450
HDN design pressure (MPa)	11.8
Superficial velocity (ft/s)	0.02
Refractory lining (inch)	4
Vessel void fraction (%0	50%
Diameter (ft)	6
Catalyst density (lb/ft^3)	36

Catalyst volume (ft^3)	411
Bed height (ft)	15
Vessel height (ft)	24
[1] NiMo/Al_2O_3 catalyst, IHS 2014	

Table 5 lists the major economic results for the HTL plant for the 2022 SOT. Costs for the 2018-2021 SOTs are also given for comparison. The only change in the HTL plant costs for this year's assessment is that the cost year has been updated from 2016 to 2020 (for all cases).

Table 5. Economic results for 110 dry ton/day sludge HTL plant (with AP NH3 stripping) (2020 dollars).

	2018 and 2019 SOT	2020 SOT	2021 SOT	2022 SOT
Capital Costs, $ million				
Installed costs				
Sludge feedstock dewatering	1.7	1.7	1.7	1.7
HTL biocrude production	64.0	18.6	15.9	15.9
HTL aqueous phase recycle treatment	3.1	3.1	2.3	2.3
Balance of plant	0.6	0.6	0.6	0.6
Total installed capital cost	69.4	24.0	20.5	20.5
Fixed capital investment	131.4	45.3	38.7	38.7
Total capital investment (TCI)	138.1	47.7	40.7	40.7
Operating Costs, $/GGE biocrude ($ million/yr)				
Variable operating cost				
Avoided sludge disposal cost	-1.81 (-6.7)	-1.81 (-6.7)	-1.79 (-6.7)	-1.79 (-6.7)
Natural gas	0.05 (0.2)	0.07 (0.3)	0.04 (0.1)	0.04 (0.1)
Chemicals	0.29 (1.1)	0.29 (1.1)	0.27 (1.0)	0.27 (1.0)
Electricity	0.06 (0.2)	0.06 (0.2)	0.05 (0.2)	0.05 (0.2)
Waste disposal	0.82 (3.0)	0.82 (3.0)	0.99 (3.7)	0.99 (3.7)
Fixed costs	1.76 (6.5)	0.94 (3.5)	0.86 (3.2)	0.86 (3.2)
Capital depreciation	1.19 (4.4)	0.41 (1.5)	0.35 (1.3)	0.35 (1.3)
Average income tax	0.35 (1.3)	0.12 (0.5)	0.10 (0.4)	0.10 (0.4)
Average return on investment	3.21 (11.9)	1.15 (4.3)	0.98 (3.7)	0.98 (3.7)
MBSP, $/gal biocrude	6.38	2.21	1.99	1.99
MBSP, $/GGE biocrude	5.93	2.06	1.85	1.85

Table 6 lists the primary economic results for the biocrude upgrading plant for the corresponding HTL cases listed in Table 5. As modeled, the centralized upgrading plant receives waste-derived biocrude shipped from multiple HTL plants, processing 114,732 gal/day of biocrude feed and producing 109,248 gal/day of fuel blendstock (34,872 gal/day jet, 53,736 gal/day diesel, and 21,216 gal/day naphtha). Note that the MFSP for the upgrading plant includes a cost of $0.10/GGE ($0.092/GGE biocrude) for transporting the biocrude 100 miles to the upgrading facility. Based on the current assumptions and initial modeled results, there appears to be negligible impact on the MFSP when jet fuel production including a deep HDN step is incorporated into the upgrading plant. As shown, there is slightly higher capital cost for the hydrotreating section due to the additional HDN reactor ($3.8MM), which adds 2 cents to the MFSP. This is offset by reduced hydrocracking capital as less heavy residue is sent to the hydrocracker in this year's configuration (see Figure 3). Consumption of HDN catalyst at the assumed catalyst life of 2 years adds neglible cost. There is only a slight change in heat duties for the two distillation columns and hydrogen consumption for the hydrocracker between the two cases.

Table 6. Economics for biocrude upgrading plant processing ~115,000 gal/day biocrude and producing SAF, diesel and naphtha (2020 dollars).

	2018 SOT	2019 SOT	2020 SOT	2021 SOT	2022 SOT (with SAF)
Capital Costs, $ million					
Installed costs					
Hydrotreating	51.4	46.2	41.8	41.8	45.6
Hydrocracking	6.7	6.7	6.7	6.7	3.2
Hydrogen plant	28.9	28.9	28.9	28.9	28.4
Steam cycle	1.8	1.8	1.8	1.8	1.5
Balance of plant	6.8	6.8	6.8	6.8	6.3
Total installed capital cost	95.6	90.4	86.0	86.0	85.0
Indirect costs	67.1	63.3	60.2	60.2	59.4
Fixed capital investment	178.8	168.8	160.4	160.4	158.5
Total capital investment (TCI)	191.2	180.5	171.5	171.5	169.5
Operating Costs, $/GGE ($ million/yr)					
Biocrude feedstock[a], including transport	6.48 (245.2)	6.48 (245.2)	2.31 (87.6)	2.09 (79.1)	2.09 (79.1)
Natural gas	0.04 (1.4)	0.04 (1.4)	0.04 (1.4)	0.04 (1.4)	0.04 (1.4)
Catalyst	3.03 (114.6)	0.91 (34.5)	0.59 (22.2)	0.13 (4.8)	0.13 (4.8)
Wastewater disposal	0.002 (0.1)	0.002 (0.1)	0.002 (0.1)	0.002 (0.1)	0.002 (0.1)
Electricity and water makeup	0.03 (1.0)	0.03 (1.0)	0.03 (1.0)	0.03 (1.0)	0.03 (1.2)
Fixed costs	0.30 (11.4)	0.29 (11.1)	0.28 (10.8)	0.28 (10.8)	0.28 (10.7)
Capital depreciation	0.16 (6.0)	0.15 (5.6)	0.14 (5.3)	0.14 (5.3)	0.14 (5.3)
Average income tax	0.06 (2.1)	0.05 (1.8)	0.04 (1.7)	0.04 (1.7)	0.04 (1.6)
Average return on investment	0.51 (19.4)	0.44 (16.6)	0.41 (15.5)	0.40 (15.1)	0.39 (14.9)
MFSP, $/GGE fuel blendstock	10.60	8.38	3.84	3.15	3.15
MFSP, $/GGE (conversion cost only)	4.12	1.90	1.40	1.06	1.06
MFSP, $gal jet	N/A	N/A	N/A	N/A	3.11
MFSP, $/gal diesel	11.36	8.98	4.12	3.37	3.51
MFSP, $/gal naphtha	10.47	8.28	3.80	3.11	3.03
Fuel Production, MMGGE/yr (MMGal/yr)					
Naphtha	9.1 (9.2)	9.1 (9.2)	9.1 (9.2)	9.1 (9.2)	6.7 (7.0)
Jet	N/A	N/A	N/A	N/A	11.4 (11.5)
Diesel	28.8 (26.8)	28.8 (26.8)	28.8 (26.8)	28.8 (26.8)	19.7 (17.7)

a Cost is for biocrude production from HTL process for case including ammonia stripping of aqueous phase.

While initial HDN testing of waste-derived jet samples removed 99% of nitrogen, lower levels may be required. Given the recalcitrant nature of some of the N-containing species (e.g., pyrolles, pyrollidines) in the HTL biocrude and trace quantities specified in the approved aviation fuels, it is possible that a modified catalyst and/or more severe or intensive operations may be needed. To investigate the potential cost impact of using a higher price catalyst or more operationally intensive hydroprocessing steps such as shorter catalyst life and low reactor WHSV, sensitivity analysis was performed around catalyst life, price, and WHSV and HDN capital. None of these parameters singularly impacted cost significantly however if a conservative case is considered where the catalyst life is reduced to 0.5 years, catalyst price is $50/lb, and the WHSV is reduced to 0.2 hr-1, the MFSP is increased by about 20 cents per GGE.

Figure 4 illustrates the annual modeled MFSP for the 2022 and previous SOTs for the combined wet waste HTL and biocrude upgrading process pathway. The complete list of combined HTL and upgrading processing area costs and key technical parameters and targets for the SOT cases are given in Appendix B. Results for the separate HTL plant are also given in Appendix B.

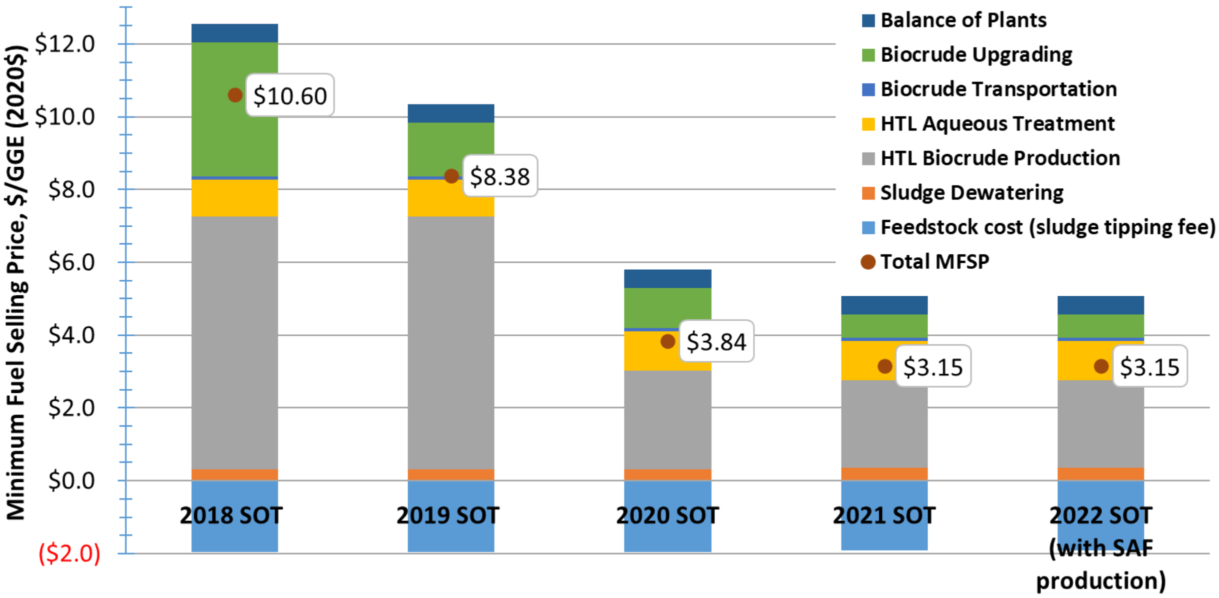


Figure 4. Combined HTL and biocrude upgrading pathway cost allocations.

Future work is needed to fully understand the impact of residual heteroatom content in the jet cut on engine performance and verify HDN performance parameters and associated cost. In addition, hydrocracking testing of the hydrotreated heavy end is necessary to verify the hydrocracker performance and the final jet, diesel and naphtha fuel cut yields for the pathway. Catalyst development and testing is also needed to enable maximum jet yields and optimal properties (e.g., isomerization) for SAF production.

5.0 Conclusions and Future Work

To support BETO's priority on application of biofuels to transportation modes not easily electrified and 2030-50 volumetric goals for producing SAF, work was conducted this year to investigate the feasibility of a jet enabled HTL pathway. To this end, the experimental team fractionated, characterized, and performed deep HDN on a jet boiling range cut from hydrotreated biocrude derived from HTL of municipal wastewater treatment sludge. The results of Tier α and Tier β testing of the HTL jet cut show that nearly all physical properties screened fall within the ranges of conventional jet fuel, indicating that this pathway may be viable for production of SAF in the future and thus warranting further investigation. Initial deep HDN testing further reduced nitrogen content of the jet sample by 99% down to 53 ppm during the initial run. Based on this data, the process and cost models were modified for the 2022 SOT to simulate production of jet, diesel and naphtha range fuel blendstocks, including a final deep HDN step of the jet product for SAF production. The results of the TEA show that there is no significant difference in MFSP for the 2022 SOT including SAF compared to the 2021 SOT that does not include SAF.

Several wet waste feedstocks including a blend of food waste engineered bioslurry (EBS®) from Waste Management and primary/secondary sludge (7.4:1 wt) from wastewater treatment, a primary/secondary sludge from wastewater treatment, waste from yogurt manufacturing, a food waste blend consisting of yogurt waste, cheese curds, soy pulp, and fry crumbs, and a pure food waste EBS®.

Results from this year's experimental and analysis tasks indicate the wet waste HTL and upgrading pathway may be viable for SAF production in the future. Further work is needed to verify performance of a SAF-centric HTL pathway and advance the technology readiness level of the HTL and upgrading technologies. To this end, work is needed to identify and mitigate any remaining "pain points" in order to de-risk the process for scale-up, piloting, and deployment. With these aspects in mind, the priority areas of R&D moving forward are the following:

HTL:

- Further work and down-selection of the best technology for treatment and nutrient recovery from aqueous phase and HTL solids.
- Initial analysis on the PDU by a subject matter expert with refinery/petrochemical design experience indicates that the HTL solids removal process design blowdown and solids filter design will likely have issues scaling to industrial scales. Work is needed to identify the most beneficial designs.

Biocrude Upgrading:

- Work to fully elucidate the impact of nitrogen and other heteroatom content on jet fuel properties and specifications and SAF application.
- Verify and optimize the performance of the final HDN step for enabling SAF production.
- Demonstrate in the lab hydrocracking of the heavy cut from hydrotreated biocrude and optimize the reactor conditions for maximized jet yield.

6.0 References

Boie W. 1953. "Fuel Technology Calculations." *Energietechnik* 3:309-316.

Cai, H., L. Ou, M. Wang, R. Davis, A. Dutta, L. Tao, K. Harris, M. Wiatrowski, E. Tan, A. Bartling, B. Klein, D. Hartley, P. Burli, Y. Lin, M. Roni, D. Thompson, L. Snowden-Swan, Y. Zhu, S. Li. 2022. *Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Hydrothermal Liuefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2021 State-of-Technology Cases.* ANL/ESD-22/5, Argonne National Laboratory, Chicago, IL.

Cronin, D.J. S. Subramaniam, C. Brady, A. Cooper, Z. Yang, J. Heyne, C. Drennan, K.K. Ramasamy, M.R. Thorson. 2022. "Sustainable Aviation Fuel from Hydrothermal Liquefaction of Wet Wastes." *Energies*: 15, 1306. https://doi.org/10.3390/en15041306

DOE. 2016. *Bioenergy Technologies Office Multi-Year Program Plan*. U.S. Department of Energy, Washington, D.C.

Edwards, J.T. 2017. "Reference jet fuels for combustion testing." In Proceedings of the 55th AIAA Aerospace Sciences Meeting, Grapevine, TX, USA, 9–13 January 2017; p. 0146.

IHS. 2014. *HIS Chemical PEP Yearbook International*, "Gas oil, vacuum, low sulfur, for FCC feed by hydrotreating vacuum gas oil." http//chemical.ihs.com/PEP

Snowden-Swan LJ, Y Zhu, MD Bearden, TE Seiple, SB Jones, AJ Schmidt, JM Billing, RT Hallen, TR Hart, J Liu, KO Albrecht, SP Fox, GD Maupin, and DC Elliott. 2017. *Conceptual Biorefinery Design and Research Targeted for 2022: Hydrothermal Liquefaction Processing of Wet Waste to Fuels*, PNNL-27186, Pacific Northwest National Laboratory, Richland, WA.

Snowden-Swan L.J., J.M. Billing, M.R. Thorson, A.J. Schmidt, D.M. Santosa, S.B. Jones, and R.T. Hallen. 2020. *Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2019 State of Technology*. PNNL-29882. Richland, WA: Pacific Northwest National Laboratory.

Snowden-Swan L.J., J.M. Billing, M.R. Thorson, A.J. Schmidt, Y. Jiang, D.M. Santosa, and T.E. Seiple, et al. 2021. *Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2020 State of Technology*. PNNL-30982. Richland, WA: Pacific Northwest National Laboratory.

Snowden-Swan L.J., S. Li, Y. Jiang, M.R. Thorson, A.J. Schmidt, T.E. Seiple, and J.M. Billing, et al. 2022. *Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2021 State of Technology*. PNNL-32731. Richland, WA: Pacific Northwest National Laboratory. doi:10.2172/1863608

Subramaniam, S., D. Santosa, C. Brady, M. Swita, K. Ramasamy, and M. Thorson. 2021. "Extended Catalyst Lifetime Testing for HTL Biocrude Hydrotreating to Produce Fuel Blendstocks from Wet Wastes." *ACS Sustainable Chem. Eng.* American Chemical Society.

Waste Management. 2018. "2018 Sustainability Report". https://sustainability.wm.com/2018/waste/organics/core#:~:text=EBS%C2%AE%20is%20a%20high,helping%20them%20approach%20zero%20waste.

Yang, Z. S. Kosir, R. Stachler, L. Shafer, C. Anderson, J.S. Heyne. 2021. “A GC GC Tier combustor operability prescreening method for sustainable aviation fuel candidates.” *Fuel*, 292, 120345.

Appendix A – Comprehensive List of Waste Feedstocks Testing Data

Table A.1. Ultimate and proximate analysis (wt%) of feedstocks tested to date in support of the HTL SOT and pathway development.

	WW06 50/50 Sludge GLWA (Dry)	WW06 50/50 SludgeGL WA (DAF)	WW09 50/50 Sludge CCCSD (Dry)	WW09 50/50 Sludge CCCSD (DAF)	WW10 CCCSD Sludge/FO G (80/20) (Dry)	WW10 CCCSD Sludge/FO G (80/20) (DAF)	WW15 Swine Manure (Dry)	WW15 Swine Manure (DAF)	MHTLS13 Primary Sludge GLWA (Dry)	MHTLS 13 Primary Sludge GLWA (DAF)	WW14 Biosolids (Dry)	WW14 Biosolids (DAF)	WW17 CCCSD Sludge (No Lime) (Dry)	WW17 CCCSD Sludge (No Lime) (DAF)	WW19A[b] Cow Manure (Dry)	WW19A[b] Cow Manure (DAF)	WW19B[b] Cow Manure (Dry)	WW19B[b] Cow Manure (DAF)
C	41.1	52.0	43.3	51.1	49.5	58.5	47.6	53.7	42.3	52.5	34.3	47.6	44.8	52.7	43.9	50.6	43.1	50.3
H	5.8	7.3	6.3	7.4	6.9	8.2	6.3	7.1	6.2	7.7	4.7	6.5	6.1	7.1	5.7	6.6	5.7	6.7
O	26.1	33.0	30.2	35.6	24.6	29.0	30.9	34.8	26.9	33.4	26.4	36.1	27.4	32.3	34.0	39.4	33.8	39.4
N	5.0	6.3	4.5	5.3	3.1	3.7	3.4	3.8	4.2	5.2	5.3	7.4	6.1	7.1	2.6	3.0	2.6	3.0
S	1.0	1.3	0.6	0.5	0.5	0.6	0.6	0.6	1.0	1.2	1.6	2.3	0.7	0.8	0.5	0.6	0.5	0.6
Ash	26.1		16.7[a]		17.2		12.5		25.6		32.6		17.1		15.9		16.7	
P	1.9		2.5		2.2		1.4		1.9		2.0		1.9		0.7		0.7	
Carb	16.7	22.8	37.2	46.1	45.2	55.2		50.1	26.7	34.9	17.5	30.5	30.8	38.2	60.3	70.0	NM	NM
Fat	22.6	30.8	6.5	8.0	15.0	18.3		24.7	20.6	27.0	11.6	19.3	14.2	17.6	10.1	11.8	NM	NM
Protein	34.1	46.4	36.7	45.4	21.6	26.4		25.2	29.0	38.0	29.6	51.0	37.6	46.7	15.7	18.2	NM	NM
FAME	11.9	16.2	13.7	17.0	26.5	32.3		16.6	15.4	20.2	5.5	13.0	9.5	11.5	5.8	6.7	NM	NM
Ash	26.6		19.2		18.1				23.7		41.4		17.4		13.8		NM	

(a) CCCSD currently treats their wastewater with lime to help incineration process. Ash content without lime is estimated at 14%.
(b) WW19-A and WW19-B were run without and with catalytic additive, respectively.
DAF = dry, ash-free.

Table A.2. Ultimate and proximate analysis (wt%) of feedstocks tested to date in support of the HTL SOT and pathway development (continued).

	WW20 Coyote Ridge Food Waste (Dry)	WW20 Coyote Ridge Food Waste (DAF)	WW21 JBLM Food Waste (Dry)	WW21 JBLM Food Waste (DAF)	WW22[(a)] Sludge/ Food Waste/ FOG (Dry)	WW22[(a)] Sludge/ Food Waste/ FOG (DAF)	WW23 EBS® Slurry Food Waste (Dry)	WW23 EBS® Slurry Food Waste (DAF)	MHTLS 15 ~66/34 Sludge GLWA (Dry)	MHTLS 15 ~66/34 Sludge GLWA (DAF)	WW24 EBS® Slurry Food Waste/ GLWA Sludge (Dry)	WW24 EBS® Slurry Food Waste/ GLWA Sludge (DAF)	WW25 43/57 Sludge GLWA (Dry)	WW25 43/57 Sludge GLWA (DAF)	WW26 Waste from Yogurt Producti on (Dry)	WW26 Waste from Yogurt Producti on (DAF)	WW27 Food Waste Blend (Dry)	WW27 Food Waste Blend (DAF)	MHTLS 16 EBS® Slurry Food Waste (Dry)	MHTLS 16 EBS® Slurry Food Waste (DAF)
C	49.3	52.3	51.5	54.1	48.2	55.4	50.8	54.8	40.8	51.7	40.2	48.5	33.4	46.9	57.8	59.3	54.7	57.0	54.3	57.2
H	7.3	7.7	7.6	8.0	7.3	8.4	6.6	7.1	5.5	7.0	5.7	6.9	5.5	6.7	8.6	8.9	7.8	8.1	8.4	8.9
O	35.5	37.7	34.3	36.0	29.1	33.4	32.2	34.7	26.4	33.5	33.4	40.3	31.8	38.8	23.9	24.5	29.6	30.9	29.1	30.7
N	3.5	3.7	3.3	3.5	4.7	5.4	3.2	3.5	5.3	6.7	3.0	3.7	5.5	6.7	6.8	7.0	3.6	3.8	2.9	3.0
S	0.0	0.0	0.2	0.2	0.6	0.7	0.2	0.2	0.9	1.1	0.6	0.7	0.8	0.9	0.3	0.3	0.2	0.2	0.2	0.2
Ash	6.5	n/a	4.1	n/a	13.5	n/a	8.6	n/a	21.1	n/a	29.5	n/a	30.1	n/a	6.7	n/a	7.3	n/a	7.7	n/a
P	1.0	n/a	0.4	n/a	1.4	n/a	0.4	n/a	2.3	n/a	0.8	n/a	2.4	n/a	1.0	n/a	0.5	n/a	0.4	n/a
Carb	53.6	56.9	53.1	55.8	31.3	36.0	41.4	44.7	26.8	33.7	27.5	39.8	20.1	29.1	8.1	8.8	31.2	34.1	41.4	44.7
Fat	18.6	19.7	20.0	21.0	23.3	26.8	27.7	29.9	14.2	17.8	23.0	33.2	15.6	22.5	42.7	46.2	38.4	41.9	27.7	29.9
Protein	21.6	22.9	20.7	21.7	30.2	34.7	22.8	24.6	38.5	48.5	18.6	27.0	33.5	48.4	41.6	45.0	22.0	24.0	22.8	24.6
FAME	5.4	5.7	16.0	16.8	16.4	18.9	21.4	23.1	9.2	11.6	12.8	18.6	10.0	14.5	39.1	38.8	22.1	24.2	21.4	23.1
Ash	5.8	n/a	4.9	n/a	13.0	n/a	7.3	n/a	20.6	n/a	31.0	n/a	30.8	n/a	7.3	n/a	8.4	n/a	7.3	n/a

(a) WW22 consisted of a 50/40/10 (dry wt basis) blend of sludge/food waste/FOG(scum)
(b) DAF = dry, ash-free

Table A.3. HTL performance data for waste feedstocks tested to date.

Operating Conditions and Results	50/50 Sludge (GLWA) WW06	50/50 Sludge (CCCSD) WW09	80/20 Sludge/FOG (CCCSD) WW10	Swine Manure WW15	50/50 Sludge (GLWA) MHTLS 13	AD Biosolids WW14	50/50 Sludge-no lime (CCCSD) WW17 SS-1	Cow Manure WW19A	Cow Manure WW19B
Temperature, °F (°C)	656 (347)	655 (346)	653 (345)	653 (345)	662 (350)	649 (343)	653 (345)	646 (341)	639 (337)
Pressure, psia (MPa)	2979 (20.5)	2845 (19.6)	2895 (20.0)	2840 (19.6)	2940 (20.3)	2840 (19.6)	2840 (19.6)_	2940 (20.3)	3000 (20.7)
Feed solids, wt%									
Ash included	20%	17.4%	16.8%	24.9%	15.3%	16.7%	14.6%	15%	15%
Ash-free basis	15%	14.5%	13.9%	21.8%	11.4%	11.3%	12.1%	12.3%	12.1%
Liquid hourly space velocity, vol./h per vol. reactor	3.6[(d)]	3.6[(d)]	3.7[(d)]	3.5[(d)]	4.0	3.5	3.5	3.5	3.5
Equivalent residence time, min.	17	17	16	17	15	17	17	17	17
Product yields[(a)] (dry, ash-free sludge), wt%									
Oil (biocrude)	44%	37%	50%	49%	41%	31%	41%	32%	39%
Aqueous	31%	34%	26%	21%	33%	35%	36%	42%	30%
Gas	16%	23%	19%	25%	19%	14%	19%	22%	29%
Solids	9%	5%	5%	5%	7%	20%	4%	3%	3%
Carbon yields									
Oil (biocrude)	58%	52%	60%	59%	51%	42%	55%	49%	53%
Aqueous	24%	29%	26%	22%	30%	31%	30%	29%	25%
Gas	8%	12%	9%	13%	9%	8%	10%	13%	15%
Solids	10%	6%	5%	7%	9%	20%	5%	10%	7%
HTL dry biocrude analysis, wt%									
C	78.5%	77.6%	77.9%	71.3%	78.5%	76.3%	75.9%	76.5%	76.5%
H	10.7%	9.9%	10.9%	10.0%	10.8%	9.4%	9.8%	9.2%	9.0%
O	4.7%	6.8%	7.2%	13.4%	5.8%	6.3%	8.5%	9.6%	9.8%
N	4.8%	5.2%	3.6%	4.3%	4.2%	5.1%	5.0%	3.9%	4.1%
S	1.2%	0.4%	0.3%	0.6%	0.6%	1.8%	0.6%	0.4%	0.3%
P	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ash	0.06%	0.07%	0.05%	0.28%	0.1%	1.0%	0.2%	0.4%	0.2%
HTL dry biocrude H:C ratio	1.6	1.5	1.7	1.7	1.7	1.5	1.5	1.4	1.4
HTL biocrude dry higher heating value, Btu/lb (MJ/kg)	16,900 (39.5)[(c)]	16,400 (38.0)[(c)]	16,900 (39.3)[(c)]	15,200 (35.3)[(c)]	17,000 (39.6)	(37.2)[(c)]	15,970 (37.1)	15,700 (36.5)	15,600 (36.4)
HTL biocrude moisture, wt%	4.4%	4.0%	3.2%	5.0%	3.5%	7.3%	7.0%	4.5%	4.8%
HTL biocrude wet density @25°C (g/ml)	0.98	0.99	0.95	0.96	0.95[(g)]	1.01[(f)]	Not ready	1.03[(g)]	1.04[(g)]
AP chemical oxygen demand (mg/L)	61,300	75,200	77,800	95,400	53,800	53,000	66,100	61,800	59,800

(a) Recovered after separations.
(b) Phosphorus partitioning is not directly modeled in Aspen because of the small quantity, most of which reports to the solid phase.
(c) Calculated using Boie's equation (Boie 1953).
(d) The experimental system includes a continuous stirred-tank reactor (CSTR) followed by a PFR. The CSTR helps prevent overheating of the feed.
(e) Runs A and B are are without and with catalytic additive in feed.
(f) Measured at 40°C
(g) Measured at 60°C
(h) WW runs were in the bench-scale system and MHTLS-13 was run in the engineering scale system.

Table A.4. HTL performance data for waste feedstocks tested to date (continued).

Operating Conditions and Results	Food Waste (From Coyote Ridge) WW20	Food Waste (From JBLM) WW21	Sludge/Food Waste/FOG (19% feed solids) WW22A	Sludge/Food Waste/FOG (25% feed solids) WW22B	Food waste (From EBS®) WW23	Sludge primary/ secondary (from GLWA) MHTLS 15	WW24 EBS® Slurry Food Waste/ GLWA Sludge	WW25 43/57 Sludge GLWA SS-1	WW25 43/57 Sludge GLWA SS-2	WW26 Waste from Yogurt Production	WW27 Food Waste Blend	MHTLS 16 EBS® Slurry Food Waste
Temperature, °F (°C)	653 (345)	642 (339)	639 (337)	639 (337)	639 (337)	655 (346)	638 (337)	648 (342)	609 (321)	647 (342)	631 (333)	660 (349)
Pressure, psia (MPa)	2855 (19.7)	2915 (20.1)	2765 (19.1)	2765 (19.1)	2840 (19.6)	2765 (19.1)	2946 (20.3)	2950 (20.3)	2956 (20.4)	2953 (20.4)	2895 (20.0)	2790 (19.3)
Feed solids, wt%												
Ash included	22.3%	25.7%	19.4%	24.6%	18.7%	15.4%	23.3%	16.0	16.0	20.0%	26.3%	17.1%
Ash-free basis	20.9%	24.6%	16.8%	21.3%	17.1%	12.0%	16.4%	11.2	11.2	18.7%	24.3%	15.8%
Liquid hourly space velocity, vol./h per vol. reactor	3.6	6.0	10.3	10.0	5.5	4.0	3.6	3.8	3.8	3.8	5.5	4.0
Equivalent residence time, min.	17	10	6	6	11	15	17	16	16	16	11	15
Product yields[(a)] (dry, ash-free sludge), wt%												
Oil (biocrude)	37%	42%	44%	45%	46%	42%	56%	35%	20%	64%	56%	52%
Aqueous	43%	36%	29%	31%	34%	36%	16%	37%	47%	20%	26%	29%
Gas	13%	20%	19%	18%	18%	17%	18%	15%	15%	12%	15%	18%
Solids	7%	2%	8%	6%	2%	5%	11%	13%	19%	3%	3%	2%
Carbon yields												
Oil (biocrude)	58%	64%	58%	61%	62%	52%	63%	47%	29%	70%	74%	69%
Aqueous	22%	22%	24%	23%	27%	33%	19%	27%	35%	22%	15%	20%
Gas	8%	11%	9%	9%	9%	9%	8%	8%	9%	5%	7%	9%
Solids	13%	3%	9%	7%	3%	7%	11%	17%	27%	3%	3%	2%
HTL dry biocrude analysis, wt%												
C	75.9%	74.1%	75.0%	74.7%	76.4%	77.8%	75.2%	77.6%	74.4%	74.9%	77.4%	75.6%
H	11.3%	11.1%	11.3%	11.6%	9.6%	12.4%	10.5%	9.6%	10.2%	11.0%	10.5%	11.7%
O	8.4%	10.6%	8.1%	8.0%	9.4%	3.6%	8.4%	5.4%	6.7%	8.5%	7.9%	8.2%
N	4.0%	4.0%	4.8%	4.9%	4.0%	5.3%	4.9%	6.2%	7.5%	5.3%	4.0%	3.6%
S	0.0%	0.0%	0.7%	0.7%	0.0%	0.9%	0.5%	1.0%	1.1%	0.3%	0.2%	0.2%
P	0.09%	0.00%	0.0%	0.00%	0.00%	0%	0.0%	0.0%	0.0%	0.00%	0.00%	0.00%
Ash	0.10%	0.11%	0.17%	0.14%	0.03%	0.03%	0.59%	0.08%	0.13%	0.04%	0.02%	0.68%
HTL dry biocrude H:C ratio (mol)	1.8	1.8	1.8	1.9	1.7	1.9	1.7	1.5	1.6	1.8	1.6	1.9
HTL biocrude dry higher heating value[(c)], Btu/lb (MJ/kg)	16,700 (38.8)	16,300 (37.8)	16,600 (38.7)	16,700 (38.9)	15,900 (37.0)	17,800 (41.4)	16,200 (37.7)	16,300 (37.9)	16,000 (37.2)	16,400 (38.2)	16,557 (38.5)	16,870 (39.2)
HTL biocrude moisture, wt%	2.6%	4.8%	3.7%	4.6%	1.7%	9.8%	2.9%	4.3%	35.5%	7.6%	3.9%	8.1%
HTL biocrude wet density @ 77°F (25°C) (g/ml)	1.00	1.01	0.96	0.96	0.98	0.97	0.95	0.98	1.00	0.92	0.96	0.94
AP chemical oxygen demand (mg/L)	90,500	111,550	81,500	100,100	74,333	81,600	78,930	58,233	58,567	95,900	89,963	69,700

(a) Recovered after separations.
(b) Phosphorus partitioning is not directly modeled in Aspen because of the small quantity, most of which reports to the solid phase.
(c) Calculated using Boie's equation (Boie 1953).

Table A.5. Hydrotreating performance data for waste feedstocks tested to date.

Component	WW06 (GLWA sludge) (HT-62005-60)	WW09 (CCCSD sludge) HT-62006-86	WW10 (CCCSD sludge/FOG) HT-62006-86	WW15 (Swine Manure)	MHTLS 13 GLWA HT282/HT283
Temperature, °F (°C)	752 (400)	752 (400)	752 (400)	752 (400)	752 (400)
Pressure, psia	1540	1535	1535	1515	1562
Guard bed catalyst	CoMo/alumina	CoMo/alumina		CoMo/alumina	CoMo/alumina
sulfided?	Yes	Yes		Yes	Yes
Main bed catalyst	CoMo/alumina	NiMo/alumina		NiMo/alumina	NiMo/alumina
sulfided?	Yes	Yes		Yes	Yes
Guard bed WHSV, wt./hr per wt. catalyst	0.46	0.68	0.65	0.42	0.72
Main bed WHSV, wt./hr per wt. catalyst	0.29	0.39	0.38	0.42	1.03
HTL biocrude feed rate, ml/h	5.6	7.3		2.16	
Time-on-stream (catalyst life)	302 hours	552 hours		133 hours	
Chemical H_2 consumption, wt/wt HTL biocrude (wet)	0.046	0.058	0.051	0.043	0.050
Product yields[a], lb/lb dry biocrude (vol/vol wet biocrude)					
Hydrotreated oil	0.82 (0.99)	0.84	0.82	0.85	0.83
Aqueous phase	0.14 (0.13)	0.13	0.17	0.13	0.16
Gas	0.08	0.08	0.06	0.06	0.04
Product oil, wt%					
C	85.6	85.0	84.8	85.7	84.7
H	14.6	14.3	15.1	12.9	14.3
O	1.0	<0.5	<0.5	<0.5	0.22
N	<0.05	0.73	0.07	1.60	0.84
S	7-10 ppm	0.03	0.14	<0.03	<0.3
Aqueous carbon, wt%	0.10	Not measured	Not measured	Not measured	Not measured
Gas analysis, volume%					
CO_2, CO	0	5	4	0	3
CH_4	51	9	33	45	19
C_2+	49	86	63	55	78
NH_3	Not measured	Not measured	Not measured	0	Not measured
NH_4HS	Not measured	Not measured	Not measured	0	Not measured
Total acid number, feed (product)	59 (<0.01)	Not measured	Not measured	Not calculated	Not calculated
Viscosity@40°C, cSt, feed (product)	400 (2.7)	Not measured	166 (3.7)	1040 (5.6)	165 (3.7)
Density@40°C, g/ml, feed (product)	0.98 (0.79)	0.99 (0.81)	0.95 (0.79)	0.96 (0.84)	0.95 (0.81)

Table A.6. Hydrotreating performance data for waste feedstocks tested to date (continued).

Component	WW22	MHTLS 13	WW20	WW21	MHTLS 15	2022 SOT Model
Temperature, °F (°C)	752 (400)	752 (400)	752 (400)	752 (400)	752 (400)	752 (400)
Pressure, psia	1560	1560	1560	1560	1560	1540
Guard bed catalyst sulfided?	NiMo/alumina No	CoMo/alumina Purchased Presulfided	CoMo/alumina Purchased Presulfided	CoMo/alumina Purchased Presulfided	CoMo/alumina Purchased Presulfided	CoMo/alumina Purchased presulfided
Main bed catalyst sulfided?	Ni/Mo/alumina No	NiMo/alumina Purchased Presulfided	NiMo/alumina Purchased Presulfided	NiMo/alumina Purchased Presulfided	NiMo/alumina Purchased Presulfided	NiMo/alumina Purchased presulfided
Guard bed WHSV, wt./hr per wt. catalyst	0.5	0.5	0.5	0.5	0.5	0.72
Main bed WHSV, wt./hr per wt. catalyst	0.5	0.5	0.5	0.5	0.5	1.03
HTL biocrude feed rate, ml/h	2.52	2.52	2.52	2.52	2.52	Commercial scale
Time-on-stream (catalyst life)	>135	284	284 to 591	591 to 1075	1075 to 2165	2000 hours (guard) 1 year (main)
Chemical H_2 consumption, wt/wt HTL biocrude (wet)	0.047	0.035	0.050	0.053	0.034	0.046
Product yields[(a)], lb/lb dry biocrude (vol/vol wet biocrude)						
Hydrotreated oil	0.84 (0.81)	0.84 (0.97)	0.83 (1.00)	0.84 (0.98)	0.81 (0.94)	0.81 (0.97)
Aqueous phase	0.09	0.15	0.12	0.12	0.12	0.12
Gas	0.07	0.05	0.06	0.05	0.06	0.10
Product oil, wt%						
C	86.0	85.1	85.2	85.1	84.7	85.3
H[(b)]	13.4	13.7	13.4	13.5	14.1	14.1
O	0.1	0.2	0.2	0.2	0.2	0.6
N	0.5	<1	1.1	1.1	<1	0.04
S	Below detection	0.0	0.0	0.0	0.0	0.0
Product oil, H:C	1.9	1.9	1.9	1.9	2.0	2.0
Aqueous carbon, wt%	Not measured	Not measured	Not measured	Not measured	Not measured	0.6
Gas analysis, volume%						
CO_2, CO	0	0	0	0	0	0
CH_4	20	32	39	42	37	39
C_2+	80	68	61	58	63	35
NH_3	Not measured	Not measured	Not measured	Not measured	Not measured	23
NH_4HS	Not measured	Not measured	Not measured	Not measured	Not measured	3
Viscosity@104°F (40°C), cSt, feed (product)	393 (3.1)	298 (3.0)	786 (3.2)	617 (3.3)	267 (2.6)	Not calculated
Density@104°F (40°C), g/ml, feed (product)	0.95 (0.81)	0.97 (0.79)	1.01 (0.81)	1.01 (0.81)	0.98 (0.79)	0.98 (0.79)

(a) Yield after phase separation.
(b) Due to problems with the CHNS analyzer, H was calculated by difference for samples WW20-22 and MHTLS15.

Appendix B – Technical Tables and Separate HTL Plant Economics

Table B.1. Processing area cost contributions and key technical parameters for the SOT cases for the combined wet waste HTL and upgrading pathway.

Processing Area Cost Contributions & Key Technical Parameters	Metric	2018 SOT with NH3 removal	2019 SOT with NH3 removal	2020 SOT with NH3 removal	2021 SOT with NH3 removal	2022 SOT with NH3 removal
Fuel selling price	$/GGE	$10.60	$8.38	$3.84	$3.15	$3.15
Conversion Contribution	$/GGE	$12.45	$10.24	$5.70	$4.97	$4.97
Perfomance Goal	$/GGE					
Production Jet	mm gallons/yr	N/A	N/A	N/A	N/A	$12
Production Diesel	mm gallons/yr	27	27	27	27	18
Production Naphtha	mm gallons/yr	9	9	9	9	7
Jet Yield (AFDW sludge basis)	gal/US ton sludge	N/A	N/A	N/A	N/A	34
Diesel Yield (AFDW sludge basis)	gal/US ton sludge	79	79	79	80	53
Naphtha Yield (AFDW sludge basis)	gal/us ton sludge	27	27	27	28	21
Natural Gas Usage (AFDW sludge basis)	scf/US ton sludge	3,055	3,055	3,717	2,588	2,561
Feedstock						
Total Cost Contribution	$/GGE fuel	-$1.95	-$1.95	-$1.95	-$1.92	-$1.92
Feedstock Cost (dry sludge basis)	$/US ton sludge	($185)	($185)	($185)	($185)	($185)
Sludge Dewatering						
Total Cost Contribution	$/GGE fuel	$0.30	$0.30	$0.31	$0.36	$0.36
Capital Cost Contribution	$/GGE fuel	$0.13	$0.13	$0.13	$0.13	$0.13
Operating Cost Contribution	$/GGE fuel	$0.18	$0.18	$0.18	$0.23	$0.23
Sludge HTL						
Total Cost Contribution	$/GGE fuel	$6.95	$6.95	$2.71	$2.40	$2.40
Capital Cost Contribution	$/GGE fuel	$4.72	$4.72	$1.40	$1.19	$1.19
Operating Cost Contribution	$/GGE fuel	$2.23	$2.23	$1.31	$1.21	$1.21
HTL Biocrude Yield (dry)	lb/lb sludge	0.44	0.44	0.44	0.45	0.45
Liquid Hourly Space Velocity (LHSV)	vol/h/vol	3.6	3.6	4.0	4.0	4.0

Processing Area Cost Contributions & Key Technical Parameters	Metric	2018 SOT with NH3 removal	2019 SOT with NH3 removal	2020 SOT with NH3 removal	2021 SOT with NH3 removal	2022 SOT with NH3 removal
Preheaters Capital Cost (installed)	$MM	56	56	10	9	9
HTL Water Recycle Treatment						
Total Cost Contribution	$/GGE fuel	$1.02	$1.02	$1.08	$1.07	$1.07
Capital Cost Contribution	$/GGE fuel	$0.23	$0.23	$0.23	$0.17	$0.17
Operating Cost Contribution	$/GGE fuel	$0.79	$0.79	$0.84	$0.90	$0.90
Balance of Plant - HTL						
Total Cost Contribution	$/GGE fuel	$0.06	$0.06	$0.07	$0.08	$0.08
Capital Cost Contribution	$/GGE fuel	$0.04	$0.04	$0.05	$0.04	$0.04
Operating Cost Contribution	$/GGE fuel	$0.02	$0.02	$0.03	$0.03	$0.03
Biocrude Transport	$/gge fuel	$0.10	$0.10	$0.10	$0.10	$0.10
Biocrude Upgrading to Finished Fuels						
Total Cost Contribution	$/GGE fuel	$3.67	$1.47	$1.09	$0.63	$0.64
Capital Cost Contribution	$/GGE fuel	$0.44	$0.37	$0.34	$0.33	$0.33
Operating Cost Contribution	$/GGE fuel	$3.22	$1.10	$0.76	$0.30	$0.30
Hydrotreating Mass Yield on dry Biocrude	lb/lb biocrude	0.82	0.82	0.82	0.82	0.82
Guard Bed Weight Hourly Space Velocity (WHSV)	wt/h/wt	0.46	0.67	0.72	0.72	0.72
Guard Bed Catalyst Lifetime	years	0.03	0.06	0.06	0.23	0.23
Hydrotreater Weight Hourly Space Velocity (WHSV)	wt/h/wt	0.29	0.39	1.02	1.02	1.02
Hydrotreater Catalyst Lifetime	years	0.03	0.06	0.06	1.00	1.00
Balance of Plant - Upgrading						
Total Cost Contribution	$/GGE fuel	$0.46	$0.44	$0.44	$0.43	$0.42
Capital Cost Contribution	$/GGE fuel	$0.28	$0.26	$0.26	$0.25	$0.25
Operating Cost Contribution	$/GGE fuel	$0.17	$0.17	$0.18	$0.18	$0.18

Processing Area Cost Contributions & Key Technical Parameters	Metric	2018 SOT with NH3 removal	2019 SOT with NH3 removal	2020 SOT with NH3 removal	2021 SOT with NH3 removal	2022 SOT with NH3 removal
Models: Case References		Sludge HTL 2018 SOT final.bkp;Sludge HTL Biocrude Upgrading 2018 SOT.bkp		Sludge HTL 2020 SOT final-base-split-hotoil_v2.bkp; Sludge HTL Biocrude Upgrading 2020 SOT	Sludge HTL 2021 SOT final.bkp; Sludge HTL Biocrude Upgrading 2021 SOT.bkp	Sludge HTL 2021 SOT final.bkp; Sludge HTL Biocrude Upgrading 2022 SOT for SAF.bkp

Table B.2. Processing area cost contributions and key technical parameters for the SOT cases for the separate wet waste HTL plant.

Processing Area Cost Contributions & Key Technical Parameters	Metric	2018 SOT with NH3 removal	2019 SOT with NH3 removal	2020 SOT with NH3 removal	2021 SOT with NH3 removal	2022 SOT with NH3 removal
HTL Biocrude selling price	$/GGE	$5.93	$5.93	$2.06	$1.85	$1.85
Conversion Contribution, Biocrude	$/GGE	$7.88	$7.88	$4.01	$3.63	$3.63
Production Biocrude	mm GGE/yr	4	4	4	4	4
Production Biocrude	mm gallons/yr	3	3	3	3	3
Biocrude Yield (AFDW sludge basis)	gal/US ton sludge	111	111	111	113	113
Natural Gas Usage (AFDW sludge basis)	scf/US ton sludge	1,865	1,865	2,527	1,378	1,378
Feedstock						
Total Cost Contribution	$/GGE fuel	-$2	-$2	-$2	-$2	-$2
Feedstock Cost (AFDW sludge basis)	$/US ton sludge	($185)	($185)	($185)	($185)	($185)
Sludge Dewatering						
Total Cost Contribution	$/GGE biocrude	$0.28	$0.28	$0.28	$0.34	$0.34
Capital Cost Contribution	$/GGE biocrude	$0.12	$0.12	$0.12	$0.12	$0.12
Operating Cost Contribution	$/GGE biocrude	$0.16	$0.16	$0.16	$0.22	$0.22
Sludge HTL						
Total Cost Contribution	$/GGE biocrude	$6.46	$6.46	$2.52	$2.23	$2.23
Capital Cost Contribution	$/GGE biocrude	$4.39	$4.39	$1.30	$1.11	$1.11
Operating Cost Contribution	$/GGE biocrude	$2.07	$2.07	$1.21	$1.12	$1.12
HTL Biocrude Yield (dry)	lb /lb sludge	0.44	0.44	0.44	0.45	0.45
Liquid Hourly Space Velocity (LHSV)	vol/h/vol	3.6	3.6	4.0	4.0	4.0

Preheaters Capital Cost (installed)	$MM	56	56	10	9	9
HTL Water Recycle Treatment						
Total Cost Contribution	$/GGE biocrude	$0.95	$0.95	$1.00	$1.00	$1.00
Capital Cost Contribution	$/gge biocrude	$0.21	$0.21	$0.22	$0.16	$0.16
Operating Cost Contribution	$/GGE biocrude	$0.73	$0.73	$0.78	$0.84	$0.84
Balance of Plant						
Total Cost Contribution	$/GGE biocrude	$0.06	$0.06	$0.07	$0.07	$0.07
Capital Cost Contribution	$/GGE biocrude	$0.04	$0.04	$0.04	$0.04	$0.04
Operating Cost Contribution	$/GGE biocrude	$0.02	$0.02	$0.03	$0.03	$0.03
Models: Case References		Sludge HTL 2018 SOT final.bkp		Sludge HTL 2020 SOT final-base-split-hotoil_v2.bkp	Sludge HTL 2021 SOT final.bkp	Sludge HTL 2021 SOT final.bkp

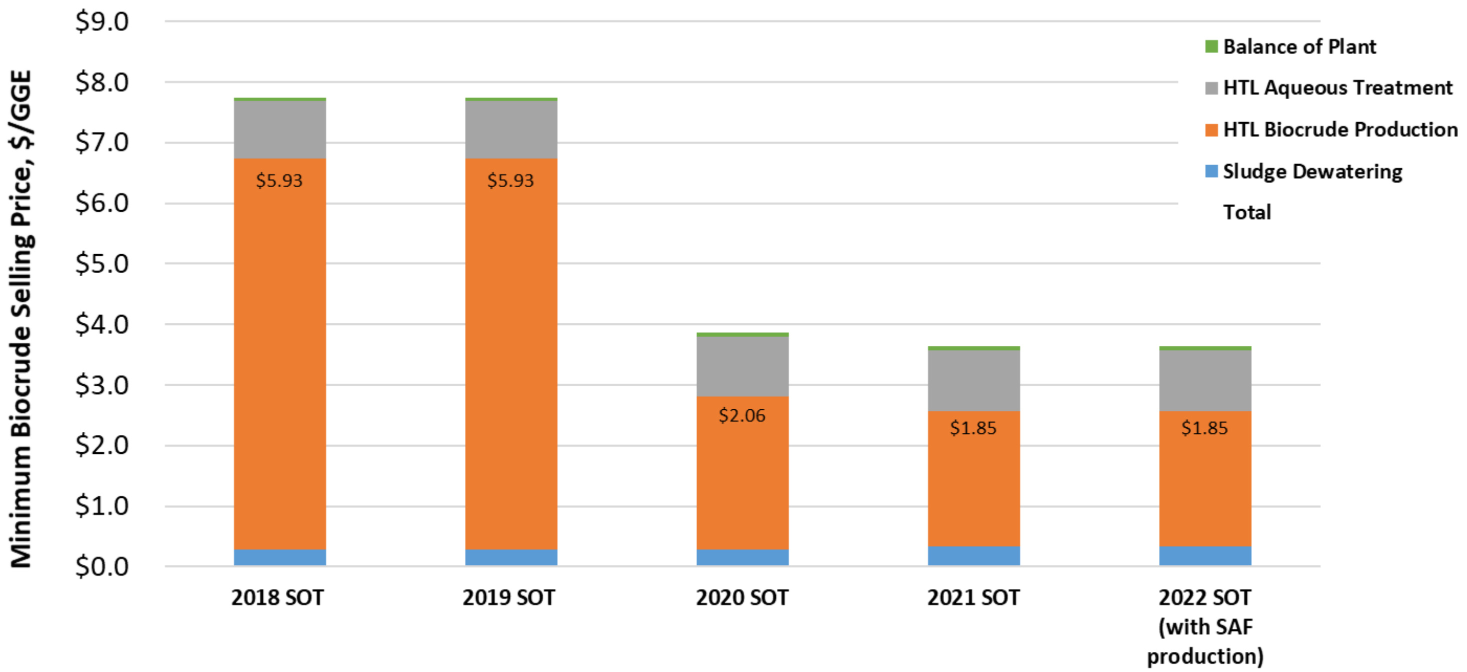


Figure B. 1. Hydrothermal liquefaction biocrude cost allocations.

Appendix C – Conversion Life Cycle Inventory and Energy and Carbon Efficiencies

Table C.1 and Table C.2 list the life cycle inventory for the hydrothermal liquefaction (HTL) and upgrading plants, respectively, that are provided to Argonne National Laboratory for Supply Chain Sustainability Analysis.

Table C.1. Hydrothermal liquefaction plant parameters for greenhouse gas and water analysis.

HTL Plant	2018/2019 SOT with NH_3 Removal	2018/ 2019 SOT without NH_3 Removal	2020 SOT with NH_3 Removal	2020 SOT without NH_3 Removal	2021 SOT with NH_3 Removal	2021 SOT without NH_3 Removal	2022 SOT with NH_3 Removal	2022 SOT without NH_3 Removal
Sludge Properties								
Solids content, %	20	20	20	20	25	25	25	25
Ash content (dry basis), %	15.02	15.02	15.02	15.02	15.02	15.02	15.02	15.02
Biocrude Properties								
Moisture content, %	4	4	4	4	4	4	4	4
Density, lb/gal	8.15	8.15	8.15	8.15	8.15	8.15	8.15	8.15
Lower heating value, Btu/gal	124,943	124,943	124,955	124,955	124,932	124,932	124,932	124,932
Inputs								
Sludge, lb/hr (dry basis)	9,167	9,167	9,167	9,167	9,167	9,167	9,167	9,167
Natural gas, lb/hr	310	135	420	245	229	194	229	194
Electricity, kW (HTL process)	376	342	407	374	326	310	326	310
Electricity, kW (at WRRF for chemical oxygen demand)	0	0	0	0	0	0	0	0
Dewatering polymer, lb/hr	31	31	31	31	42	42	42	42
Quicklime (CaO), lb/hr	994	0	994	0	407	0	407	0
Cooling water makeup, lb/hr	190	190	190	190	197	197	197	197
Outputs								
Biocrude, lb/hr	3,533	3,533	3,533	3,533	3,592	3,592	3,592	3,592
Aqueous phase, lb/hr	29,814	34,694	29,814	34,694	23,612	26,159	23,612	26,159
Wet solids,[(a)] lb/hr	5,681	5,681	5,681	5,681	5,684	5,684	5,684	5,684
Solids from HTL aqueous treatment	2,091	0	2,091	0	862	0	862	0
Carbon Efficiency								
Biocrude C / Feed C	65.4%	65.4%	65.4%	65.4%	66.9%	66.9%	66.9%	66.9%
Biocrude C / (Feed + NG) C	61.9%	63.8%	60.7%	62.6%	64.3%	64.7%	64.3%	64.7%
Energy Efficiency (LHV)	67.5%	70.9%	65.5%	68.7%	70.3%	71.0%	70.3%	71.0%

(a) 59% moisture content assumed
SOT = state of technology; WRRF = wastewater treatment and water resource recovery facility; NG = natural gas

Table C.2. Upgrading plant parameters for greenhouse gas and water analysis.

Upgrading Plant	2018 SOT	2019 SOT	2020 SOT	2021 SOT	2022 SOT
Fuel Product Properties					
Diesel density, lb/gal	6.66	6.66	6.66	6.66	6.66
Diesel lower heating value, Btu/gal	124,394	124,394	124,423	124,423	129,289
Naphtha density, lb/gal	6.13	6.13	6.13	6.13	6.21
Naphtha lower heating value, Btu/gal	114,650	114,650	114,652	114,562	111,849
Jet density, lb/gal	n/a	n/a	n/a	n/a	6.45
Jet lower heating value, Btu/gal	n/a	n/a	n/a	n/a	114,507
Inputs					
Biocrude, lb/hr	38,961	38,961	38,961	38,962	38,962
Natural gas, lb/hr	2,182	2,182	2,182	2,182	2,133
Electricity, kW	1,673	1,673	1,673	1,673	1,978
Cooling tower chemical, lb/hr	0.4	0.4	0.4	0.4	0.2
Boiler chemical, lb/hr	0.3	0.3	0.3	0.3	0.3
Hydrotreating catalyst, lb/hr	811	317	184	34.7	34.7
Hydrocracking catalyst, lb/hr	0.3	0.3	0.3	0.3	0.1
HDN catalyst, lb/hr	0.0	0.0	0.0	0.0	1.2
Hydrogen plant catalyst, lb/hr	0.4	0.4	0.4	0.4	0.4
Cooling water makeup, lb/hr	25,069	25,069	25,050	25,050	19,591
Boiler feedwater makeup, lb/hr	11,022	11,022	11,022	11,021	10,830
Outputs					
Diesel, lb/hr	22,577	22,577	22,583	22,583	14,913
Naphtha, lb/hr	7,124	7,124	7,119	7,119	5,492
Jet, lb/hr	n/a	n/a	n/a	n/a	9,376
Wastewater, lb/hr	22,773	22,773	22,460	22,460	22,734
Carbon Efficiency					
Fuel C / Biocrude C	87.0%	87.0%	87.0%	87.0%	87.0%
Fuel C / (Biocrude + NG) C	82.5%	82.5%	82.5%	82.5%	82.5%
Energy Efficiency (LHV)	85.5%	85.5%	85.5%	85.5%	85.5%

Appendix D – Cost Factors and Financial Assumptions

Table D.1. Cost factors for direct and indirect project costs.

Direct Costs	
Item	% of Total Installed Cost (TIC)
Buildings	4.0%
Site development	10.0%
Additional piping	4.5%
Total Direct Costs (TDC)	18.5%
Indirect Costs	
Item	% of TDC
Prorated expenses	10%
Home office & construction fees	20%
Field expenses	10%
Project contingency	10%
Startup and permits	10%
Total Indirect Costs	60%
Working Capital	5% of FCI
Land	HTL: 6 acres @ $15,000/acre Upgrading: 6% of Total Purchased Equipment Cost

Table D.2. Financial assumptions for the economic analysis.

Assumption Description	Assumed Value
Internal rate of return (IRR)	10%
Plant financing debt/equity	60% / 40% of total capital investment (TCI)
Plant life	30 years
Income tax rate	21%
Interest rate for debt financing	8.0% annually
Term for debt financing	10 years
Working capital cost	5.0% of fixed capital investment (excluding land)
Depreciation schedule	7-years MACRS[(a)] schedule
Construction period	3 years (8% 1st yr, 60% 2nd yr, 32% 3rd yr)
Plant salvage value	No value
Start-up time	6 months
Revenue and costs during start-up	Revenue = 50% of normal Variable costs = 75% of normal Fixed costs = 100% of normal
On-stream factor	90% (7,920 operating hours per year)

(a) Modified accelerated cost recovery system

Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7665)

www.pnnl.gov